TECHNISCHE UNIVERSITÄT BERGAKADEMIE FREIBERG

Graduiertenkolleg
„Geowissenschaftliche und Geotechnische Umweltforschung“
Interdisziplinäres Ökologisches Zentrum
Lehrstuhl für Hydrogeologie

Exkursionsführer

Geologisch-geotechnisch-ökologische Exkursion
nach

Slowenien

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Koordinator Graduiertenkolleg

Diese Seite bleibt leer

Geologisch-geotechnisch-ökologische Exkursion nach Slowenien

vom 18. September — 3. Oktober 2000

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Teilnehmer

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Dr. Christian WOLKERSDORFER
Katja ZIMMERMANN

Programm

Montag, den 18. September 2000

06:00 Abfahrt Otto-Meisser-Bau Freiberg
19:00 Ankunft in Werfen

Übernachtung: Pension Huber, Werfen

Dienstag, den 19. September 2000

06:30 Frühstück
07:20 Abfahrt
08:00 Eisriesenwelt

Geologie und Ökologie der Eisriesenwelt Werfen

Leitung: Eisriesenwelt

19:00 Ankunft in Bled (Veldes)

Übernachtung: Jugendherberge Bled, Bled (Veldes)

Mittwoch, den 20. September 2000

06:45 Frühstück
07:45 Abfahrt
08:00 Bleder See

Ökologie des Bleder Sees

Leitung: Spela Rekar, Ökologische Station Bled

16:00 Bergsturz

Folgen des Erdbebens 1998

Leitung: Andrej Gosar, Slowenisches Ministerium für Umwelt und Raumplanung Ljubljana

19:00 Ankunft in Soča

Übernachtung: Pension Lovec, Soča

Donnerstag, den 21. September 2000

07:00 Frühstück
08:00 Abfahrt
10:00 Kriegsmuseum Kobarid
13:00 Bergwerk Idrija

Geologisch-lagerstättenkundliche Verhältnisse der Quecksilberlagerstätte Idrija

Leitung: Dipl.-Ing. Geol. Bojan Režun, Dipl.-Ing. Tatjana Dizdarevič (Rudnik ŽS Idrija)

20:00 Ankunft in Vojsko

Übernachtung: Vojsko, ALIČ Turistična Kmetija, Spodnja Idrija

Freitag, den 22. September 2000

07:00 Frühstück
08:00 Abfahrt
09:00 Col

Hydrogeologische Verhältnisse am Rande des Ternovaer Waldes – Hubelj-Quelle, Testfeld Sinij vrh

Leitung: Dipl.-Ing. geol. Dr. Barbara Čenčur Curk (IRGO Ljubljana)

19:00 Karst Štanjel und Überraschung

Das Europäisch-Slowenische Karstprojekt

Leitung: Dušana Švagel, Grad Štanjel

19:00 Ankunft in der Unterkunft

Übernachtung: Gostilna Fratnik, Štanjel (St. Daniel)

Samstag, den 23. September 2000

07:00 Frühstück
08:00 Abfahrt
10:00 Skocjanske Jama (Höhle von St. Kazian)

Enten und ein World Heritage Objekt in Slowenien

Leitung: Skocjanske Jama

14:00 Divaca

Risnik – Karstphänomene

Leitung: Prof. Matschullat, Dr. Wolkersdorfer (TU Bergakademie Freiberg)

19:00 Ankunft in Piran (Pirano)

Übernachtung: Bungalowanlage Maona, Piran (Pirano)

Sonntag, den 24. September 2000

08:00 Frühstück
09:30 Piran (Pirano)
11:00 Sečovejske Soline, Sečovlje (Sicciole)
14:00 Supotski slap, Koštabona

Salinenschwimmen und Slap-Suchen

Leitung: Branko Cermelj, Ökologische Station Piran, Dr. Ch. Wolkersdorfer

19:00 Ankunft in Piran (Pirano)

Übernachtung: Bungalowanlage Maona, Piran (Pirano)

Montag, den 25. September 2000

07:00 Frühstück
08:00 Abfahrt
10:00 Autobahnbaustelle, Kozina

Verkehrswegebau und Umweltschutz im Karst

Leitung: Dr. Tadej Slabe, Karstforschungsinstitut Postojna

11:30 Karstforschungsinstitut Postojna (Adelsberg)
13:00 Abfahrt nach Laze
17:00 Mülldeponie Logatec

Kommunale Müllprobleme im Karst

Leitung: Dr. Ch. Wolkersdorfer, Prof. J. Matschullat, TU Bergakademie Freiberg

spät Ankunft in Laze

Übernachtung: Speleo Camping Laze, Laze

Dienstag, den 26. September 2000

07:00 Frühstück
08:00 Abfahrt
09:00 Karst von Notrjinska

Ljubljanica – „Fluß der Sieben Namen"

Leitung: Prof. Dr. F. Šušteršič, Universität Ljubljana

18:00 Ankunft in Laze

Übernachtung: Speleo Camping Laze, Laze

Mittwoch, den 27. September 2000

06:30 Frühstück
07:30 Abfahrt
09:00 Žirovski vrh

Die Uranlagerstätte Žirovski vrh

Leitung: Dipl.-Ing. Geol. I. Gantar, Dipl.-Ing. L. Zmago (Rudnik Žirovski vrh)

18:00 Ankunft in Škoflijca

Übernachtung: Pension „Grandovec", Škoflijca

Donnerstag, den 28. September 2000

06:30 Frühstück
07:30 Abfahrt
08:30 IRGO
10:00 Tunnelprojekt 5, Trojane

Ingenieurgeologische Fragestellung beim Tunnelbau an der Autobahn Lubljana-Maribor

Leitung: Prof. J. Likar, IRGO, Ljubljana

16:30 Laško
21:00 Ankunft Črna na Koroškem

Übernachtung: Hotel Club Krnes, Črna na Koroškem

Freitag, den 29. September 2000

05:00 Frühstück
05:30 Abfahrt
07:00 BergwerkVelenje

Grundwasserprobleme und Bergbau im Šalek Tal

Leitung: Dipl.-Ing. Bojan Lajlar, Dipl.-Ing. Marco Mavec, Premogovnik Velenje

16:00 Novi Dol

Paläo-Umwelt und Paläoklima im Ostalpenraum

Leitung: Dipl.-Geol. Dr. A. Bruch, Universität Tübingen

21:00 Ankunft Črna na Koroškem

Übernachtung: Hotel Club Krnes, Črna na Koroškem

Samstag, den 30. September 2000

07:30 Frühstück
08:30 Abfahrt
09:00 Bergwerk Mežica (Mieß)

Blei-Zink-Bergbau in den Karawanken

Leitung: Dipl.-Ing. Geol. Suzana Štrucl (Rudnik Svinka in Cinka Mežica)

15:00 Burg Celje
19:00 Ankunft Rogaška Slatina

Übernachtung: Aparthotel Slatina, Rogaška Slatina

Sonntag, den 1. Oktober 2000

08:00 Frühstück
09:00 Rogaška Slatina

Lebensquell Thermalquelle

Leitung: Dr. Peter Junes, Zrdavilišče Rogaška

18:00 Ankunft in Jeruzalem
18:30 Überraschung

Übernachtung: Gostišče Brenholc, Jeruzalem

Montag, den 2. Oktober 2000

06:00 Frühstück
07:00 Abfahrt
09:00 Mineralwasserfabrik Radenska, Radenci

Wasser aus hundert Quellen

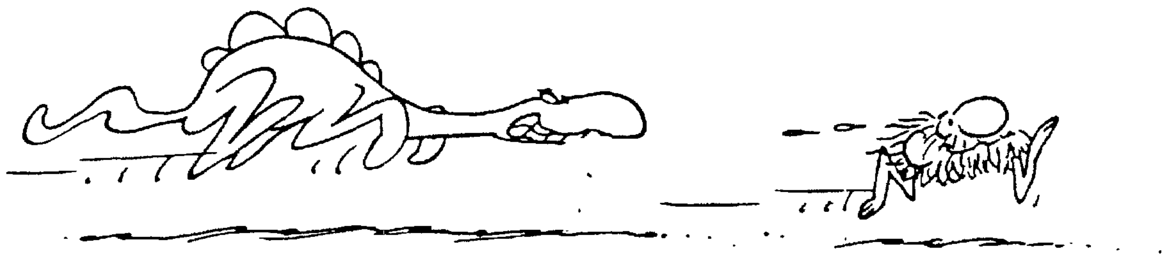
Leitung: Dipl.-Ing. Dušan Žižek, Radenska tri Srza

14:00 Abfahrt nach Linz
21:00 Ankunft in Linz

Übernachtung: Jugendherberge Linz

Dienstag, den 3. Oktober 2000

07:00 Frühstück
08:00 Abfahrt
19:00 Ankunft in Freiberg



Wir wünschen Ihnen viel Spaß in **Slowenien** und hoffen, daß Sie für sich und Ihre Zukunft etwas mit zurück nach Freiberg nehmen können.

Univ.-Prof. Dr. J. Matschullat Dr. Ch. Wolkersdorfer

P.S.: Abgabe des Exkursionsberichts spätestens am 24. Dezember 2000 – und wenn Sie sich und uns einen Gefallen tun wollen: bitte nicht mehr als fünf Schreibmaschineseiten Text!

Titelbild: Triglav in den Julischen Alpen. Geologische Übersichtskarte Sloweniens.

Unterkünfte

18.9.2000—19.9.2000
Pension Huber - Plainberg
Reitsam 54
A-5452 Pfarrwerfen
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19.9.2000—20.9.2000
Mladinsko Prenočišče Bledec
Grajska cesta 17
SI-4260 Bled
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20.9.2000—21.9.2000
Penzion Lovec
SI-5232 Soca
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21.9.2000—22.9.2000
ALIČ Turistična Kmetija
Srednja kanomlja 44
SI-5281 Spodnja Idrija
☏: 00386/65/742100

22.9.2000—23.9.2000
Gostilna in Prenočišča Fratnik
Kobdilj 51c
SI-6222 Štanjel
☏: 00386/67/79-116

23.9.2000—25.9.2000
Maona d.o.o. Piran
Arze 5
SI-6330 Piran
☏: 00386/5/6731291

25.9.2000—27.9.2000
Speleo Camping Laze
Laze 6b
SI-1370 Laze - Logatec
☏: 00386/61/744760

27.9.2000—28.9.2000
Penzion „Grandovec"
Dolenjska cesta 336
SI-1291 Škoflijca

☎: 00386/61/666449

28.9.2000—30.9.2000

Hotel Club Krnes
Mountain Bike Park
Center 153
SI-2393 Črna na Koroškem
☎: 00386/602/38-114

30.9.2000—1.10.2000

Aparthotel Slatina
Celjska c. 6
SI-3250 Rogaška Slatina

☎: 00386/63/818270

1.10.2000—2.10.2000

Gostišče Brenholc Jeruzalem
Jeruzalem 8
SI-2259 Ivanjkovci
☎: 00386/62/714504

2.10.2000—3.10.2000

Jugendgästehaus Linz
Stanglhofweg 3
A-4020 Linz
☎: 0043/732/664434

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Geologische Entstehungsgeschichte Sloweniens

nach Prof. Stanko BUSER

übersetzt von Irena TREBUŠAK; sprachlich überarbeitet von Ch. WOLKERSDORFER

Die geologische Geschichte Sloweniens ist sehr bunt und reicht vermutlich bis ins Präkambrium zurück. Dann wäre sie wenigsten 600 Millionen Jahre alt. Im Pohorje, Kozjak und Strojna sowie südlich von Črna na Koroškem befinden sich die ältesten Gesteine Sloweniens. Diese metamorphen Gesteine sind aus Sedimenten oder Magmatiten entstanden. Es handelt sich um Gneise, Glimmerschiefer, Amphibolite, Eklogite, Marmore und verschiedene Schiefer. Wegen des fehlenden Fossilinhalts läßt sich ihr Alter nicht bestimmen. Einige Experten stufen sie in das Präkambrium und Kambrium ein, andere in das Ordovizium bis Devon. Im letzten Fall wären sie „nur" 500 Millionen Jahre alt.

Die Gebiete, in denen Metamorphite vorkommen, werden den Ostalpen bzw. Alpiden zugerechnet. Südlich davon liegen die Dinariden. Ihre Grenze bildet die Periadriatische Naht, die den ehemaligen Kontakt zwischen der Afrikanischen und Europäischen Kontinentalplatte wiedergibt.

Gesicherte Alter liegen erst für die devonischen Gesteine in den Südkarawanken zwischen Logarška dolina (Logarskatal) und Jezersko fest. Das Unterdevon wird von plattig ausgebildeten Tiefseekalken gebildet, in denen Konodonten vorkommen. Im Mitteldevon wurden Flachwasserriffkalke aus Korallen und Hydrozoen abgelagert. Das Oberdevon ist wiederum durch Tiefseekalke vertreten.

Während des Unterkarbons war das Gebiet der Südkarawanken von Tiefsee bedeckt. Es entstanden heute geschieferte Flyschtonsteine, Sandsteine und Kalksteine. Nach einer kurzdauernden Festlandsperiode entstanden im Oberkarbon flachmarine Quarzsandsteine, Konglomerate, geschieferte Tonsteine und Kalksteine mit Foraminiferen, Bivalvien und Korallen. In der Nähe von Litija enthalten diese Sedimente Blei- und Zinkerze sowie Baryt und in den Karawanken Eisenerze.

Die unterpermischen Sedimentgesteine entsprechen denen des Oberkarbons, nur in den Südkarawanken überwiegen Kalksteine. Aus dieser Zeit stammen die Fossilien des weltbekannten Fundortes Dolžanova soteska (Dolžanschlucht) bei Tršič. Im mittleren Perm zog sich das Meer aus dem größten Teil Sloweniens zurück. Auf dem Festlandsbereich herrschte anderes Klima mit Sedimentation typischer roter Sandsteine, Schluffsteine, Tonsteine und bunter Breccie. Bei Žirovski vrh enthalten diese Gesteine Uranerz. Im oberen Perm transgredierte das Meer wieder über das gesamte Territorium Sloweniens. Die Flachmeerbereiche waren von Algen bedeckt und an einigen Stellen lebten verschiedene Muscheln und Brachiopoden. Aus dieser Zeit stammen auch schwarze Kalksteine und Dolomitsteine und südlich von Čirna na Koroškem Granit und Granodiorit.

Triasische Gesteine sind für Slowenien besonders wichtig. Von der Unteren bis Mittleren Trias wurden flachmarine Kalksteine abgelagert, die später zu Dolomitsteinen umgewandelt wurden. Die obere Mittlere Trias (Ladinium) war eine revolutionäre Ära für das slowenische Territorium. An Störungen zerbrach das Gebiet in tektonische Blöcke, die zum Teil in tiefmarinen Einfluß, zum Teil in festländischen gerieten. Längs der großen Störungszonen drang Magma ein und Vulkane förderten Aschen, die später zu Tuffen wurden. Daneben kamen tiefmarine Plattenkalke mit Hornsteinen, Tonsteine und Sandsteine zur Ablagerung. Häufige Fossilien in diesen Gesteinen sind Bivalvien, Ammoniten, Konodonten und Radiolarien. Einhergehend mit der vulkanischen Aktivität entstand die bedeutende Quecksilberlagerstätte von Idrija.

Bis zur Oberen Kreide war Zentralslowenien von Tiefsee bedeckt. Daher wird dieses Gebiet Slowenisches Becken oder auch Innere Dinariden genannt. Das Gebiet nördlich davon war während der oberen Trias flachmarin, und es wurden anfänglich Plattenkalke mit Hornsteinen, später mehrere 100 Meter mächtige Dachsteinkalke sedimentiert. Entsprechend des Ablagerungsmilieus und der Gesteinstypen, die in den Julischen, Kamniker und Savinjischen Alpen vorkommen, werden sie den Südalpen zugerechnet.

In der unteren Oberen Trias wurden südlich des Slowenischen Beckens Flachwasserkalke sedimentiert, die später meist zu Dolomitsteinen umgewandelt wurden. Verkarstung dieser eisenhaltigen Kalksteine führte zu deren Rotfärbung. Heute werden sie bei Hotravlje und Lesno Brdo als Bausteine zu Schmuckzwecken gewonnen. Die Gebiete von Notranjska und Dolenska sind durch Vorkommen roter Sandsteine, Tonsteine, Breccien und Bauxit der mittleren Oberen Trias gekennzeichnet. Flachwasserkalksteine der oberen Oberen Trias wurden dort später zu Dolomitsteinen umgewandelt. Das gesamte Gebiet südlich des Slowenischen Beckens mit Flachwassersedimentation zwischen Oberer Trias und Oberer Kreide wird als Äußere Dinariden bezeichnet.

Im flachmarinen Bereich der Nordkarawanken, nördlich der Periadriatischen Naht, entstanden in der Mittleren und Oberen Trias Kalksteine mit Blei- und Zinkerzen, die in Mežica abgebaut wurden. Interessanterweise können in diesem Gebiet keine Spuren vulkanischer Aktivität entsprechend der in den südlich liegenden Dinariden gefunden werden.

Aus dem unteren Teil des Unteren Juras (Lias) sind in den Südalpen Flachwasserkalke bekannt. Später wurde dieses Gebiet über den Meeresspiegel hinausgehoben, gelangte aber bald wieder unter tiefmarinen Einfluß mit Ablagerung roter Knollenkalke.

Der Zentralteil Sloweniens war im Jura von Tiefsee bedeckt und es lagerten sich Plattenkalke mit Hornsteinen, Tonsteinen und Mergel ab. Südlich dieses Grabens befand sich ein großes Flachwasserplateau, auf dem nur Flachwasserkalke sedimentiert wurden. Besonders interessant sind dunkle Kalksteine mit langen weißen Bivalvienschalen. Im Bauwesen ist dieses Gestein als Podpe-Marmor bekannt, den der Architekt Jože Plečnik für seine besten Kunstwerke verwendete. Interessant sind auch Korallen- und Hydrozoenkalke aus dem Oberen Jura. Sie entstanden aus Riffen, die denen des australischen Great Barrier Riffs entsprechen.

Die Südalpen und Zentralslowenien standen in der Kreide unter tiefmarinem Einfluß. Anfänglich entstanden grüne Flyschmergel und Sandsteine, später rote Mergel und Mergelkalksteine. Diese wurden in den Südalpen später erodiert und nur noch in Rdeči rob und Tolmin sind sie als geologische Besonderheiten vorhanden. In Zentralslowenien wurden die kreidezeitlichen Plattenkalke nach dem Ort Volče bei Tolmin auch als Volčekalkstein bezeichnet. Durch endogene Kräfte wurden diese Kalksteine schön gefaltet. Am Ende der Kreide wurden die Südalpen über den Meeresspiegel hinausgehoben. Die südlichen Teile Sloweniens waren in der Kreide vom Flachmeer bedeckt und dort lagerten sich mächtige, geschichtete Plattenkalksteine ab. Aus dieser Zeit stammen die schönsten slowenischen Karstgesteine für architektonische Zwecke, die früher in Vrhovlje, Kopriva, Tomaj und Kazlje gewonnen wurden. Heute arbeitet nur noch ein Steinbruch in Lipica.

Am Ende der Kreide war der größte Teil des slowenischen und kroatischen Istriens Festland, die Kalksteine verwitterten, und aus der roten Karsterde entstand später Bauxit. Durch erneute Transgression entstanden die nach dem Ort Kozina benannten Kozinakalksteine. Später bauten Foraminiferengehäuse die Nummuliten- und Alvedinkalksteine auf. Vor dem letzten Meeresrückzug aus slowenischem Gebiet wurde das Meer nochmals tiefer und auf seinem Boden entstanden Flyschmergel und Sandsteine, die heute den fruchtbaren Boden vom Vipava- und Pivkatal, dem Brkinigebiet und dem Küstenland bilden.

Nach einer ziemlich langen Festlandsperiode in Zentralslowenien entstehen im Mittleren Tertiär (Oligozän) größere Moorbecken, in denen Kohle- und Mergelschichten abgelagert wurden. Dazu gehören die Kohleablagerungen zwischen Laško, Trbovlje und Zagorje in der Nähe von Zabukovica und Pečovnik. Später wurden diese Gebiete sowie die Südalpen von Osten her transgrediert und unterlagen einer Flachwassersedimentation. Heute können die Gesteine dieser Zeit bei Bohinj, im oberen Savatal und den Kamniker Alpen gefunden werden. Wegen der Subduktion der Afrikanischen unter die Eurasische Platte begann in der Stajerska und Gorenska im Oligozän starke vulkanische Aktivität. Die Asche der Vulkane bildete am Festland und dem Meer Tuffablagerungen. In dieser Zeit intrudierte auch der Tonalit von Pohorje. Im westlichen Teil Pohorjes durchschlug die Dazitlava die Erdoberfläche.

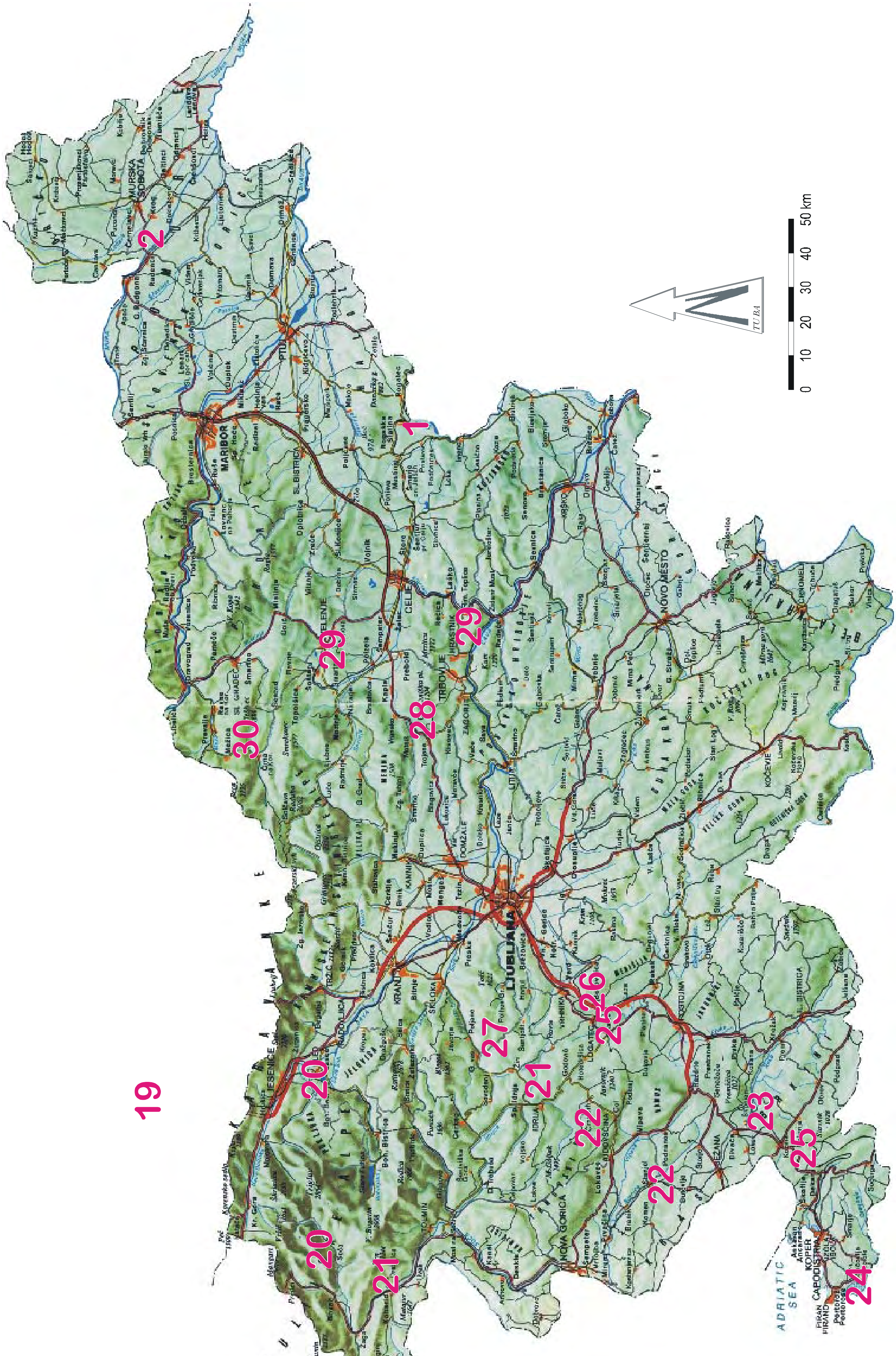
Am Ende des Oligozäns und am Anfang des Miozäns lagerten die Flüsse im Flachmeerbereich riesige Sand-, Kies-, und Tonmengen ab, die sich später zu Sandsteinen, Konglomeraten und Tonsteinen verfestigten. In der Mitte des Miozäns wurden die Gesteine Sloweniens gefaltet und zum Teil als große Decken überschoben. Diese Faltungen und Überschiebungen sind eine Folge der Unterschiebung der Afrikanischen Platte unter die Eurasische. Nach dieser revolutionären Ära überflutet das Meerwasser erneut die Gebiete von Štajerska und Dolenjska und aus dieser Zeit stammen die Kalk- und Mergelsteine mit Bivalvien, Gastropoden, Korallen und Seeigeln. Bald danach weicht das Panonische Meer in östlicher Richtung zurück. Die zurückgebliebenen Salz- oder Süßwasserbecken wurden durch Flußsedimente mit Quarzsand, Kies und Ton aufgefüllt. Im Prekmurje können in diesen Schichten Öl und Gas gefunden werden, das vermutlich schon im Miozän entstand. Das entstandene Festland wurde durch endogene Kräfte in Schollen zerbrochen, gehoben und gesenkt.

Im Mittleren Pliozän entstanden in Zentralslowenien größere tektonische Eintiefungen, die sich später mit Wasser füllten. Große oberoligozäne Wälder um diese Seen waren die Grundlage für die Entstehung mächtiger Lignitschichten in Velenje und weniger mächtiger Lignitschichten bei Ilirska Bistrica und zwischen Krmelj und Šentjanč.

Im Pliozän begann erneut eine tektonische Aktivität. In dieser Zeit war Slowenien zum Großteil ein Plateau. Wegen der langanhaltenden Hebung von Kalk und Dolomitsteingebieten kam es zur Verkarstung und der Verlegung von Flüssen unter die Oberfläche.

An langen Störungen entstanden zu Anfang der Eiszeiten große Eintiefungen wie die von Ljubljana, Brežice-Krško und Celje sowie das Ptuj Feld. In diese Eintiefungen lagerten die Flüsse Kiese und Sande aus den Glazialgebieten ab. Die bunte Landschaft Sloweniens ist während der vergangenen 10.000 Jahre geformt worden, nachdem die Inlandsgletscher dem heutigen warmen Klima zurückwichen.

Anmerkung der Übersetzer: Die Einführung in die Geologie Sloweniens von Prof. Buser wurde für den geologischen Laien geschrieben. Um den Charakter des Textes zu erhalten, wurde die Übersetzung zum Großteil nicht in die Fachsprache übertragen.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Exkursion Slowenien vom 08.07. - 15.07.1995

Bericht zu den Themen: Geologie Sloweniens, Baugesteine in Ljubljana, Uranbergwerk Zirovski Vrh

Bernd Schreiber

Geologische Verhältnisse Sloweniens

Slowenien, ein Land mit einer Größe von 20000 km^2, wird durch verschiedene Gebirgszüge geprägt, die auch jeweils unterschiedliche geologische Vergangenheiten haben. Im Norden Sloweniens befinden sich die Karawanken als östliche Fortsetzung der Karnischen Alpen. Die Julischen Alpen im Nordwesten Sloweniens stellen mit dem Berg Triglav (2864 m) die größten Erhebungen des Landes dar. Westlich von Sloweniens Hauptstadt Ljubljana erstrecken sich die Inneren Dinariden in Ost-West-Richtung. Südlich der Inneren Dinarden grenzen die Äußeren Dinariden an.

Die meisten Gebirge Sloweniens haben ihren Ursprung in der Alpidischen (Miozän) und der Dinarischen Gebirgsbildung (Pliozän bis Pleistozän) infolge der Subduktion der Afrikanischen unter die Eurasiatische Kontinentalplatte. Entsprechend der Längserstreckung der Gebirgszüge und dem Streichen tektonischer Vorzugsrichtungen kann das dinarische Streichen (NW-SE) vom alpidischen Streichen (E-W) unterschieden werden. Ein wichtiges Strukturelement ist die Periadratische Naht, die den Eurasiatischen Block von der Adriatischen Platte (Nordteil des Afrikanischen Blockes) und somit auch die Alpen im Norden von den Dinariden im Süden trennt. Die Periadriatische Naht ist von Ungarn bis nach Österreich nachgewiesen und verläuft innerhalb Sloweniens etwa in Höhe der Stadt Velenje in E-W-Richtung durch die Karawanken. Charakeristikum der Periadriatischen Zone sind vor allem entlang der Naht intrudierte Tonalite (Oligozän) bzw. Granodiorite und mitbeförderte Schollen aus Metamorphiten tieferer Stockwerke. Diese Gesteine (Muskovit-Gneise, Zweiglimmer-Gneise, Amphibolite, Marmore, Eklogite), die in den Regionen Pohorje (große Antiklinalstruktur zwischen Ravne na Koroskem und Maribor), Kozjak und Strojna vorkommen, sind mit kambrischen oder eventuell präkambrischem Alter die ältesten Gesteine Sloweniens. Südlich der Periadriatischen Zone treten keine Metamorphite mehr auf. Tonalite befinden sich außerdem im Kern des Pohorje.

Die geologischen Verhältnisse Sloweniens sind weiterhin durch intensive Deckentektonik geprägt. Im Zuge der kompressiven Beanspruchung der Gesteine im alpidischen Raum fand neben Faltung auch Deckenbewegung statt, nördlich der Periadriatischen Zone mit Deckenüberschiebungen nach Norden, südlich der Periadriatischen Zone hingegen mit Deckenüberschiebungen in Richtung Süden. Die Deckentektonik Sloweniens weist zum Teil komplizierte Muster auf (bei z.B. Idrija Überlagerung von drei Decken). Die Transportweiten der Decken betragen z.T. 30-40 km (Krn-Deckenüberschiebung im Norden Sloweniens).

Im Gegensatz zu den (prä-) kambrischen Metamorphiten und altpaläozoischen Grünschiefern und Phylliten z.B. im Kobansko (nördlich vom Pohorje) zeichnet sich das Jungpaläozoikum und Mesozoikum durch die Sedimentation von teilweise mächtigen Karbonatfolgen aus. Die Sedimentation von 600 m mächtigen Riffkalken im Devon wurde durch einsetzende orogene Bewegungen unterbrochen, anschließend wurden die Massenkalke von unterkarbonischen Flyschen diskordant überlagert. Aus dieser Zeit ist bereits der erste Paläokarst (Ausfüllung von Hohlräumen mit Flyschsedimenten) überliefert. Weiterhin erwähnenswert sind jungpaläozoische Ablagerungen wie z.B. Mittelkarbonische Fusulinenkalke, oberkarbonische submarine Molassesedimente (Quarzsandsteine, Konglomerate, Tonsteine) und mittelpermische Rotsandsteine (Grödener Fazies, siehe unten). Ab dem Ladinium (Trias) führte die Absenkung des E - W verlaufenden Slowenischen Troges im heutigen Bereich der Inneren Dinariden zur paläogeographischen Vorprägung und zur Ausbildung verschiedener Fazies. Während im Gebiet der Inneren Dinariden eine Trogsedimentation einsetzte, kam es im Norden und Süden zur Bildung von karbonatischen Plattformen mit der Sedimentation mächtiger Kalksteine (teilweise Umwandlung zu Dolomiten) einer Flachwasserfazies (Julische Karbonatplattform im N (u.a. Wettersteinkalk, Dachsteinkalk), Dinaridische Karbonatplattform im S -> Äußere Dinariden (u.a. Hauptdolomit)). Diese im Ladinium einsetzende Bruchbildung in E-W-Richtung und Entstehung einzelner Schollen führte zur Förderung von Diabasen, Tuffen, Quarzkeratophyren und Quarzporphyren. Die Grenzzonen des Slowenischen Troges stellen auch rezent seismische Schwächezonen dar.

Im Ladinium entstandene Frakturzonen dienten örtlich als Bahnen für hydrothermale Wässer und weisen dadurch lokale Vererzungen auf (z.B. Quecksilberlagerstätte in Idrija).

Mehrere Kilometer mächtige, z.T. Rudisten führende Kalksteine und Dolomite des Juras und der Kreide sind besonders im Bereich der Äußeren Dinariden in Südwest-Slowenien zu finden. Dort setzte vor bereits 16 Mio. Jahren im Zuge weiträumiger Hebungen die Verkarstung ein. Durch die Entstehung von intramontanen Becken mit teilweise rezenter Absenkungstendenz, wie z.B. bei Ljubljana, kam es durch Reliefversteilungen auch im Quartär zur Intensivierung des Karstes und der Verlegung des Entwässerungsnetzes in zunehmend tiefere Stockwerke. Intramontane Becken mit jungen Subsidenzbewegungen sind in Slowenien u.a. bei Velenje zu finden, in denen es insbesondere während des Jungtertiärs zur Ablagerung von mächtigen klastischen Sedimenten und teilweise auch Kohlen bzw. Lignit kam. Weiterhin erwähnenswerte tertiäre Gesteine sind mächtige miozäne Konglomeratserien im Osten Sloweniens (Panoniden) als Indikatoren von verstärkten Bodenunruhen der Alpidischen Gebirgsbildung. Im Zuge der Alpidischen Tektonisierung kam es infolge niedrig hydrothermaler Fluidmigrationen zur Bildung von Pb- und Zn-Erzlagerstätten bei Mezica in den Nordkarawanken.

Die dinarische Bruchbildung fand überwiegend vom Oberpliozän bis in das Pleistozän statt. Zahlreiche dinarisch (NW - SE) streichende Blattverschiebungen in Slowenien weisen auch rezente Lateralbewegungen auf. (z.B. Idrija-Störung: z.T. 8-9 km dextraler Versatz, jährliche Bewegung im mm-Bereich)

Baugesteine Sloweniens

Zahlreiche, in Slowenien vorkommende Gesteine werden als Bausteine für verschiedene Bauwerke genutzt. In Sloweniens Hauptstadt Ljubljana ist diese Vielfalt von Natursteinen slowenischer und ausländischer Herkunft zur Verwendung von Bausteinen bzw. Gebäudeverzierungen zu finden. Zur Verkleidung von Gebäudefassaden und für Treppen und Mauern finden oftmals mesozoische Kalksteine Verwendung wie z.B. die für die Äußeren Dinariden typischen dunklen Liaskalksteine mit hellen, mehrere cm großen Rudistenschalen (Podpec-Marmor) Malmkalke (am Rathaus; mit Hydrozoenkolonien und einer oolithischen Matrix) und kretazische Rudistenkalke. Teilweise eingeschaltete Dolomitgerölle sind stärker verwittert als der umgebende Kalkstein. Auch in den Bausteinen, wie z.B. in triassischen Kalksteinen, sind oft Paläokarsterscheinungen zu beobachten (zementierte Klüfte). Joze Plecnik, ein berühmter Architekt, der u.a. an dem Bau der Nationalbibliothek (1939-1941) beteiligt war, nutzte ebenfalls kretazische Kalksteine (mit Pachiodeata, Oberkreide) und die dunklen Liaskalke. Für Pflastersteine und Bürgersteige werden oftmals Magmatite verwendet, so z.B. Bozener Quarzporphyr (karbonische Vulkanite aus Südtirol), Granodiorit und Granit. Einige Bauwerke sind mit mehreren Gesteinen versehen (Dichterdenkmal im Stadtzentrum: Gabbro, Granit, Kalktuff aus Mazedonien). Ein aus Ammonitico Rosso-Kalkstein (Knollenkalke, Lias-Malm, z.T. Ammoniten führend) gefertigter Brunnen vor dem Bischofspalast fällt durch seine intensive Rotfärbung auf.

Neben slowenischen Natursteinen sind in Ljubljana auch weltbekannte Bausteine wie Carrara-Marmor aus Norditalien und nordischer Larvikit zu finden.

Uranbergwerk Zirovski Vrh

Das Uranbergwerk Zirovski Vrh (Vrh (slowenisch): Berg) befindet sich ca. 20 km südwestlich der Stadt Skofja Loka. Das in dem Bergwerk gewonnene Uran diente vorrangig der Versorgung des Kernkraftwerkes Krsko. Erstmals entdeckt wurde die Uranlagerstätte im Jahr 1960. Ab 1961 wurden umfangreiche Explorationsprogramme durchgeführt, die bis 1968 unter der Leitung des Landes Jugoslawien standen und anschließend von der slowenischen Provinzregierung übernommen wurden. 1976 fiel die Entscheidung zum Ausbau eines Bergwerkes, in dem schließlich nach der ersten Erschließung des Erzkörpers (1981) im Jahre 1984 erstmals im größeren Umfang Uranerz gefördert wurde. Da jedoch der Uranpreis auf dem Weltmarkt besonders in den 80er Jahren stark fiel und das Uranbergwerk Zirovski Vrh zu unproduktiv war, um sich dem Weltmarktpreis anzupassen

(Beispiel: Uranpreis auf Weltmarkt 1990: 10-20 $/Pfund, Produktionskosten Zirovski Vrh 1990: 60 $/Pfund), mußte das Bergwerk Zirovski Vrh 1991 den Betrieb einstellen. Derzeitige Arbeiten dienen lediglich der endgültigen Schließung und umweltrelevanter Problemstellungen wie z.B. Deponierung von Bergematerial (taubes Gestein) und Erz-Aufbereitungsrückständen. Das Bergwerk förderte in 5 Jahren insgesamt ca. 482 t Uranerz (U_3O_8) mit einer maximalen jährlichen Produktion von ca. 126 t Uranerz im Jahre 1985.

Die Uranlagerstätte, die sich in einer tektonischen Decke befindet, liegt in den Grödener Sandsteinen, einer permischen Formation aus überwiegend fluviatilen liegenden grauen und hangenden roten Sandsteinen (gradiert) und Konglomeraten mit teilweise eingeschalteten Tonsteinen (mudstones). Der Grödener Sandstein, der im Bereich von Zirovski Vrh auf einer Länge von 7-10 km und einer Breite von maximal 2 km in NNW-SSE-Richtung ausbeißt, ist von den Italienischen Südalpen über Südösterreich und Slowenien bis nach Ungarn verbreitet. Weitere Uranlagerstätten im Grödener Sandstein treten jedoch nur in in den Meesek-Bergen (Ungarn) auf. Im Liegenden des Grödener Sandsteins schließen sich permokarbonische Schwarzschiefer, im Hangenden oberpermische Bellerophon-Dolomite an. Der Erzkörper befindet sich in den grauen Sandsteinen des Unteren Grödener Sandsteins (Mittel-Perm) und hat eine Länge von 200 m, eine Breite von 100 m und eine Tiefe von 180 m. Aufgrund einer intensiven alpidischen Faltung hat der Erzkörper, der Schichtung entsprechend, eine sigmoidale Form. Die einzelnen Vererzungen sind linsenförmig ausgebildet mit Längen von einigen 100 m, Breiten von ca. 100 m und Mächtigkeiten von ca. 4 m.

Die Herkunft des Urans ist noch nicht geklärt, jedoch ist belegt, daß es sich um epigenetische, niedrig-hydrothermale Uranmineralausscheidungen handelt. Im Grödener Sandstein auftretende Keratophyrfragmente geben einen Hinweis auf den möglichen Ursprung des Urans. Eingeschaltetes organisches Material führte vermutlich zur Reduzierung der uranbeladenen Lösungen, so daß Uranminerale auskristallisieren konnten. In der Lagerstätte kommen vor allem die Uranminerale Pechblende (UO_2, mit Pb-Spuren) und untergeordnet Coffinit ($USiO_4$) in Form von feinkörnigen Aggregaten im Zement vor. Die Urangehalte des Erzes betragen 0,01-1,0 Gew.-%, im Mittel ca. 0,1 %. Im Erzkörper treten zusätzlich Mineralisationen von zahlreichen Sulfiden und Gangartminerale (Quarz, Calcit, Dolomit etc.) auf.

Das Uranerz wurde in vier Sohlen abgebaut. Aufgrund der hohen Radonkonzentrationen in der Luft war eine gute Bewetterung Vorraussetzung für den Bergbaubetrieb. Jeder abbaubedingte Hohlraum wurde mit einem Bergematerial-Zement-Gemisch rückverfüllt. Das Grubengebäude umfaßte insgesamt 90 km Strecken. Die Förderung von Bergematerial (< 150 g U_3O_8/Tonne Gestein) betrug im Durchschnitt 125% des geförderten Erzes. Nach dem Abbau erfolgte die Trennung von Bergematerial und Erz durch radiometrische Messungen. Das Bergematerial wurde direkt zur Deponierung einige Kilometer südlich der Mine transportiert, während das Erz zwecks Aufbereitung zur Erzhütte, die sich auch auf dem Bergwerksgelände befindet, befördert wurde. Über aufwendige Aufbereitungsprozesse wurde der sogenannte yellow cake (Ammoniumdiuranat) hergestellt, der zur Weiterverarbeitung zum Kernkraftwerk Krsko transportiert wurde. Das Uran wurde letztendlich als nuklearer Brennstoff im Kernkraftwerk Krsko verwendet.

Die derzeitige Hauptproblematik liegt bei der Deponierung der Aufbereitungsrückstände (Wassergehalt: 14%) von der Erzhütte, ein Material, das höhere Umweltauflagen verlangt als das gewöhnliche Bergematerial und daher gesondert deponiert werden muß. Für den Deponiestandort wurde eine Fläche wenige Kilometer östlich des Bergwerkes ausgewählt. Die Deponie wurde auf einer morphologischen Erhebung angelegt, damit insbesondere im Sommer vorhandene höhere Radonbelastungen der Luft durch Wind stärker verdünnt werden können. Sie umfaßt ein Volumen von 400000 m^3 Aufbereitungsrückständen und hat eine Erstreckung von 500 m in N-S-Richtung und 300 m in E-W-Richtung. Insgesamt besitzt die Deponie ein Fassungsvermögen von ca. 600000 m^3. Aufgrund der Schließung des Bergwerkes bleiben ca. 200000 m^3 Fassungsvermögen ungenutzt.

Der Wahl dieses Deponiestandortes gingen detaillierte Kartierungen und Bohrungen voraus. Hauptargument war hierbei die Beschaffenheit des Untergrundes als natürliche Abdichtung unter der Deponiebasis, der aus obertriassischen (Karnium) siliziklastischen Gesteinen (Sandstein, Siltstein, Konglomerat, Karbonate) besteht. Im Liegenden der Siltsteine stehen zudem Tuffite an. Kf-Werte von 10^{-5}m/s (Konglomerat) bis 10^{-7}m/s (Siltstein) schienen als Deponiebasis relativ geeignet.

Eine 1 m dicke Schicht Bergematerial und eine Kunststofflage stellen die "Basisabdichtung" der Deponie dar. Eine endgültige Oberflächenabdeckung wird mit der Aufschichtung von siltigem Gesteinsmaterial aus dem Bau eines Entwässerungstunnels (siehe unten) erstellt. Ein Rückhaltebecken am Fuß des Deponiekörpers fängt das Oberflächenwasser auf, das durch einen Überlauf, abgesehen von der Sedimentation des Schlammes im Becken, ungeklärt in den nächsten Vorfluter gelangt.

Als der Standort zur Deponierung der Aufbereitungsrückstände bereits genutzt wurde, stellte sich heraus, daß sich die Deponiefläche auf einer großen, Rutschmasse mit einem Volumen von ca. 2,5 Mio m^3 befindet. Die konkav gewölbt verlaufende Gleitfläche (vgl. listrische Störung) fällt, entsprechend der Hanglage, nach NNW ein. Zu erkennen ist die Gleitfläche der Rutschung anhand der Verwerfung älterer Störungsflächen und auch anhand der Abschneidung von Bohrlöchern. Im Bereich des Ausbisses der Rutschungsfläche wurde zudem die am Rand der Deponie verlaufende Drainage-Rinne zerstört. Stärkere Regenfälle, wie z.B. im Jahre 1990, und eine mittlerweile größere Auflast auf dem Rutschungskörper führten zur Reaktivierung der Rutschung mit Gleitbewegungen bis zu 1 mm/Tag. In den oberen Zonen der Deponie bildeten sich offene Spalten, die aufgrund der Aufnahme von Oberflächenwasser zusätzlich eine Gefährdung für das Bodenreich und den nächsten Vorfluter darstellten und daher mit Ton verfüllt wurden.

Um die Gefährdung der Deponie infolge eines Abrutschens zu minimieren, wird derzeit unter der Deponie ein Entwässerungstunnel vorgetrieben. Zweck des Tunnelbaus ist, den Grundwasserspiegel auf das Niveau des Tunnels abzusenken und dem Rutschungskörper somit Wasser zu entziehen. Der Tunnel, mit Gleitbögen ausgebaut und zusätzlich mit Stahlgitter und Spritzbeton stabilisiert, verläuft unter der Rutschung überwiegend im Siltgestein und hat zur Entwässerung ein Gefälle von maximal 3° zum Mundloch. Unter dem östlichen Rand der Deponie verzweigt sich der Tunnel in zwei Seitenstrecken, die in einem Winkel von 90° zum Haupttunnel verlaufen. In die Seitenstrecken (Länge je 150 m) werden zur zusätzlichen Entwässerung des Gebirges mehrere Horizontalbohrungen vorgetrieben.

Durch Rutschungsvorgänge an der Schnittstelle Tunnel-Rutschfläche ist die Spritzbetonwand des Tunnels örtlich zerschert, hinzu kommt ein hoher Quelldruck der anstehenden Siltgesteine.

Erste Erfolge des Entwässerungstunnels zeichneten sich im oberen Bereich (Konglomerate) und im unteren Bereich der Deponie ab, in denen das Grundwasser bis auf das Tunnelniveau um bis zu 20m abgesenkt werden konnte, die im zentralen Bereich anstehenden Siltsteine konnten jedoch bisher noch nicht ausreichend entwässert werden. Dieser Tatbestand entspricht auch den Ergebnissen vorher durchgeführter Pumpversuche, die starke Grundwasserschwankungen und -absenkungen in den oberen und unteren Bereichen ergaben, im zentralen Bereich die Grundwasserabsenkung jedoch sehr gering war. Die Gleitbewegungen konnten bisher auf 0,1mm/Tag minimiert werden. Regelmäßige Extensiometermessungen im Tunnel und Oberflächenvermessungen (zweimal im Jahr) dienen zur ständigen Überwachung der Rutschung.

GEOLOGISCHE STRUKTUR IM TUNNELBEREICH

BUDKOVIČ T

EINLEITUNG

Bei der Zusammenstellung der beim Ausbruch des Karawankentunnels durchgeführten geologischen Beobachtungen wurden die handschriftlichen Aufzeichnungen von A. Ločniškar, V. Juvančič, L. Placer, J. Uhan, D. Skaberne, M. Marinko und T. Budkovič verwendet. Die Daten über die Oberflächengeologie wurden den Erläuterungen und der Geologischen Grundkarte für Klagenfurt (Buser, 1980), Villach und Pontebba (Jurkovšek, 1987), dem „Geologisch-geotechnischen Bericht für das Ausschreibungsprojekt" des Karawanken-Straßentunnels (Geološki zavod Ljubljana, Verfasser Drobne, 1979) sowie der Wiederaufnahme der geologischen Karte 1:5000 in den Jahren 1988–90 (Budkovič, 1990) entnommen. Die Ortsbrust des Tunnels wurde laufend im Maßstab 1:100 kartiert. Während des Tunnelvortriebs wurden so 1.100 Örter kartiert. Bei jedem Abschlag wurde auch eine Probe genommen.

Um eine Gefahr von Wassereinbrüchen und Gasaustritten rechtzeitig festzustellen, wurden entlang der Tunnelachse je drei Schlagbohrlöcher unter verschiedenen Neigungswinkeln hergestellt. Ab Station 2300 m wurde jeweils eines dieser Bohrlöcher in der Richtung 330°, quer zur vorherrschenden Richtung der geologischen Struktur, gebohrt. Das Bohrklein wurde beobachtet und das lithologische Gefüge prognostiziert. Auf diese Weise wurde versucht, die Grenze zwischen den undurchlässigen Gesteinsschichten des Oberkarbons-Unterperms und den durchlässigen Schichten der Trias rechtzeitig und möglichst genau zu bestimmen. Die Daten der Kartierung wurden zuerst auf dem Grundriß und dem Längenschnitt im Maßstab 1:100 eingetragen.

Zur Orientierung der Baumannschaften diente ein Profil im Maßstab 1:1000, auf dem die wichtigeren Daten eingetragen wurden. Zur besseren Übersicht der geologischen Verhältnisse im Tunnelbereich wurde ein geologischer Längenschnitt im Maßstab 1:5000 auf Grund der geologischen Tunnel- und Oberflächendaten ausgearbeitet.

LITHOSTRATIGRAPHISCHE VERHÄLTNISSE

Oberkarbon und Unterperm

Die Schichten des Oberkarbons und des Unterperms bilden in der Entwicklung der klastischen Sedimentite (in Österreich Auernik – und Rattendorfer Schichten) die ältesten Gesteinsschichten im Tunnelbereich. Bei der geologischen Beobachtung der Örter und bei der geologischen Oberflächenkartierung wurden sie als lithostratigraphische Einheit betrachtet. Sie sind im Tunnelbereich zerrüttet und tektonisch verschoben.

Gemäß der Daten aus den Erläuterungen zur Geologischen Grundkarte für Klagenfurt, Villach und Pontebba beträgt ihre Dicke über 1000 m. Die Schichten stehen zwischen Station 1721 und 2386 m geschlossen an und setzen sich aus Tonschiefer Siltstein, Sandstein, Quarzkonglomerat, Kalkbreccie und Kalkstein zusammen (Bild 1). Die feinkörnigen klastischen Sedimentite und der Kalkstein haben wegen der Menge an organischen Stoffen eine schwarze bis dunkelgraue Farbe. In den Schichten kommt auch Methan vor.

Der Tonschiefer besteht aus den tonigen Mineralen Illit, Chlorit und Montmorillonit. Außerdem enthält er noch Quarz, Siderit, Ankerit und Dolomit. Der Tonschiefer verursachte durch sein Anschwellen die größten Schwierigkeiten.

Im Siltstein überwiegen tonige Mineralien, Pyrit und größere Quarzmengen als im Schieferton.

Der Sandstein enthält Quarz, Quarzglimmer, Lithiumquarz und karbonatischen Quarz.

Das Quarzkonglomerat besteht aus gut gerundeten, 2–5 cm großen Quarzkieseln und enthält auch viel Lidit- und Kalkschotter.

Die Kalkbreccie setzt sich aus Kalksteinbrocken und karbonatischen Sandkörnern zusammen und hat eine dunkelgraue Farbe. Sie enthält auch zahlreiche fossile Reste.

Der Kalkstein ist dunkelgrau bis schwarz und häufig mit Kalzitadern durchzogen. Er ist stellenweise quarzig und dolomitisch. Manchmal enthält er Körner autogenen Quarzes. Es sind zahlreiche fossile Reste anzutreffen.

Aus den Bohrlöchern KT-3 und K-J wurden Kalksteinproben entnommen und mikropaläontologisch untersucht. Die im unteren Teil des Bohrlochs KT-3 gefundenen Fossile weisen auf das Oberkarbon (Gzelian) und die im im oberen Teil auf das Unterkarbon hin. Da die Gesteine des Oberkarbons lithologisch nicht von denen des Unterperms getrennt werden können und die mikropaläontologischen Untersuchungen dieser Gesteinsproben noch nicht abgeschlossen sind, wurden sie zur ausgewogenen lithostratigraphischen Einheit der klastischen Sedimentite des Oberkarbons-Unterperms zusammengefaßt (in Österreich Auernik- und Rattendorfer Schichten).

Trogkofel-Kalkstein

Dieser Kalkstein wird zur oberen Stufe des Unterperms gerechnet. Er ist etwa 100 m dick und rötlich, rosa, weiß oder hellgrau. Im Tunnelbereich enthält er wenig Fossile, obwohl er anderswo reich an Fossilen ist. Der Kontakt zwischen den Schichten des Oberkarbons, des Unterperms und des Trogkofel-Kalksteins ist auf der Oberfläche, über dem Tunnel, tektonisch. Im Tunnel ist dieser Kalkstein nicht anzutreffen.

Mittelperm

Tarvisio-Breccie, Grödener Schichten

Diese Gesteine liegen in den Karawanken gewöhnlich auf dem Trogkofel-Kalkstein, können aber auch den klastischen Sedimentiten des Unterperms liegen. Auf der Oberfläche, über dem Tunnel, ist auf dem Trogkofel-Kalkstein ein graues Quarzkonglomerat mit Linsen grauen Quarzsandsteins anzutreffen. Dieses steht im Tunnel zwischen den Stationen 1565 und 1703 m an. Die grauen klastischen Sedimentite sind auf Grund der Oberflächendaten 30 m dick und im Tunnel selbst etwas dicker. Über ihnen liegt ein Komplex, in dem sich Tarvisio-Breccie, rotes Quarzkonglomerat, Quarzsandstein und roter Tonschiefer abwechseln. Roter Tonschiefer steht im Tunnel als tektonische Einlagerung im Bellerophon-Dolomit schon zwischen Station 933 und 1098 m an. Diese Schichten sind geschlossen zwischen Station 1096 und 1606 m und zwischen 1606 und 1720 m wieder als tektonische Einlagerungen anzultreffen.

Die Tarvisio-Breccie setzt sich hauptsächlich aus Trümmern roten, rosa und grauen Trogkofel-Kalksteins mit Bindemittel aus rotem Tonstein zusammen (Bild 2). Zwischen den Kalkstücken können auch weiße und rosa Quarzkiesel auftreten.

Rotes Grödener Quarzkonglomerat und Sandstein setzten sich größtenteils aus Kieseln und Körnern weißen und rosa Quarzes zusammen.

Der rote Tonschiefer enthält weniger tonige Minerale als die schwarzen klastischen Sedimentite des Oberkarbons und des Unterperms, jedoch mehr Karbonate und Plagioklase.

Oberperm

Bellerophon-Dolomit

Im Tunnel steht er als tektonische Einlagerung zwischen Station 975 und 1098 m an, wo er mit rotem Tonschiefer abwechselt. Er ist dickbankig und hat eine manchmal eher dunkelgraue Farbe. Zwischen den dicken Dolomitschichten befinden sich auch dünne Gänge schwarzen Tonsteins.

Untere Trias

Schichten der Unteren Trias (in Österreich Werfener Schichten)

Die Schichten der Unteren Trieas werden vom Tunnel zwischen Station 315 und 933 m und zwischen Station 2654 und 2767 m durchquert. Sie werden in untere (in Österreich Seiser) und obere (in Österreich Campiler) Schichten gegliedert. In den unteren finden sich roter Tonstein und Siltstein, gelblicher Dolomit und rötlicher oolithischer Kalkstein (Bild 3). Rötlicher Tonstein und Siltstein sind manchmal grün verfärbt. Stellenweise sind sie mit Pflanzenresten versehen und schwarz gefärbt. Im roten und im grünen Tonstein befinden sich Linsen rosa und weißen Gipses, der später auch in den Spalten verteilt ist.
Die oberen Schichten der Unteren Trias setzten sich überwiegend aus dunkelgrauem, dünnbankigem Kalkstein, dolomitischem Kalkstein und Dolomit zusammen.

Mittlere Trias

Anisdolomit

Dieser Dolomit steht im Tunnel zwischen Station 2767 und 2831 m an und liegt unter dem Erosionskontakt mit der Ukova- (Uggowitzer) Breccie. Er ist grau, manchmal auch bräunlich gefärbt. Sein Alter wurde durch mikropaläontologische Untersuchungen noch nicht bestätigt.

Ukova- (Uggowitzer) Breccie

Dem Alter nach wird die Ukova- (Uggowitzer) Breccie dem Ladin zugerechnet. Es gibt zwei Typen von Breccie: Die erste setzt sich aus Trümmern bunten und schwarzen Kalksteins aus verschiedenen älteren Zeiträumen zusammen, das Bindemittel ist tonig und hat eine rotbraune Farbe. Ähnlich ist die Tarvisio-Breccie, da sie auch Trümmer des Trogkofel-Kalksteins enthält. Der zweite Typ enthält vor allem Trümmer grauen Kalksteins, das Bindemittel ist kalkig und grau. Im Tunnel steht Beccie des zweiten Typs zwischen Station 2831 und 2851 m an. Im Flußbett des Presušnik, über dem Tunnel, ist die gleiche Breccie, jedoch in größerer Dicke, anzultreffen.

Obere Trias

Cordevol- (Schlern-) Dolomit

In der Basis des Cordevol-Dolomits (in Österreich Schlerndolomit genannt) befindet sich dunkelgrauer Dolomit mit Hornstein, der vom Tunnel zwischen Station 2851 und 2893 m durchquert wird. Auf ihm liegt hellgrauer bis weißköniger Dolomit. Im Tunnel steht auch leicht rötlicher dolomitischer Kalkstein an, in dem selten eher dunkel gefärbte Dolomitgänge anzutreffen sind. Im Cordevol-Dolomit steht auf Station 3028 m eine grüne, 20 cm dicke Tuffschicht an. An der Grenze des Dolomits ist der Tuff oxidiert und braun. Der Dolomit wird der Oberen Trias bzw. dem Karn zugerechnet.
Der Dolomit wird vom Tunnel zwischen Station 2893 und 3258 m durchquert.

Schwarzer Mergel des Karn und plattiger Mergelkalk, stellenweise mit Hornstein

Diese Schichten beginnen im Tunnel ab Station 3258 m und reichen noch auf die österreichische Seite. Der untere Teil der Schichtfolge besteht überwiegend aus Mergel, im oberen Teil überwiegt Kalkstein mit Hornstein.

Quartär

Moräne und Hangschutt

Der Tunnel verläuft vom Portal bis Station 315 m in einer Moräne, auf der Hangschutt liegt. Die Moräne setzt sich vor allem aus Trümmern der Werfener Schichten aus der Unteren Trias und des Bellerophon-Dolomits zusammen. Stellenweise liegen zwischen feinerem Material auch größere Gesteinstrümmer zutage.

Tektonische Verhältnisse im Tunnelbereich

Der Tunnelbereich wird im Rahmen der tektonischen Vorgänge bezüglich der verschiedenen Gesteinseigenschaften in mehrere Abschnitte geteilt. Der erste Abschnitt wird aus Schichten der Unteren Trias gebildet. Im Anfangsteil besteht eine große Antiklinale (First auf Station 320 m) und Synklinale (First auf Station 560 m). Die Verwerfungen verlaufen in diesem relativ unzerrütteten Bereich meist in ostwestlicher Richtung. Stark gefalteter, bunter Mergel mit Gips und Anhydrit, dünnbankiger Dolomit und dolomitischer Kalkstein bilden den Abschnitt zwischen Station 560 und 933 m. Die Achsen der Falten verlaufen meist in alpiner Richtung (EW).
Selten verlaufen Verwerfungen in dinarischer Querrichtung (NE-SW). Sie enden an den Verwerfungen mit dinarischer und alpiner Richtung. Selten sind auch dinarische subvertikale Verwerfungen.
Der zweite Tunnelabschnitt liegt zwischen Station 933 und 1700 m und verläuft durch Tarvisio-Breccie, graues (wahrscheinlich Grödener) Quarzkonglomerat, roten Tonschiefer und grauen dickbankigen Dolomit des Oberperms. Im massiven, roten Tonschiefer sind außer der Schieferung keine anderen meßbaren strukturellen Elemente vorhanden. Zwischen den Schichten der Unteren Trias und den Grödener Schichten verläuft eine subvertikale Verwerfung in ostwestlicher Richtung. Zwischen Station 975 und 1098 m liegt an ostwestlichen Verwerfungen im Bellerophon-Dolomit eingelagarter, roter Grödener Tonschiefer. Die Tarvisio-Breccie zwischen Station 1148 und 1300 m verläuft generell in ostwestlicher Richtung und ist gegen Norden steil geneigt oder subvertikal. Die Einschlüsse von Sandstein und Tarvis- Breccie treten zwischen Station 1350 und 1450 m in horizontaler bis subvertikaler Lage auf. Die Einschlüsse grauen Konglomerats im roten Tonschiefer auf Station 1475 m sind gegen Norden geneigt. Auf Station 1570 m gehen die roten Grödener Schichten in grauen (wahrscheinlich Grödener) Sandstein und graues Konglomerat über. Bezüglich der normalen Schichtfolge (älteres graues Konglomerat liegt auf jüngerem roten Tonschiefer) und der Schichtneigung gegen Norden kann von einer inversen Schichtung zwischen Station 1300 und 1600 m gesprochen werden.
Das graue Konglomerat ist auf Station 1703 m von der subvertikalen dinarischen Verwerfung getrennt. Die meisten Verwerfungen in den Grödener Schichten verlaufen in dinarischer Querrichtung und sind ziemlich steil bis subvertikal. Einige Verwerfungen verlaufen auch in ostwestlicher Richtung, sehr selten sind subvertikale dinarische Verwerfungen. Zwischen Station 1470 und 1620 m steht eine gefaltete Verschiebung an, an der sich Einlagerungen von klastischen Sedimentiten des Oberkarbons und des Unterperms befinden (Bild 4).
Der dritte Tunnelabschnitt zwischen Station 1720 und 2386 m verläuft in klastischen Sedimentiten des Oberkarbons-Unterperms. Der gesamte Abschnitt ist tektonisch durchgeknetet. Die meisten strukturellen Elemente haben eine dinarische Querrichtung. Eine Ausnahme bildet die Zone zwischen Station 1700 und 1804 m, die in dinarischer Richtung verläuf. Der einzige längere, nicht durchknetete Abschnitt liegt zwischen Station 1825 und 1900 m. Zwischen Station 2385 und 2402 m befindet sich eine Einlagerung roten Mergels mit Gips- und Anhydritlinsen der Unteren Trias. Eine Gipslinse, die den gleichen Schichten zugehört, ist auch zwischen Station 2422 und 2452 m eingelagert (Bild 5).

Zwischen Station 2595 und 2600 m befindet sich in den klastischen Sedimentiten des Oberkarbons-Unterperms eine Einlagerung der Ukova- (Uggowitzer) Breccie mit rotem, tonigem Bindemittel. Er liegt an einer in dinarischer Querrichtung verlaufenden Verwerfung, die lokal (im Tunnel) gegen Südosten und regional gegen Nordwesten geneigt ist. Diese wurde nach der Hrušenska planina Hrušica-Verwerfung benannt, an der eine linke Gleitung vollzogen wurde.

Der vierte Tunnelabschnitt beginnt auf Station 2610 m in triassischen Sedimentiten. Zwischen Station 2610 und 2767 m stehen Schichten aus der Unteren Trias an, die gegen Norden geneigt sind. Auch die Schichten des Anisdolomits zwischen Station 2767 und 2838 m sind gegen Nordwesten geneigt. Im Cordevol- (Schlern-) Dolomit, der auf Station 3250 ansteht, sind die Schichten gegen Nordosten geneigt. Der gesamte Cordevol- (Schlern-) Dolomit ist klüftig. Zwischen Station 3030 und 3042 m durchquert der Tunnel eine breitere, subvertikale dinarische Verwerfungszone. An dieser kam es zu einem Wassereinbruch, der eine Unterbrechung der Vortriebsarbeiten verursachte. Eine zweite, breitere dinarische Verwerfungszone schneidet den Cordevol- (Schlern-) Dolomit zwischen Station 3180 und 3185 m. Die Grenze zwischen Cordevol- (Schlern-) Dolomit, schwarzem karnischem Kalkstein und Mergel ist wieder eine in dinarischer Querrichtung verlaufende Verwerfung, die steil gegen Nordwesten geneigt ist. An dieser wurde eine kleinere linke Gleitung vollzogen, wie aus den geologischen Verhältnissen an der Oberfläche ersichtlich ist.

Außer den dinarischen subvertikalen Verwerfungen auf Station 3280 und 3355 m verlaufen die strukturellen Elemente auch in diesen Schichten in dinarischer Querrichtung – sowohl die Falten als auch die Verwerfungen bis zur österreichischen Staatsgrenze. Die Falten entstanden, wie bei der Oberflächenkartierung festgestellt wurde, auf Grund der Verschiebungen an den Verwerfungen.

PETKOVŠEK B

INGENIEURGEOLOGISCHE VERHÄLTNISSE IM KARAWANKENTUNNEL – SÜD

METHODOLOGIE DER INGENIEURARBEIT

Die Ortsbrust des Tunnels wurde im gesamten Zeitraum des Vortriebs von zwei Ingenieurgeologen verzeichnet, so daß die Geologie vor Ort jeden Tag sukzessive registriert wurde. Das Verzeichnis wurde nach einer Vorlage (Bild 1) angefertigt und

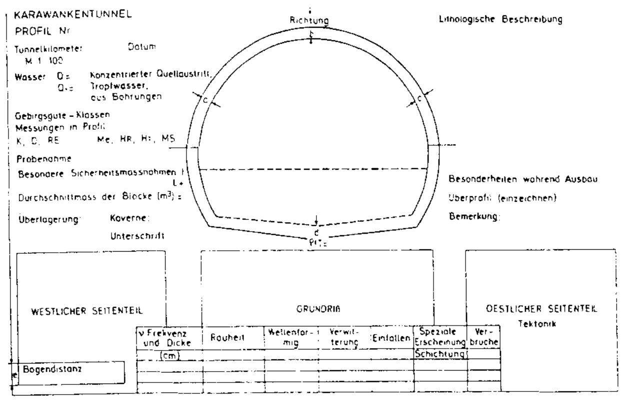


Bild 1

wurde später im Büro noch ergänzt.

Die Vorlage für das geologische Verzeichnis des Gebirges wurde so ausgearbeitet, daß das Gebirge auf Grund des Verzeichnisses nach den geltenden geomechanischen Klassifikationssystemen bewertet werden konnte. Diese Kriterien waren:

- Klüftigkeit des Gebirges (Dichte der Klüfte, RQD, Zahl der Kluftsysteme, durchschnittliche Größe des Geschiebes, Einfallen der Verwerfungen und Klüfte bezüglich Tunnelrichtung)
- Qualität der Spalten (Rauhigkeit, Welligkeit, Verwitterungsprozeß, Versatz)
- Lithologisches Gefüge und Standfestigkeit des nicht zerstörten Gebirges (einachsige Druck- und Zugfestigkeit bzw. Verhältnis zwischen Standfestigkeit und intaktem Spannungszustand des Gebirges in der Tiefe des Tunnels; Scherfestigkeit)
- Druck und zufließendes Bergwasser
- Schwierigkeiten beim Vortrieb, die durch das Gebirge bedingt sind (Methan, Wasserempfindlichkeit usw.)

Tabelle 1

Profil Nr.	Station (m)	Maximale Konvergenz	Max. Konv. nach 6 Monaten	Kategorie des Aushubes	IG Zone
1	7,6	59	45	H	1
2	22	72	71	H	1
3	52,5	90	86	H	1
4	75	94	92	H	1
5	95,5	48	49	H	1
6	109,5	38	37	H	1
7	141	46	44	H	1
8	167,5	17	16	H	1
9	199,5	43	41	H	1
10	230	19	16	H	1
11	246	18	16	H	1
12	278,5	20	17,8	H	1

4	75	94	92	H	1
3	52,5	90	86	H	1
2	22	72	71	H	1
1	7,6	59	45	H	1
5	95,5	48	49	H	1
7	141	46	44	H	1
9	199,5	43	41	H	1
6	109,5	38	37	H	1
12	278,5	20	17,8	H	1
10	230	19	16	H	1
11	246	18	16	H	1
8	167,5	17	16	H	1

Auf Grund der beschriebenen Parameter wurde das nach dem Kriterium des geologischen Alters global geordnete Gebirge in drei Gruppen gegliedert und dann in quasihomogene Zonen eingeteilt, in denen alle Parameter nach den drei Klassifikationssystemen bewertet wurden: nach Barton (Q), Bieniawski (RMR) und dem Österreichischen Klassifikationssystem.

Ab Station 740 m wurde im Tunnel mit den Vorausbohrungen begonnen, die bis zu drei nicht kerngebohrte Bohrlöcher von der Ortsbrust aus zur Feststellung der hydrogeologischen und ingenieurgeologischen Verhältnisse vor der Ortsbrust umfaßte. Die Vorausbohrungen wurden die ganze Zeit über von einem Geologen beobachtet, der jedesmal nach dem beendetem Vorausbohren eine Prognose der geologischen Verhältnisse für den Tunnelausbruch im vorausgebohrten Abschnitt erstellte.

Da die Kontrolle der getroffenen Stützmaßnahmen durch die geomechanischen Messungen im Tunnel erfolgte, wurde in den im Tunnel durchschnittlich alle 24 m aufeinanderfolgenden Meßquerschnitten systematisch die Konvergenz gemessen. Die Meßergebnisse der maximalen Konvergenzen bieten außer der Kontrolle der Stützmaßnahmen auch die Angabe des Schwierigkeitsgrads des Tunnelvortriebs durch die einzelne quasihomogene Zone.

MESSERGEBNISSE

Der erste Tunnelabschnitt verlief in *QUARTÄREN SEDIMENTGESTEINEN,* in einer pleistozänen, lockeren, sehr heterogenen Moräne mit Kalksteinblöcken. Die Moräne verfestigte sich im letzten Intervall, beim Kontakt mit dem Gebirge, zu Breccie.
In diesem Tunnelabschnitt wurden 12 Konvergenzmeßquerschnitte eingebaut. Für alle in das nicht verfestigte Erdreich eingebauten Meßquerschnitte war charakteristisch, daß die Firstsetzungen größer als die seitlichen Verdrückungen waren. Die Setzungen erreichten den Höchstwert an der Stelle, wo die Überlagerungshöhe über dem Tunnel nur etwas (1,2 mal) größer als der Ausbruchsquerschnitt des Tunnels ist. Tabelle 1 der maximalen Konvergenzen zeigt, wie diese längs des Abschnitts angeordnet waren:
Außer Zahl der Meßquerschnitte, Station und maximale Konvergenz (in mm) ist zur Bewertung der globalen Konvergenzstabilität noch die Größe der maximalen Konvergenz 6 Monate nach der Messung angegeben, als die Konvergenzen in der Mehrzahl schon stabilisiert waren. Weiters sind noch die Ausbruchklasse und die Kategorie der Tunnelsicherung (nach der österreichischen Klassifikation, nach der der Tunnel gebaut wurde) und die Bezeichnung der quasihomogenen Zone angegeben. Im zweiten Teil der Tabelle sind dieselben Daten nach den Werten der größten Konvergenz gereiht.

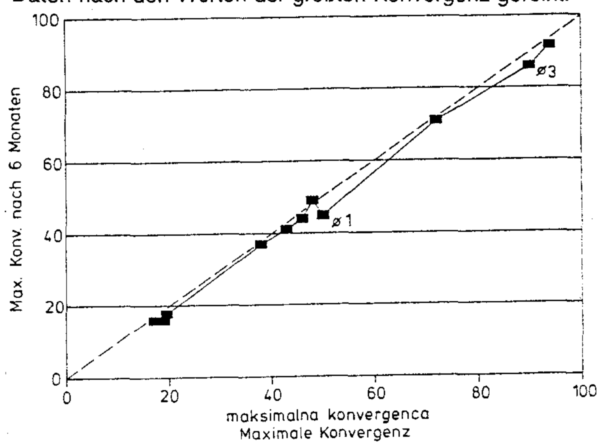


Bild 2

Aus dem Diagramm des Vergleichs der endgültigen maximalen Konvergenzen mit jenen nach 6 Monaten ist ersichtlich, daß sich die Konvergenz in allen Meßquerschnitten, mit Ausnahme von 1 und 3, schon vor Ablauf der 6 Monate und in jenen nach 6,5 Monaten stabilisierte (Bild 2).
Auf der jugoslawischen Seite standen zweimal *MESOZOISCHE SCHICHTEN AN:*
- zwischen Station 315 und 933 m
- von Station 2610 m bis zur Staatsgrenze (3437 m).

Auf Grund der geomechanischen Parameter wurden im ersten Abschnitt der mesozoischen Schichten folgende Gesteinszonen festgestellt, innerhalb derer das Gebirge auf den Tunnelvortrieb gleich reagierte:

Zone	Durchschnittskoeffizient nach 3 Klassifikationssystemen
1. Zerklüfteter Dolomit	0,85
2. Schichtserie stark zerklüfteter Mischgesteine	0,80
3. Dolomit, weniger zerklüftet	0,67
4. Dolomit, kompakt	0,45
5. Kalkstein und Mergelkalk, schwach zerklüftet	0,40
6. Mergelkalk, zerklüftet	0,60
7. Dolomit, brecciös	0,95
8. Dolomit und Tonstein	0,75
9. Tonschiefer	0,80
10. Verwerfung mit Mylonit und Wasser	1,0
11. Gefalteter Schieferstein und stark zerrütteter Dolomit	0,95
12. Gemischte Gesteinsserie zerrütteter Schichten	0,80

Anmerkung: Der Klassifikationskoeffizient wurde so ermittelt, indem die Klassifikationsergebnisse nach den drei Systemen bezüglich der Stellung der Zone im Klassifikationssystem bewertet wurden. Der Höchstwert des Koeffizienten bedeutet die schlechteste Gesteinskategorie.

Für den Tunnelvortrieb war die Kalk- und Mergelkalkzone (Zone 5 zwischen 420 und 450 m: II. bis III. Kategorie nach der österr. Klassifikation) am günstigsten und die Verwerfung voll Mylonit und Wasser (Zone 10 zwischen 728 und 765 m: VI. Kategorie nach der österr. Klassifikation) am ungünstigsten. In dieser Zone kam es auch zu einem plözlichen Wassereinbruch, der Sanierungsarbeiten notwendig machte.
In Tabelle 2 sind die größten Konvergenzen in den Meßquerschnitten dieser Gesteinszone angegeben.

Tabelle 2

Profil Nr.	Station (m)	Maximale Konvergenz	Max. Konv. nach 6 Monaten	Kategorie des Aushubes	IG Zone
31	774	129	121	5	11
32	805,5	111,5	109	5	11
30	775	69,2	58	5	10
33	827,5	65,5	63	5	12
27	734,5	50,7	44,36	5	10
22	607,5	44,8	35,2	5	7
28	739,5	41,6	38,06	5	10
17	449	40,5	33,7	3	5
29	745	39,6	35,2	6	10
13	315,5	25,9	21	H	1
14	334,5	24,5	21,6	4	2
23	624,5	23,4	17,5	5	7
20	543	23,01	19,95	3	6
21	594	23	12	3	6
34	845	21,8	14,6	5	12
15	358,5	19,2	15	4	2
18	474,5	13	11	3	6
25	676,5	11,8	5,9	5	8
26	709	10,6	4,39	3,5	9
16	406	10,1	4,3	3	4
35	891,5	8,1	6	3	2
19	520	4,5	1	4	6
24	648	2,7	2,6	5	7

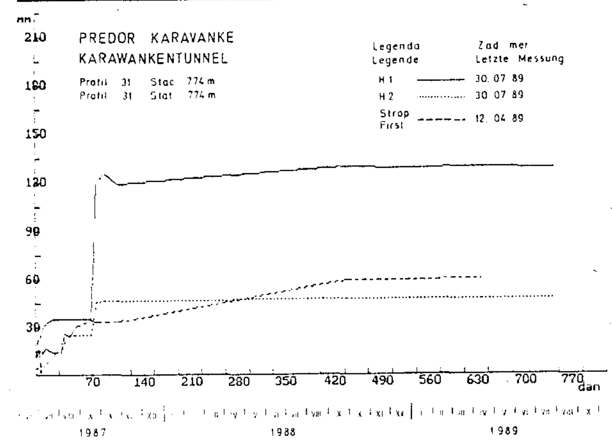


Bild 3

Die Konvergenz entwickelte sich im Gebirge in der Richtung der Verdrückung der Kalottenseiten am stärksten.
Die Konvergenzen waren offensichtlich in den Zonen 10 bis 12, wo das Gebirge stark zerrüttet ist, trotz der getroffenen maximalen Stützmaßnahmen am größten. Sie stabilisierten sich hauptsächlich schon nach 6 Monaten (Bild 3).

Eine Ausnahme bilden die Meßquerschnitte 22, 30 und 31, die sich nach einem Jahr stabilisierten (Bild 4, 5).

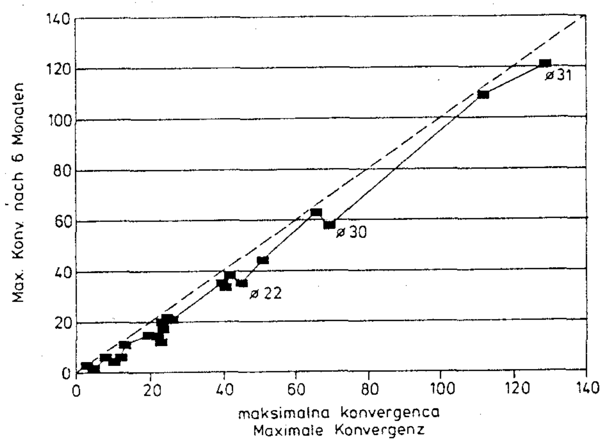


Bild 4

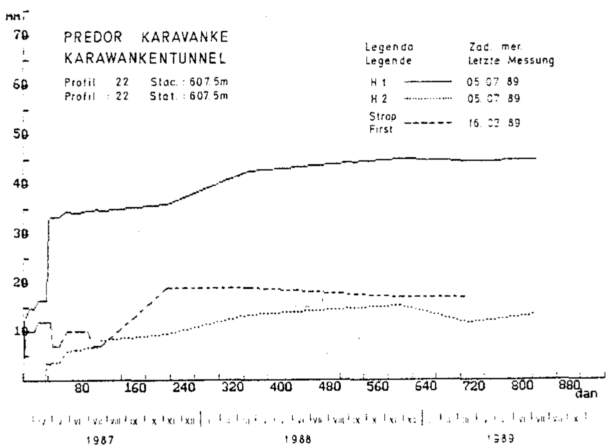


Bild 5

In den *PALÄOZOISCHEN SCHICHTEN*, die zwischen den Stationen 933 und 2610 m anstehen, wurden folgende quasihomogene Zonen festgestellt (dabei wurden die permokarbonischen Schichten von den permischen getrennt, da sich diese beiden Sedimentationen nach den geotechnischen Eigenschaften sehr unterscheiden):

A. Permische Sedimentgesteine (933–1720 m)

Zone	Durchschnittskoeffizient nach 3 Klassifikationssystemen
1. Tektonische Zone (62 m)	0,97
2. Gefalteter Tonstein und brecciöser Dolomit (117 m)	0,80
3. Stark schieferiger Siltstein mit Dolomit- und Breccieblöcken (174 m)	0,67
4. Gemischte Schichtserie von Breccie und Schieferstein mit Sandstein-Einschlüssen und Konglomeratblöcken:	
– schwach zerrüttet	0,63
– stark zerrüttet	0,76
5. Karbonatisches Gestein, etwas zerklüftet	0,57

In den permischen Schichten waren Bellerophon-Dolomit, Tarvisio-Breccie und kalkiger Sandstein für den Tunnelvortrieb am günstigsten. In dieser Zone wurden nur 102 Tunnelmeter aufgefahren. Das Gebirge zählt nach der österr. Klassifikation zur III. Kategorie.
Die schwierigsten Abschnitte stellen die tektonischen Zonen mit durchknetetem rotem Tonschiefer und zerrütteten Gesteinsbrocken von Tarvisio-Breccie und Kalkstein dar. Die Gesamtlänge dieser Abschnitte beträgt 62 m. Das Gebirge zählt nach der österr. Klassifikation zur VI. Kategorie.
Die Meßergebnisse der Konvergenz sind für diesen Abschnitt aus Tabelle 3 ersichtlich. Auch hier wurden die größten Konvergenzen in der Richtung der Verdrückung der Kalottenseiten gemessenen.
Die Konvergenzen sind im Durchschnitt größer, was der schlechteren Gebirgsqualität zuzuschreiben ist. Die Kategorie der Tunnelsicherung ist im Durchschnitt die gleiche wie im Bereich der mesozoischen Sedimentgesteine.

Tabelle 3

Profil Nr.	Station (m)	Maximale Konvergenz	Max. Konv. nach 6 Monaten	Kategorie des Aushubes	IG Zone
52	1449	506,3	371,1	5	1
58	1555	346,9	265,5	5	1
53	1467,5	323	274,4	5	1
54	1481,5	282,9	219,5	5	1
51	1435,5	257,2	187,4	4	3
57	1550,5	225,15	143	5	1
55	1499,5	183,1	105,6	4	4,2
59	1579	179,8	162,6	5	4,2
56	1527	123	74,9	4	4,2
48	1325	111,1	110	4	3
50	1404,5	102,7	60	4	4,1
49	1367	75,7	57,6	4	4,1
37	976	65,8	70	4	2
47	1291	58,2	33,9	4	4,2
45	1225	53,3	3,7	4	4,1
46	1259,5	47,9	2,2	4	5
39	1042,5	47,5	24,2	4	2
40	1071,5	39,2	7,08	4	2
44	1193	30,2	9,1	4	4,1
38	1008,5	25,6	13,7	4	2
36	933	22,7	21,4	3	5
41	1106,5	16	4,2	4	3
42	1123	12	4,4	4	3
43	1158	2		4	5

Im tektonisch stärker zerrütteten Gebirge sind die Konvergenzen trotz der wirkungsvollen Stützmaßnahmen größer als in den weniger zerrütteten Abschnitten. Ihren Höchstwert von 506 mm erreichte die Konvergenz in dieser Zone im Meßquerschnitt 52, auf Station 1449 m, im Bereich einer größeren Verwerfung.

Das Diagramm des Vergleichs der Konvergenzen nach 6 Monaten mit den Endwerten, das der globalen Bewertung der Standfestigkeit der Meßquerschnitte ab dem 6. Monat dient, zeigt, daß sich die Mehrzahl der Konvergenzen nach 6 Monaten noch nicht stabilisierte (Bild 4). In den Meßquerschnitten 48, 51–55, 57 und 58 ist das am besten erkennbar. In den Meßquerschnitten 40–46, die auch eine längere Unstabilität aufweisen, konnten die Messungen eine längere Zeit nicht durchgeführt werden, die Daten über die Konvergenz nach 6 Monaten sind daher unvollständig. Im Bereich der Meßquerschnitte 51–55 wurde die endgültige Tunnelstabilität erst nach

Sanierungsarbeiten erzielt, die zusätzliche Ankerung und Nachprofilierung der Tunnelschale umfaßten.
Der in einer stark zerrütteten gemischten Schichtserie von Breccie und Schieferstein eingebaute Meßquerschnitt 48 stabilisierte sich nach 15 Monaten.

B. Permokarbonische Sedimentgesteine (1720–2386 m)

Die Einteilung des Gebirges in Zonen nach den Parametern der geomechanischen Klassifikationen ergab folgende Ergebnisse:

Zone	Durchschnittskoeffizient nach 3 Klassifikationssystemen
1. Günstigstes Gebirge: Konglomerat, Sandstein und Kalkstein, wenig zerrüttet (99 m)	0,73
2. Mischgestein: in gleichem Ausmaß vertretener schuppiger Tonschiefer und Sandstein, auch anstehende Konglomeratblöcke (148 m)	0,95
3. Lithologisch günstiges Gebirge (wie 1.), aber stark zerrüttet (72 m)	0,95
4. Mischgestein, stark zerrüttet (166 m)	1,00
5. Durchgekneteter Tonschiefer (292 m)	1,00
6. Tonschiefer (14 m)	0,86

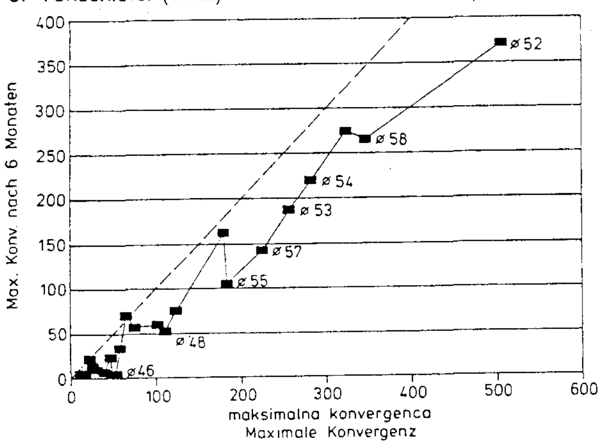


Bild 6

Das günstigste Gebirge in diesen Schichten ist ein einem kurzen Abschnitt von 99 m Länge vertreten, während di Zone mit den ungünstigsten Gebirgsverhältnissen in diesem Teil 458 m beträgt. In den Zonen 4 und 5 waren zur Sicherung der Tunnelstabilität noch umfassende zusätzliche Stützmaßnahmen erforderlich.
Bei tektonisch stark zerrüttetem Gebirge erleichtert das günstigere lithologische Gefüge auf Grund der Zerrüttung die Verhältnisse bei der Wahl der Stützmaßnahmen nicht, was aus den Durchschnittskoeffizienten der obigen Tabelle ersichtlich ist.
Die Meßergebnisse der Konvergenzen sind der Größe nach geordnet (Tabelle 4).
Die Meßergebnisse der Konvergenzen zeigen, daß die Einschlüsse härteren, zerrütteten Gesteins in den Verwerfungen nicht zur Tunnelstabilität beitragen. Die starken Verwerfungen weisen häufig derartige, im plastischen Gebirge eingeschlossene Gesteinsbrocken auf, diese besitzen jedoch ein zu geringes Ausmaß, als daß sie die Tunnelstabilität beeinflussen könnten.
Wo das Gebirge im ganzen lithologisch günstiger ist, sind die Konvergenzen trotz starker Zerrüttung wesentlich kleiner (z. B. Meßquerschnitte 62–64, Tabelle 4). Der relativ kleine Wert der Konvergenzen dieses Gebirges und dieses Tunnelabschnitts (325–504 mm) garantiert in den Fällen die Tunnelstabilität noch nicht, da sich die Konvergenzen in den Meßquerschnitten 77, 78 und 101 noch 12 bis 17 Monaten entwikkelten.

Tabelle 4

Profil Nr.	Station (m)	Maximale Konvergenz	Max. Konv. nach 6 Monaten	Kategorie des Aushubes	IG Zone
66	1725	1530,4	1346	6	4
68	1737	1477,6	1050	6	4
67	1733,5	1413,4	1095	6	4
69	1748	1254,3	1031	6	5
103	2337	1154,1	1040	6	2
105	2380	1141,4	971	6	5
70	1757	1054,9	825	6	5
65	1718,5	999,7	820	6	3
96	2180	996	920	6	2
95	2162	963,4	910	6	6
91	2094	913,8	820	6	5
71	1766	894,6	737	6	5
104	2357,5	851,4	725,5	6	5
90	2080	838,7	755	6	5
97	2201	812,5	703	6	2
98	2224,5	811,6	763	6	5
102	2307	789,9	725	6	5
93	2123,5	769,8	670	6	4
89	2060	744,7	673	6	5
92	2107,5	725,8	635	6	5
73	1797	696,8	602	6	5
87	2031,5	656,1	565	6	4
99	2245,5	617,3	561	6	5
88	2044	598,9	515	6	5
72	1779,5	575,1	453	6	5
82	1945	532,2	485	6	5
94	2140,5	514,6	470	6	5
101	2289,5	504,4	450	6	3
100	2263	497,4	423	6	5
85	1996	477,4	422	6	3
74	1812	438,3	370	6	4
84	1969	428,2	374	6	4
83	1958,5	425,7	409	6	5
86	2011	423,9	375	6	4
75	1825	365,3	317	6	1
77	1861,5	350	176	5	1
81	1939	341,1	281	6	5
79	1904	329,3	232	5	4
60	1607	285,2	255	5	2
78	1880	253,7	220	5	1
61	1629	247,9	236	5	2
76	1845	247,3	186	6	1
80	1928	242,3	280	5	1
64	1691	175,7	130	5	3
62	1655	170,5	135	5	3
63	1670	150,6	115	6	3

Für die Entwicklung der Konvergenzen im lithologischen Mischgestein ist der Zerrüttungsgrad in den permokarbonischen Schichten für die Zeit seiner Stabilisierung von entscheidender, für seinen Endwert jedoch von geringerer Bedeutung.
Auch im dunkelgrauen schuppigen Schieferstein beeinflußt der Grad der tektonischen Zerrüttung die Entwicklung des Endwertes der Konvergenzen nicht wesentlich, viel mehr jedoch die Geschwindigkeit der Stabilisierung.
Aus der Kolonne der Konvergenzgeschwindigkeiten ist ersichtlich, daß die Konvergenzen nach zwei Jahren noch nicht zum Stillstand kamen:
- am häufigsten im durchkneteten Tonschiefer
- im lithologisch günstigerem Gebirge, wo die Kreuzungen der unterirdischen Anlagen liegen.

Das Diagramm der Konvergenzstabilität (Bild 7) beweist, daß die Konvergenz nach 6 Monaten im Grunde in allen Meßquerschnitten nicht stabilisiert ist.

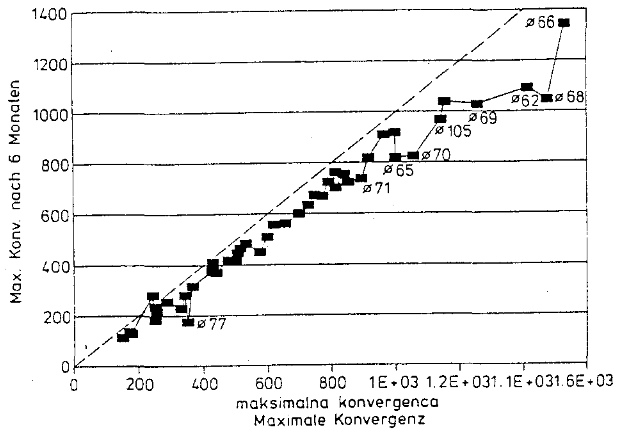


Bild 7

Aus Bild 7 ist ebenso klar ersichtlich, daß nach 6 Monaten jene Meßquerschnitte am wenigsten stabil waren, wo der Wert der Konvergenz mehr als 800 mm betrug.
Die Tunnelstabilität wurde im gesamten permokarbonischen Abschnitt erst durch zusätzliche Stützmaßnahmen gewährleistet.
Der letzte Tunnelabschnitt verläuft zuerst entlang einer Verwerfung zwischen permokarbonischen und triassischen Schichten und im weiteren ohne Unterbrechung im Schlerndolomit aus der Oberen Trias und im Mergelkalk. Auch dieser letzte Abschnitt wurde daher in zwei getrennte Gruppen eingeteilt, innerhalb derer das Gebirge in quasihomogene Zonen gegliedert wurde.

A. *IN DER GRUPPE DER VERWERFUNG* (2386–2610 m) wurden 3 quasihomogene Gebirgszonen festgestellt:

Zone	Durchschnittskoeffizient nach 3 Klassifikationssystemen
1. Mischgestein (152 m)	0,96
2. Tonschiefer (41 m)	0,87
3. Dunkelgrauer Kalkstein (15 m)	0,69

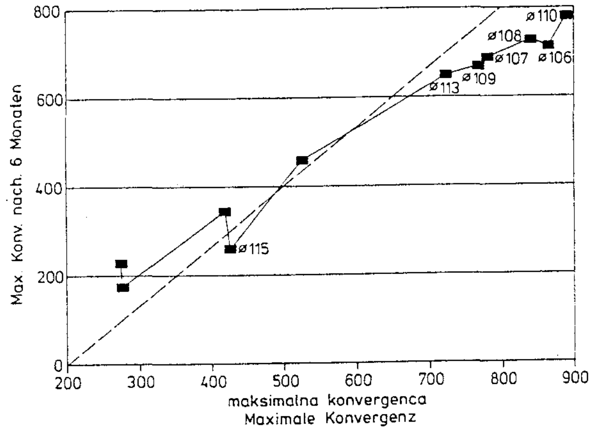


Bild 8

Das für den Tunnelvortrieb günstigste Gebirge ist die Deckscholle des dunkelgrauen Kalksteins, am ungünstigsten ist die durchgeknetete Zone des Tonschiefers mit zerklüfteten härteren Gesteinssbrocken (Kalkstein, Sandstein und Konglomerat). Der allein anstehende Tonschiefer ist tektonisch schwach zerrüttet, da er nicht von härteren Einschlüssen deformiert wird.

Die Meßergebnisse der Konvergenzen sind aus Tabelle 5 ersichtlich
Die Höchstwerte der Konvergenz zeigen, daß deren Entwicklung von der Lithologie nicht wesentlich beeinflußt wird. Das Verhalten des Mischgesteins ist so ungünstig wie der durchgeknetete Tonschiefer. Wichtiger für die Entwicklung der Konvergenzen ist die Nähe eines stabilen Gebirges: Kleiner sind die Konvergenzen in den näher bei stabilen triassischen Sedimentgesteinen eingebauten Meßquerschnitten (z. B. 20 m vom Meßquerschnitt 115 weiter und in der Zone des dunkelgrauen Kalksteins zwischen 2512 und 2527 m, weswegen auch die Meßquerschnitte 111 und 112 kleine Konvergenzen aufweisen).
Das Diagramm des Vergleichs der maximalen Konvergenzen mit den Werten nach 6 Monaten (Bild 8) zeigt, daß sich die Meßquerschnitte in der Mitte der Verwerfung als letzte stabilisierten. Es sind dies die Meßquerschnitte 106, 107, 108, 109 und 110, somit all jene, deren maximale Konvergenz mehr als 700 mm beträgt.
Das Gebirge stabilisierte sich an den Stellen, wo die Konvergenz nach 6 Monaten mehr als 650 mm beträgt, erst nach umfassenden zusätzlichen Stützmaßnahmen. Zu einem ähnlichen Abschluß gelangte man auch bei der Interpretation der Meßergebnisse der Konvergenzen im permokarbonischen

Tabelle 5

Profil Nr.	Station (m)	Maximale Konvergenz	Max. Konv. nach 6 Monaten	Kategorie des Aushubes	IG Zone
110	2478,5	889,5	780	6	2
106	2408,5	864	715	5	1
108	2451	839,2	730	5	1
107	2427	780,6	689	5	1
109	2464	767,6	670	5	1
113	2544	723,1	650	5	1
114	2566	526,1	460	6	1
115	2582	425,3	260	5	1
111	2501,5	417,9	345	5	1
116	2601	276,2	175	5	2
112	2530,5	274,4	230	5	1

Schieferstein, nur daß hier die Grenze bei 800 mm lag.

B. In der letzten Gruppe *DER TRIASSISCHEN SEDIMENTGESTEINE* (2610–3437 m) wurden 7 quasihomogene Zonen festgestellt:

Zone	Durchschnittskoeffizient nach 3 Klassifikationssystemen
1. Günstigstes Gebirge (50 m)	0,50
2. Zerklüftete karbonatische Gesteine (74 m)	0,69
3. Mergelschiefer (163 m)	0,57
4. Stark zerklüfteter Dolomit (178 m)	0,78
5. Dolomit + Siltstein (113,5 m)	0,63
6. Brecciöser Dolomit (143 m)	0,81
7. Wasserführende Verwerfung (45 m)	1,00

Das günstigste Gebirge bilden dunkelgrauer Kalkstein und grauer, nicht bankiger Dolomit. Der Kalkstein hat im letzten Tunnelabschnitt noch eine mergelige Beimischung. Die Schichtneigung ist im Kalkstein konstant.
Die Ergebnisse der letzten Konvergenz-Meßwerte sind aus Tabelle 6 ersichtlich:
Die Tabelle 6 mit den rangierten Ergebnissen zeigt, daß sich die Konvergenzen am stärksten in den Zonen 3, 4 und 5 entwickelten, d. h. im Mergelschiefer, im stark zerklüfteten Dolomit und im Dolomit, der an der Ortsbrust zusammen

mit Siltstein ansteht. Der Tunnel wurde in diesen Zonen maximal in der IV. Kategorie aufgefahren.
Die relativ großen Konvergenzen in diesen Zonen, die jedoch wesentlich kleiner als die Konvergenzen in den paläozoischen Sedimentgesteinen sind, sind durch die größere Deformierbarkeit des Siltsteins und des Mergels zu erklären, die an der Ortsbrust neben dem Dolomit anstehen. Außerdem liegt der Bereich dieser Meßquerschnitte in nächster Nähe des tektonischen Kontaktes mit den permokarbonischen Sedimentgesteinen.
Da die Daten des am stärksten zerrütteten Gebirges nicht mit den Ergebnissen verglichen werden können, wo die Meßquerschnitte (im Bereich des Wassereinbruchs, auf Station 3010–3050 m) erst viel später eingebaut wurden, und zwar nach erfolgter Injektion, sind die Meßwerte der Konvergenz niedrig.

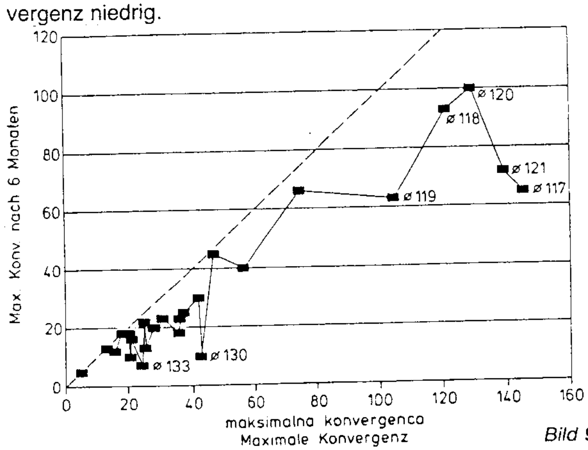


Bild 9

Das Diagramm des Vergleichs des Endwertes der Konvergenzen mit jenen nach 6 Monaten (Bild 9) zeigt, daß die Konvergenzen nach 6 Monaten noch immer in den Meßquerschnitten anstiegen, wo deren Werte am größten sind, somit in der Nähe des tektonischen Kontaktes mit den permokarbonischen Sedimentgesteinen. Die Mehrzahl dieser Meßquerschnitte wurde in der Zone des stark zerklüfteten Dolomits eingebaut.
Die Konvergenzen kamen im Meßquerschnitt 130, d. h. im Bereich der wasserführenden Verwerfung und rund um diese, nach 250 Tagen und bei den übrigen Meßquerschnitten vor Anfertigung der Innenschale zum Stillstand.
Die Höchstwerte der Konvergenz sind in all diesen Meßquerschnitten gering, sie betragen nicht mehr als 145 mm.

Das Diagramm der maximalen Konvergenzen entlang des Tunnels (geologischer Längenschnitt) ermöglicht den Vergleich des Höchstwertes der Konvergenzen mit dem geologischen Gefüge und dem Grad der tektonischen Zerrüttung des Gebirges. Wie ersichtlich, entwickelten sich die Höchstwerte der Konvergenz im Bereich der tektonisch durchge-

Tabelle 6

Profil Nr.	Station (m)	Maximale Konvergenz	Max. Konv. nach 6 Monaten	Kategorie des Aushubes	IG Zone
117	2611	145,3	65	5	2,5
121	2691	139,2	72	4	2,3
120	2672,5	129,2	100	4	2,3
118	2635	121,1	93	5	2,4
119	2649,5	104,6	63	4	2,4
139	3315	74,7	66	4	2,5
127	2889,5	56,5	40	4	2,6
134	3157	46,8	45	5	2,4
130	2991	42,6	10	4	2,4
128	2918	42	30	5	2,4
122	2719	37,2	25	4	2,5
141	3384	35,9	23	4	2,3
132	3043	35,8	18	6	2,7
137	3262,5	30,6	23	5	2,6
123	2750	28,1	20	4	2,1
129	2954,5	25,4	13	5	2,6
140	3339	25,2	22	4	2,3
133	3107,5	24,5	7	6	2,2
125	2816	21,2	16	4	2,2
136	3223,5	20,7	10	4	2,2
138	3283	20,4	18	4	2,5
126	2850	18,2	18	4	2,6
124	2784	16	12	4	2,6
135	3186	13,4	13	5,5	2,6
131	3023	5,1	5	6	2,7

kneteten Zonen in den permokarbonischen Trümmergesteinen und im Bereich der starken Verwerfung, die den tektonischen Kontakt zwischen den permokarbonischen Schichten und den karbonatischen Gesteinen der Unteren Trias bildet. Sehr groß sind die Konvergenzen im gesamten Abschnitt der permokarbonischen Trümmergesteine, außer an den Stellen, wo sich im Gebirge geringfügig zerrüttete Kalksteinbrocken größeren Ausmaßes ablagerten. Viel kleiner (5–10mal kleiner) sind die Konvergenzen in den permischen und triassischen Trümmergesteinen, deren Werte sich jenen aus den permokarbonischen Trümmergesteinen nur an der Stelle des tektonischen Kontaktes mit diesen nähern.

Im Bereich der überwiegend in der Trias entstandenen karbonatischen Gesteine sind die Konvergenzen am kleinstein. In diesen Abschnitten ist das Wasser das Hauptproblem für den Tunnelvortrieb.
Die beiden Bereiche der Wassereinbrüche, die während des Tunnelvortriebs große Schwierigkeiten verursachten, weisen nach den getroffenen Sanierungsarbeiten keine größeren Konvergenzen auf; diese stabilisierten sich auch nach der Sanierung des Gebirges.

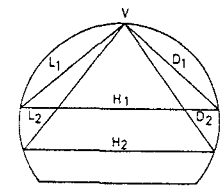
SCHLUSS

Die Konvergenzen sind in den permokarbonischen Trümmergesteinen am größten. Wesentlich kleinere weisen die permischen Sedimentgesteine auf, obwohl diese lithologisch nicht grundlegend anders sind. Sie sind anders in der mineralischen Zusammensetzung der Schiefersteine und im Grad der tektonischen Zerrüttung. Die kleinsten Konvergenzen gibt es in den triassischen Schichten.
Im härteren und brüchigeren, tektonisch stark zerklüfteten Gebirge sind die Werte der Konvergenz 5–10mal geringer als im stark plastischen Gebirge. Wenn dieses Gebirge tektonisch nicht stärker zerrüttet ist, stabilisierte sich die Konvergenz auf Werte, die 20–30mal geringer sind als jene im plastischen Gebirge. Die Höchstwerte der Konvergenz wurden in den Verwerfungen der permokarbonischen Trümmergesteine und im Kontakt der Verschiebung zwischen den permokarbonischen Trümmergesteinen und den überwiegend karbonatischen Gesteinen aus der Trias gemessen. In diesen Abschnitten kam die Konvergenz spätestens nach den zusätzlichen Stützmaßnahmen auch zum Stillstand. Im plastischen Gebirge beeinflußt der Grad der tektonischen Zerrüttung des Gebirges den Endwert der Konvergenz weniger als die Zeit ihrer Stabilisierung.

GEOMECHANISCHE MESSUNGEN IM TUNNEL

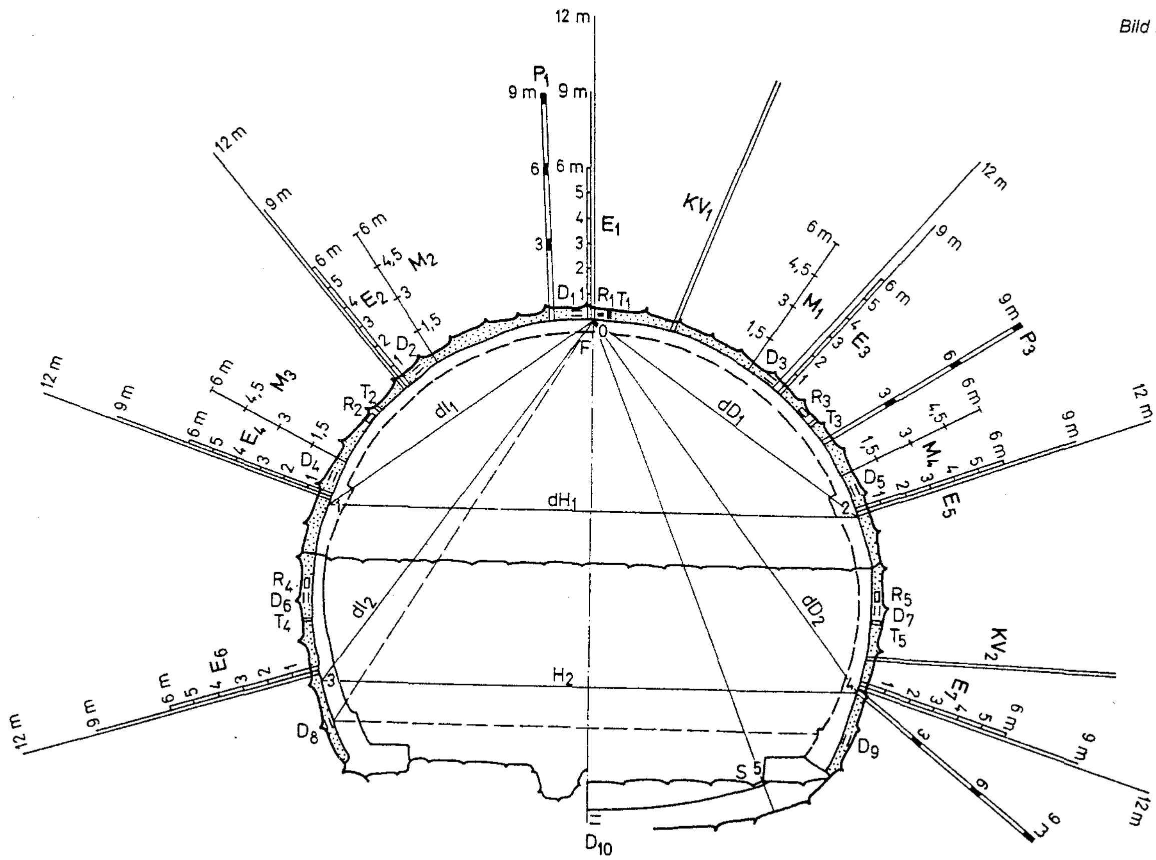
Ein Bestandteil der Neuen Österreichischen Tunnelbaumethode sind die geomechanischen Messungen, die der Kontrolle der getroffenen Stützmaßnahmen dienen. Im Karawankentunnel wurden zur Messung der Konvergenz 142 Meßquerschnitte eingebaut. Der durchschnittliche Abstand zwischen den Meßquerschnitten beträgt 24 m. In den Meßquer-

Razdalje merjene v konvergenčnih profilih



Abstände gemessen in den Meßquerschnitten

Bild 2



MERILNA OPREMA VGRAJENA V MERSKI PROFIL TIPA 1/2
IM MESSPROFIL TYP 1/2 EINGEBAUTE MESSAUSRÜSTUNG

Ei	Ekstenzometri Exstensometer	Pi	Vrtine za preiskave z elastmetrom Bohrungen für Untersuchungen mit Elastmeter
Mi	Merilna sidra Messanker	Di	Merilniki tangencialne deformacije obloge Messdosen der tangentialen Belagdeformation
Ri	Merilniki radialnih tlakov Radiale Druckmessdose	KVi	Vrtine za geomehanske vzorce Bohrungen für geomechanische Proben
Ti	Merilnik tangencialnih tlakov Tangentiale Druckmessdose		

schnitten wurden die in der Skizze dargestellten Abstände gemessen (Bild 1):
Die Abstände H_1, H_2 und die Firstsetzungen wurden ständig kontrolliert, während die Abstände L_1, D_1, L_2 und D_2 nur Hilfsabstände sind, die nur am Anfang der Meßquerschnitte gemessen wurden, als die Entwicklung der Konvergenz am größten war.
Außer der Konvergenz wurde an 10 Messquerschnitten noch die Verformungen des Gebirges und der primären Betonschale gemessen. Die Meßquerschnitte 84 und 117 (Stationen 1969 und 2611) waren zur Beobachtung der Verformungen und der Spannungen im gesamten System der Stützmaßnahmen des Tunnels am besten ausgestattet. In diesen wurden die folgenden Meßgeräte eingebaut (Bild 2):
Der Meßquerschnitt 84 wurde im permokarbonischen Tonschiefer, somit im stark plastischen Gebirge, und der Meßquerschnitt 117 im Dolomit eingebaut, der beim Tunnelvortrieb viel geringere Verformungen aufwies.

Bild 3

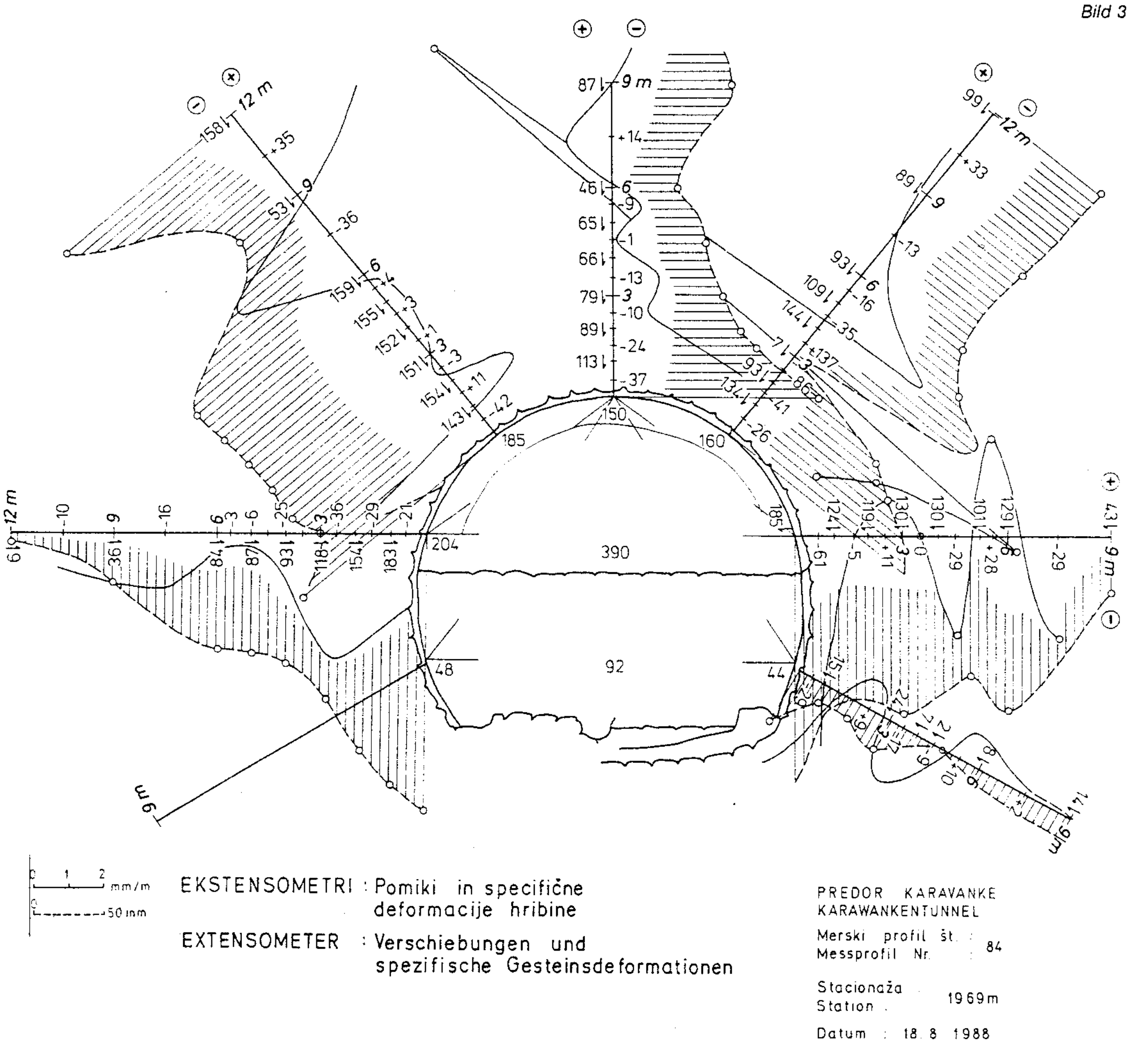


Bild 3: zeigt die Gebirgsverformungen rund um den Tunnel im Tonschiefer, im Querschnitt. Die Deformationen sind groß und ungleichmäßig und wurden mit bis zu 12 m langen Extensometern gemessen. Der Querschnitt gilt für den Zeitraum, als die Konvergenz im Grunde schon auf den Wert von 390 mm stabilisiert war.

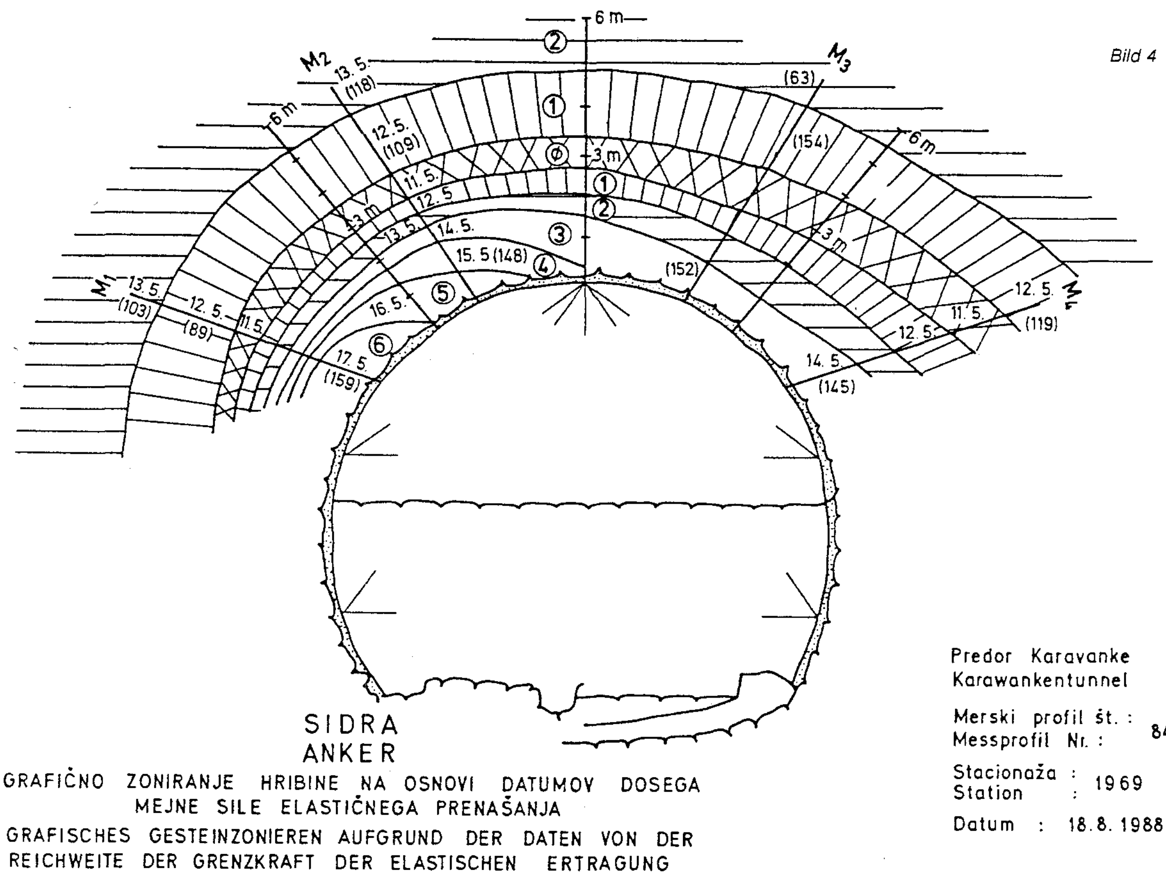
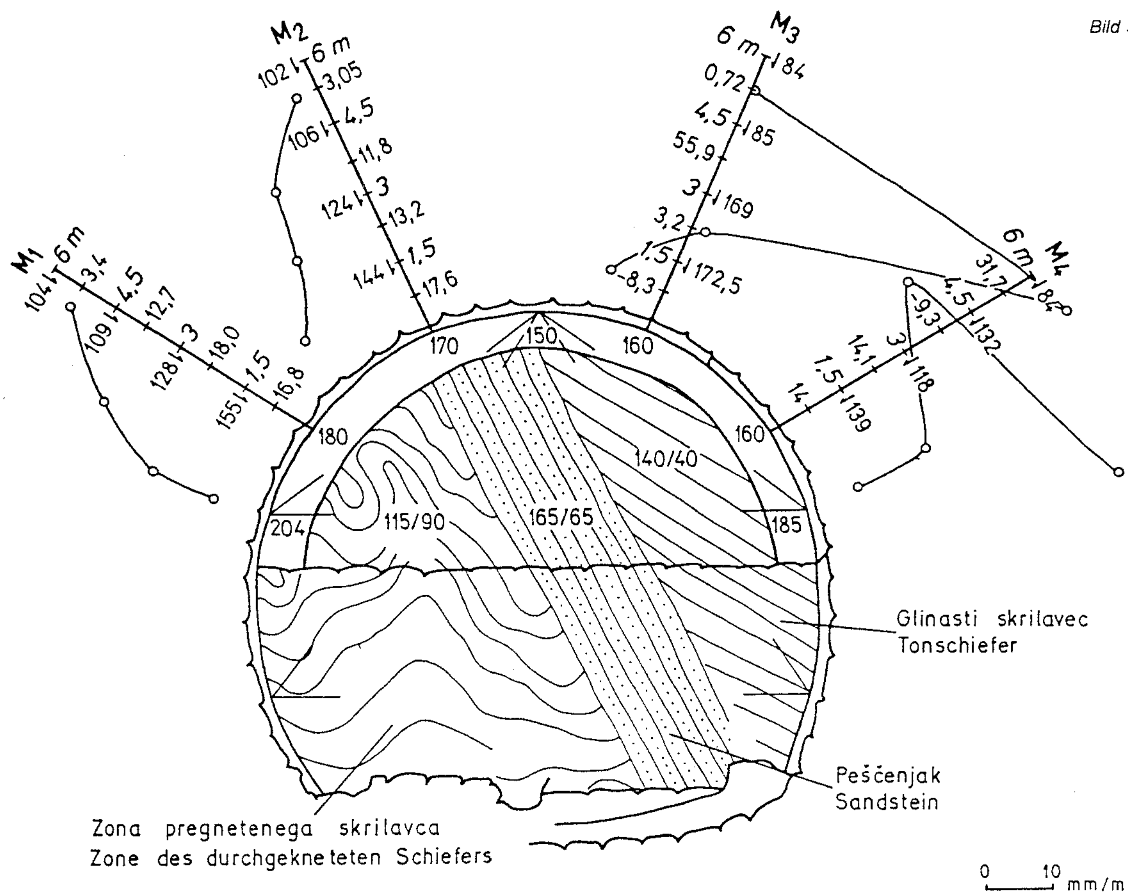


Bild 4: zeigt die zeitliche Entwicklung der plastischen Deformation der Anker rund um den Tunnel im Querschnittl. Die Anker wurden zuerst und am stärksten zwischen 3,0 und 4,0 m vom Tunnel belastet. Die Ankerdeformationen waren auf Grund der äußerst schlechten Gebirgsqualität sehr groß. Die Schwelle der plastischen Deformation wurde in dem angeführten Intervall schon am ersten Tag nach dem Einbau überschritten. In den folgenden Tagen verbreiterte sich die Zone der plastischen Deformation von dieser Stelle nach innen und nach außen. Sämtliche Anker waren bereits nach sechs Tagen plastisch deformiert, einige waren auch gerissen.

Bild 5

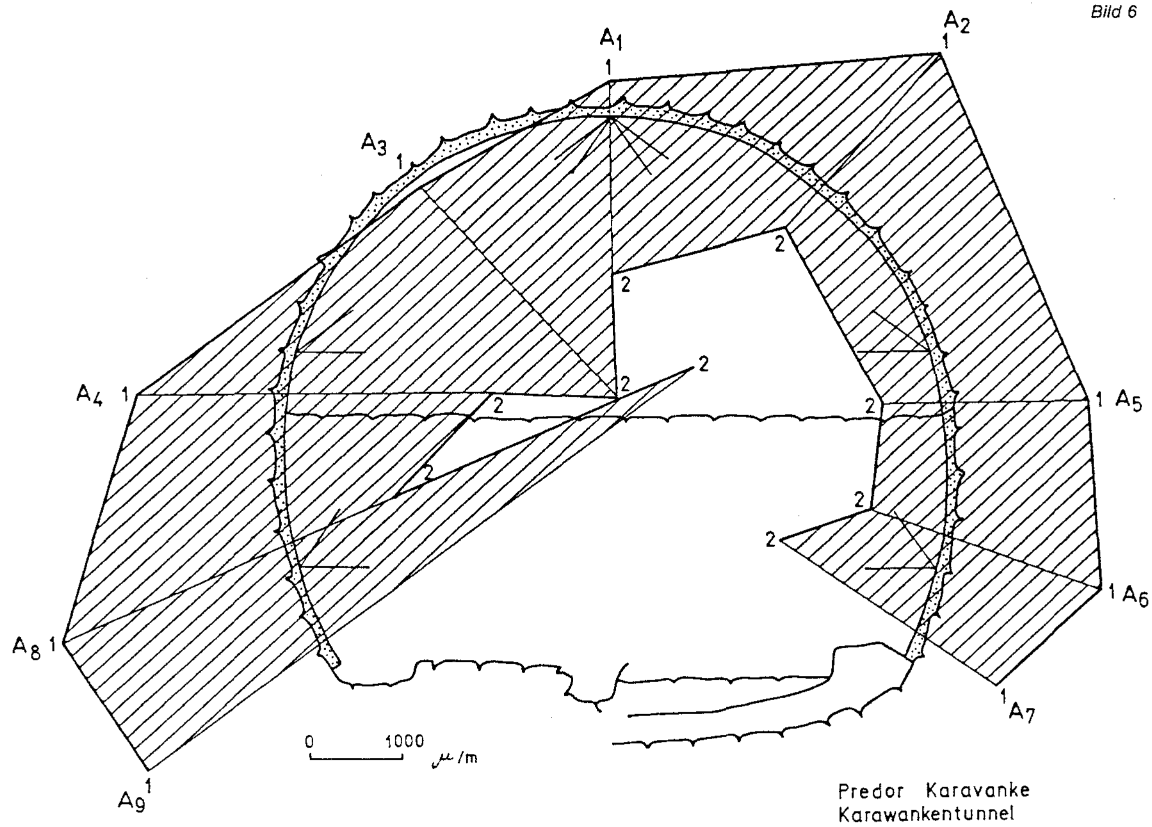


SIDRA
ANKER

DIAGRAMI SPECIFIČNIH DEFORMACIJ, PREČNO NA PREDOR
DIAGRAMME DER SPEZIFISCHEN DEFORMATIONEN QVER DURCH DEN TUNNEL

Bild 5: zeigt spezifische Ankerverformungen in dem Zeitraum, als die Konvergenz so gut wie zum Stillstand kam. Aus dem Diagramm ist ersichtlich, daß die Anker in den besseren Gesteinsschichten, auf der rechten Tunnelseite, stärker belastet sind als jene auf der linken Seite, wo sie zu kurz sind (die Meßanker sind nur 6 m lang). Auf der linken Seite ist das Gebirge zu sehr gelockert, als daß die Anker zusammen mit dem Gebirge die Belastung im vollen Ausmaß übernehmen könnten.

Bild 6



SPECIFIČNE DEFORMACIJE V BRIZGANEM BETONU - PREČNI PREREZ

SPEZIFISCHE DEFORMATIONEN IM SPRITZBETON - QVERSCHNITT

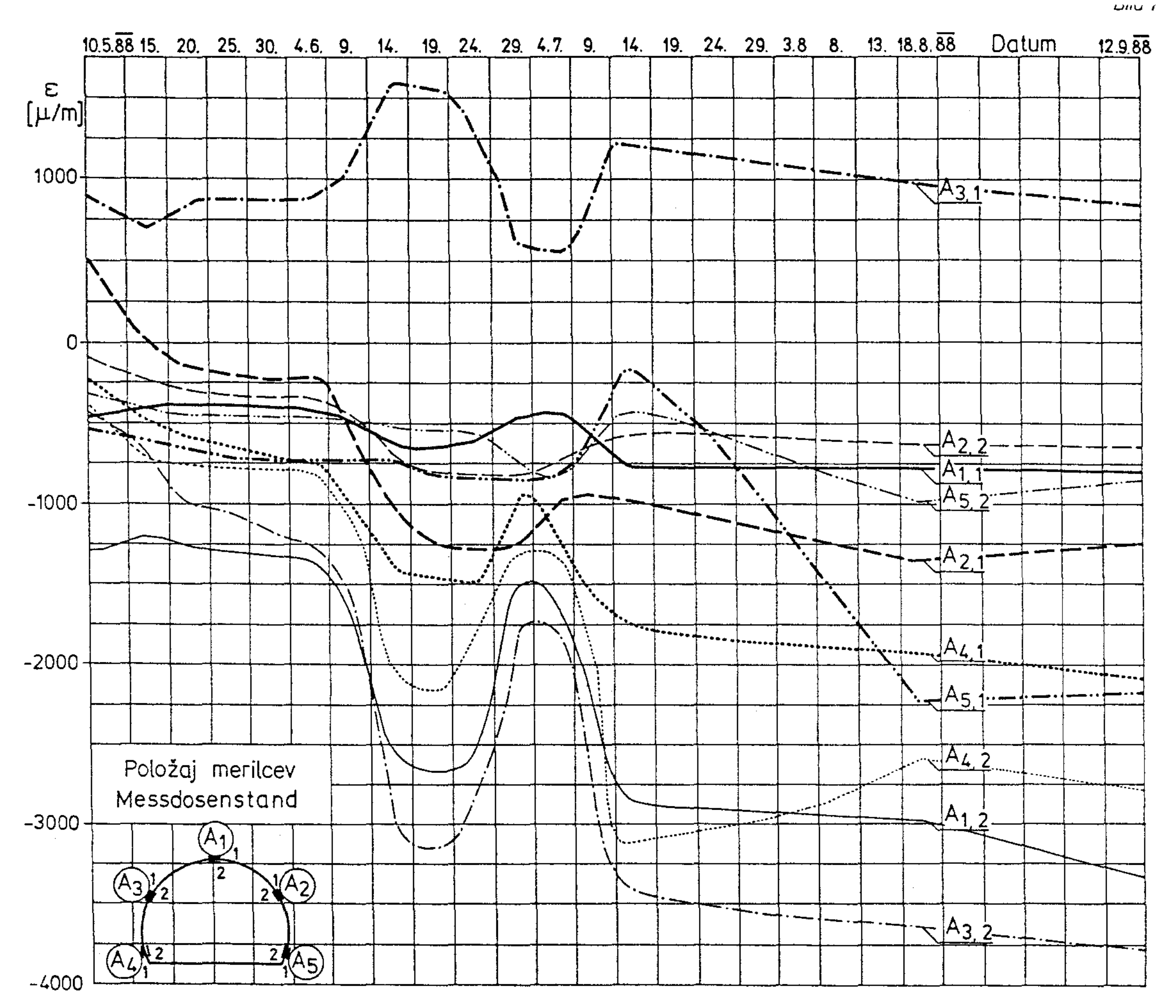
Predor Karavanke
Karawankentunnel

Merski profil št. : 84
Messprofil Nr. :

Stacionaža : 1969
Station :

Datum : 18. 8. 1988

Die Folge davon ist, daß die Spritzbetonschale auf dieser Tunnelseite viel stärker belastet ist (Bild 6). Die Belastungen wurden mit Verformungsmeßgeräten gemessen, die in der Betonschale tangential eingebaut wurden.



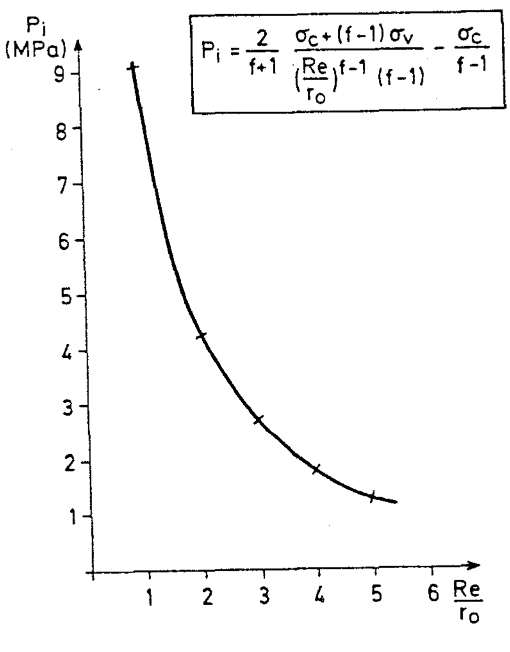
MERITEV RAZTEZKOV V BETONSKI OBLOGI
MESSAUSDEHNUNGEN IM BETONBELAG

Stacionaža : 1969
Station :
Datum :

Das Diagramm der zeitlichen Entwicklung der Deformationen (Bild 7) des Spritzbetons zeigt den Einfluß der bei der Tunnelsicherung im permokarbonischen Tonschiefer verwendeten Deformationsschlitze auf die Entwicklung der spezifischen Verformungen im Spritzbeton und damit indirekt das Nachlassen der Spannung in der primären Betonschale. Das Abklingen der Spannung ist eine Folge dafür, daß sich die Deformationsschlitze schließen.

Bild 8: zeigt die charakteristische Kurve des gesamten Systems der Stützmaßnahmen im permokarbonischen Tonschiefer und gibt das Verhältnis zwischen der Spannung in der Betonschale und dem Radius der gelockerten Zone rund um den Karawankentunnel an.

Bild 8



$$P_i = \frac{2}{f+1}\,\frac{\sigma_c + (f-1)\sigma_v}{\left(\frac{Re}{r_o}\right)^{f-1}(f-1)} - \frac{\sigma_c}{f-1}$$

P_i Pritisk na podporje
Druck auf die Stützanlage

Re Radij vplivne zone
Radius der Einflusszone

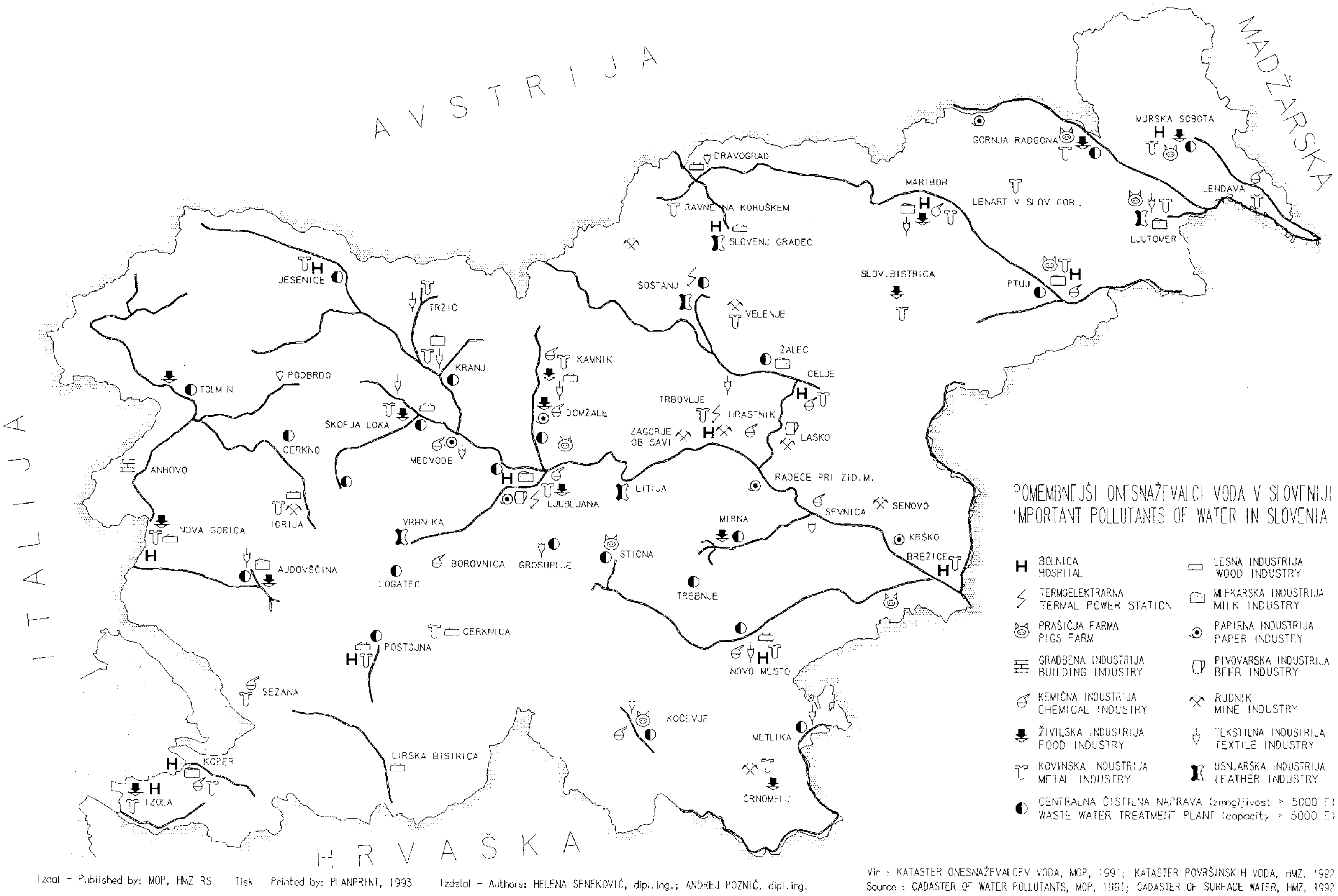
r_o Radij predora
Tunnelradius

σ_c Enoosna tlačna trdnost hribine
Einachsige Druckfestigkeit des Gesteins

σ_v Vertikalna komponenta napetostnega stanja
Vertikale Komponente des Spannungszustandes

f Strižni parameter hribine
Gesteinscherparameter

ŽUPAN, M. (1993): Water Quality in Slovenia Year 1992. 194 S.; Ljubljana (Hydrometeorological Institute of Slovenia).



ŽUPAN, M. (1993): Water Quality in Slovenia Year 1992. – 194 S.; Ljubljana (Hydrometeorological Institute of Slovenia).

4.4.1. INTRODUCTION

The evaluation of surface stratified waters in the Republic of Slovenia is being implemented by the Institute of Biology of the University of Ljubljana since 1974, when intensive research of Lake Bled started. In 1992, lake monitoring encompassed research of Lake Bled and Lake Bohinj as well as the lakes of the Triglav National Park. The present report is a summary of a full report on the results obtained within the framework of lake monitoring in 1992 (1).

4.4.1.1. Research Programme

This Lake Monitoring Programme has been set up on the basis of recommendations by Vollenweider (2) and OECD (3) for sampling most important physical, chemical and biological parameters.

The 1992 Lake Bled Monitoring Programme encompassed routine monthly analyses of physical, chemical, and biological parameters in the profile of east and west lake basin (see enclosed Map of Lake Bled), monthly analyses of physical and chemical parameters in influents and effluents as well as in the Sava Bohinjka River above and below the outflow of the hypolimnetic outflow from Lake Bled, saprobiological analyses of the influents and effluents as well as the Sava Bohinjka in two seasons of the year.

The Lake Bohinj Monitoring Programme encompassed routine monthly analyses of physical, chemical, and biological variables in the depth profiles at three points and performing physical and chemical analyses for the influents and effluents of the lake (See map of Lake Bohinj). Twice annually samples for saprobiological analyses of the main influents were taken.

In 1992, an investigation of the mountain lakes of the Triglav National Park both at the beginning as well as at the end of the vegetation season was implemented. For all water samples, basic physical and chemical parameters were analysed, influencing the development of phytoplankton, zooplankton and bacterioplankton in the littoral and populations in the benthos of the lakes and their influents. Biological investigations covered invertebrates, algae and macrophytes. Some research had been already implemented in previous years (4.5).

4.4.2. METHODS AND STANDARDS

4.4.2.1. Sampling

In Lake Bled, sampling in depth profiles was carried out vertically at intervals of two meters in both east and west lake basins. February sampling was omitted due to precarious ice.

Depth profile sampling in Lake Bohinj was performed at three sampling points. At all three sampling points, samples were taken at intervals of 3 meters to the depth of 15 m, and below that at intervals of 5 meters. Thus, regular monthly sampling produced 8 samples at T1 (25 m), and 12 samples at both T2 (45 m) and T3 (45 m). February sampling on Lake Bohinj was also omitted due to precarious ice.

In the lakes of the Triglav National Park, sampling was performed according to the depth of individual lakes. In shallow lakes, samples were taken on the surface and on the bottom, in deeper lakes also at mid-depths.

Lake influents and effluents were sampled once every month for physical and chemical analyses, and twice a month for saprobiological analyses.

4.4.2.2. Basic Physical and Chemical Analyses

The following physical parameters were measured at the sampling points: water transparency with Secchi disc, temperature with a thermistor (Iskra MI 7021), pH (Iskra MA 5705), electric conductivity with a conductimeter (Iskra MA 5968) as well as absolute and relative concentration of dissolved oxygen by means of an oxygen probe (WTW OXI96).

In laboratory, chemical parameters were determined according to the following standard methods (6, 7, 8):

- by spectral/photometrical analysis (Iskra Spekol 221 MA 9524): silicon, nitrate, nitrite, ammonium, iron, total phosphorus, orthophosphate;
- titrimetrically: COD (permanganate method), dissolved oxygen and sulphate;
- by flame photometry (Flapo-4,Carl-Zeiss, Jena): potassium, sodium, and calcium.

4.4.2.3. Biological Analyses

The biological analysis comprised the following groups:

- zooplankton: with a 60 μm net;
- phytoplankton: with a 30 μm net;
- zoobenthos: with a 500 μm net;
- benthical algae: by scraping them off the surface of stones;
- macrophytes: by hand or scraper.

All samples were preserved in a 4% formaldehyde solution for subsequent laboratory investigation of species. Simultaneously, the relative frequency of single taxa in samples was determined.

The quantity of chlorophyll a (9) was determined at all sampling points of the depth profile in Lake Bled and Lake Bohinj. In the case of the lakes of the Triglav

National Park, which lie high in the mountains, these measurements were carried out at several points along the vertical profile if a particular lake was deeper than 5 m. Samples were taken either with a plankton net or by filtering 2 litres of water through a glass filter (Watman GF/C). To evaluate the biomass per unity of the lake surface, samples of zooplankton were taken, namely three parallel vertical samples at a time. Zooplankton samples were not taken if a lake was shallower than 1.5 m.

On the basis of the List of Bioindicator Organisms (IBU and HMZ for the year 1992) the identified taxa were classified into saprobic levels and the determined frequency of taxa was used to calculate the saprobic indices of individual lake influents as well as of the mountain lakes of the Triglav National Park (10, 11, 12, 13, 14). The method used was Pantle-Buck (15), modified by Zelinka-Marvan (16).

4.4.2.4. Valid Regulations for Evaluation of the Quality of Still Waters

In evaluating the quality of lake influents, valid regulations were considered, which, unfortunately, were outdated and insufficient (17). That is why in evaluating lakes beside these regulations, recommendations of Vollenweider (2) and OECD (3) had been observed. According to the regulations enumerated above, lake influents are classified into four quality classes, and lakes into five: ultraoligotrophic, oligotrophic, mesotrophic, eutrophic and hypereutrophic lakes. This classification of lakes is based on the quantity of total phosphorus, total inorganic nitrogen, the mean and maximum values of chlorophyll **a**, as well as the mean and minimum transparency depth (Secchi disc).

4.4.3. RESULTS OF RESEARCH IN 1992

4.4.3.1. Lake Bled

4.4.3.1.1. Phytoplankton

Changes in species and specimens abundance of algae at certain depths and in the lake as a whole were very dynamic. Monthly sampling was hardly enough to follow the main trends in the phytoplankton biocoenosis. Activities were particularly intensive during the spring homothermic period, when several species bloomed simultaneously.

In 1992, the total number of algae, their biomass, as well as the chlorophyll **a** content all showed a similar trend of increase and decrease. As in 1991, in 1992 the multiplication of algae was most pronounced in April, and accordingly the biggest growth of algae as to their numbers and biomass was observed in the west basin in the surface layers (total number 3.4 x 10^7 ml, biomass 12.5 mg/l at a depth of 2 m), whereas the development in the west basin at that time was slightly slower (total number 1.8 x 10^7 ml, biomass 8.7 mg/l at a depth of 2 m). During that period, Oscillatoria has reached its peak in the layer between the surface and the depth of 8 meters. In the east basin a maximum concentration of 715 filaments in a ml sample at a depth of two meters, and 590 filaments in a ml sample in the west basin in a surface sample (figure 4.4.1). To the total biomass also contributed diatoms such as *Synedra acus* and *Cyclotella meneghiniana*, a cryptophyte *Cryptomonas ovata* and a representative of the chrisophytes, *Uroglena americana*. The spring peak of algal blooming in 1992 was very similar to what had happened in 1991. The development of phytoplankton biomass also reflected in the distribution of increased concentrations of chlorophyll **a**.

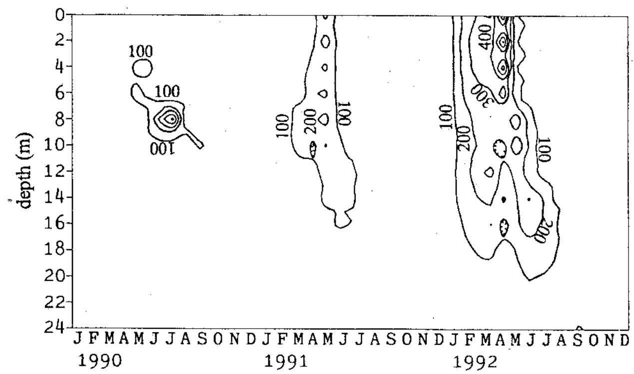


Figure 4.4.1: Vertical distribution of alga *Oscillatoria rubescens* (number of filaments ml-1) in Lake Bled for the period of 1990 - 1992.

The second peak of phytoplankton population was observed in September and October, while in November the biomass of the phytoplankton in Lake Bled was lowest. Thus the situation was quite different than in 1991, when the lowest biomass was noted already in September. In September and October, increased biomass was determined at the border between metalimnion and hypolimnion, namely in September in the east basin at the depth of 14 m (6.1 mg/l), and in the west basin at the depth of 12 m (3.8 mg/l). During that period the greatest number of algae was found at 22 m in the west basin (1.7 x 10_8/ml), accounted for by cianobacteria

Microcystis aeruginosa, which did not show in the biomass (5.8 mg/l). The top of biomass was formed by two chrisophytes *Dinobryon divergens* and *Dinobryon sociale*, and to a lesser extent diatoms, namely the following two species, *Cyclotella comta* and *Stephanodiscus sp*.

In October the majority of algae sank down to a depth of 20 m in the east and west basin, although this did not show in the data for biomass, which meant that the algae had already died. That was indicated by increased concentrations of ammonium at those depths. In November, a biomass minimum was determined in both the east basin (0.18 mg/l) as well as the west basin (0.09 mg/l). In December the number of algae and the biomass again started to increase gradually.

The distribution of chlorophyll **a** concentrations in both east and west basin differed from that of 1991. In general, chlorophyll **a** values in 1992 both in their maximum and mean concentrations were higher for the east basin than the west basin, quite the reverse as in 1991. Maximum concentrations reflected above all the spring blooming of cianobacteria Oscillatoria, diatoms Synedra and Asterionella as well as the yellow-brown alga Uroglena. The September peak was reached in the blooming of the chrysophyte alga Dinobryon in metalimnion, which was more pronounced in the east basin.

4.4.3.1.2. Zooplankton

In 1992, the representatives of the following six species of organisms were detected in the zooplankton population: Cladocera *Ceriodaphnia reticulata*, *Daphnia hyalina* and *Diaphanosoma brachyurum*, Copepoda *Cyclops vicinus*, *Eudiaptomus transylvanicus* as well as the dipterous larvae *Chaoborus fluvicans*. The vertical distribution of the species *Daphnia hyalina* was similar as in 1991, but with certain differences. In the east basin, the peak was reached at the depth of 6 m in July, while in the previous year the peak was reached also in July, but a depth of about 10 m. The next peak in September 1992 was at greater depth than in 1991. In October, November, and December, the highest number of Daphnia were distributed at a depth of 6 m, while in 1991 the main population of Daphnia were at a greater depth.

Similar conditions prevailed in the west basin of the lake, with the peak distribution of Daphnia reached in July at a depth of 8 m, which means a whole month later than in 1991. In October, November, and December 1992, the main population was distributed at a greater depth than in the east basin and in the previous year.

The distribution of the other two Cladocera, Ceriodaphnia and Diaphanosoma was similar as in 1991, although appearing earlier in 1992 and thus enabling us to follow them for a longer time period. Thus Ceriodaphnia were detected in both lake basins from July to December (in 1991 only from August to November), and Diaphanosoma from July to November (in 1991 only in September and October).

The development of the populations of Copepoda Eudiaptomus and Cyclops followed a different pattern than in the year before. The Cyclops was less numerous, appearing through the entire year in the layer up to 10 m, except in September, when present only at the bottom of both lake basins. In the previous year, it was detected only in the time period from January to July as well as in December. Similar was the appearance of Eudiaptomus.

4.4.3.1.3. Physical and Chemical Parameters

In 1992, the lake started to freeze exceptionally early. On the New Year the ice covered the entire lake surface, except at those spots, where the lake receives its influents, the Radovna as well as other major influents. Because of a thaw from January 20 till the end of February the ice was not strong (up to 10 cm thick), and it melted in the first days of March. The homothermic period lasted till April, when temperature stratification began to appear in both lake basins. In June, July, and August, the thermocline lay between 6 and 8 m in both lake basins, in September and October between 8 and 10 m in both lake basins. The maximum temperature of the lake, 23.3°C, was recorded in August in the east lake basin.

Water transparency in both lake basins was smallest in April (1.7 m). The time of best water transparency was August, when a value of 10.5 m was measured in the east basin, and a value of 11.5 m in the west basin. During the summer months, water transparency lagged behind that of 1991.

The contents of dissolved oxygen in 1992 differed much from that of 1991 in both epilimnion and hypolimnion. In epilimnion in 1991, there was more dissolved oxygen in both lake basins than in 1992 (figure 4.4.2.). On the other hand, oxygen conditions in hypolimnion in 1992 were much better than in 1991. While in 1991 the period of oxygen concentrations below 1 mg/l in both lake basins lasted from March till the beginning of December, in 1992 that period was limited to the July-August period in the east basin, and the June-August period in the west basin. The layer of low oxygen concentration in 1992 reached down to a depth of 20 m inclusive in both lake basins. Better aeration at the bottom of the lake in 1992 was probably due to the influent the Radovna, which was ever since the beginning of stratification increased to 500 l/s and for a certain period even to 700 l/s. Increased inflow of the Radovna during the stratification period is an effective measure to ensure better supply of oxygen to lower layers.

Values of dissolved orthophosphate, assessed in individual time periods were lower for 1992 than for 1991. This was true for both epilimnion and metalimnion, but above all for hypolimnion. The values of total phosphorous were occasionally increased due to the blooming of individual species of algae, and were particularly high in April when they amounted to their maximum value of 2.15 mg/l at a depth of two meters in the west lake basin.

Table 4.4.1: Limit values according to OECD (1982) and values of individual parameters measured in Lake Bled.

trophic level	phosphorous total (µg/l)	nitrogen inorg. (µg/l)	chlorophyll a mean v. (µg/l)	chlorophyll a max.v. (µg/l)	water transparency mean v. (m)	water transparency min.v. (m)
ultraoligotrophic	≤4	≤200	≤1	≤2.5	≥12	≥6
oligotrophic	≤10	200-400	≤2.5	≤8	≥6	≥3
mesotrophic	10-30	300-650	2.5-8	8-25	6-3	3-1.5
eutrophic	35-100	500-1500	8-25	25-75	3-1.5	1.5-0.7
hypereutrophic	≥100	≥1500	≥25	≥75	≤1.5	≤0.7
Bled 1991						
east basin	8.7	310	21.4	5.4	5.5	1.8
west basin	7.9	390	35.6	4.8	5.4	1.5
Bled 1992						
east basin	12.4	560	32.8	5.1	6.0	1.7
west basin	25.5	520	30.0	4.7	6.0	1.7

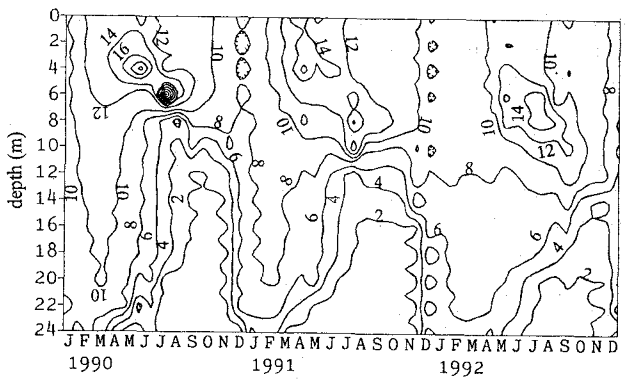


Figure 4.4.2: Vertical distribution of dissolved oxygen (mg l-1) in Lake Bled in the 1990 - 1992 period.

Values of nitrogen compounds were higher in 1992 than in 1991. In August, i.e. at the time when anaerobic conditions predominated, ammonium values in bottom layers in both lake basins rose (up to 6.0 mg/l in the east basin and 4.8 mg/l in the west basin). Occasionally increased nitrite values were detected, up to 2.4 mg/l in the east basin and 5.1 mg/l in the west basin.

On the basis of the total contents of phosphorous, inorganic nitrogen, water transparency and chlorophyll **a** contents, table 4.4.1 illustrates the ranging of Lake Bled into the trophic levels according to OECD recommendations (3). According to chlorophyll **a** values, Lake Bled is classified as mesotrophic to eutrophic.

Values of total phosphorous and nitrogen compounds in 1992 indicated that conditions in Lake Bled were somewhat worse than in 1991.

4.4.3.1.4. Influents and Rehabilitation Measures

The main influents of Lake Bled, contributing most water, are the Mišca, the Krivica, the Solznik, the Ribčev Graben as well as the Ušivec. With regard to the measured values of chemical and physical parameters it may be concluded that the Mišca, the Krivica as well as the Solznik sporadically, and the Ušivec constantly, pollute this lake. An essential increase of in the content of the nutrients in 1992 was determined in the Ribčev Graben, the catchment area of which has suffered intensive liquid manuring.

The Radovna remained polluted and rich with oxygen for the major part of the year. Occasional increases in the values of nutrients point to irregular pollution, a fact further corroborated by saprobiological analyses. In 1992, the total amount of inflow of the Radovna into the lake amounted to 10,627,200 m^3, while the amount of water drawn out through the hypolimnetic outflow amounted to 8,590,752 m^3. The mass balance of nutrients brought into the lake by influents and drawn out of the lake through the hypolimnetic outflow, was negative. 1.7 times more total phosphorus and 1.9 times more total inorganic nitrogen were drawn from the lake that brought into it by its influents. The difference between the input and output quantity of water was due to the fact that the water balance does not cover all influents and effluents (underground, precipitation and other sources).

Table 4.4.2 shows values of physical and chemical parameters as well as saprobic index, as measured in the influents of Lake Bled in 1992.

Table 4.4.2: Physical and chemical parameters and saprobic index (S.I.) in the influents of Lake Bled.

Param. unit	NO3 mg/l	NO2 mg/l	NH3 mg/l	P-o	P-tot $mgPO_4/l$	SiO2 mg/l	COD mgO_2/l	O2 mg/l	cond. µS/cm	S.I.
INFLUENTS										
The Krivica										
max	10.0	0.01	1.0	0.16	0.53	3.5	4.1	13.4	476	
mean	4.0	0.00	0.1	0.03	0.12	2.4	2.5	11.0	318	1.97
min	2.2	0.00	0.00	0.00	0.01	1.8	0.9	9.1	212	
The Mišca										
max	11.6	0.04	1.2	0.1	0.38	4.5	9.4	12.1	470	
mean	6.9	0.03	0.3	0.04	0.1	3.2	3.4	10.9	363	2.05
min	5.0	0.02	0.00	0.00	0.01	1.9	1.1	9.3	297	
The Ribčev Graben										
max	2.8	0.01	1.5	0.00	0.02	3.6	7.5	12.2	417	
mean	1.8	0.00	0.2	0.00	0.01	3.0	3.4	10.6	302	1.58
min	0.9	0.00	0.00	0.00	0.00	1.7	1.1	8.8	263	
The Solznik										
max	13.7	0.03	0.97	0.02	0.06	6.9	8.4	10.6	752	
mean	2.7	0.01	0.25	0.00	0.01	4.4	4.3	6.0	446	1.72
min	0.25	0.00	0.02	0.00	0.00	2.6	2.0	2.6	286	
The Ušivec										
max	14.7	0.01	0.97	0.09	0.08	6.1	7.4	9.9	530	
mean	10.8	0.00	0.12	0.02	0.03	4.7	3.1	8.8	515	
min	6.4	0.00	0.00	0.01	0.00	3.7	1.0	6.9	332	
The Radovna										
max	3.8	0.01	1.05	0.01	0.29	1.4	4.1	16.3	257	
mean	2.2	0.00	0.04	0.00	0.04	0.9	2.7	12.5	190	1.52
min	1.2	0.00	0.00	0.00	0.00	0.0	1.6	10.8	136	
OUTFLOWS										
The Jezernica										
max	2.9	0.02	1.86	0.02	0.03	1.6	5.8	13.3	399	
mean	1.0	0.01	0.31	0.00	0.01	0.8	3.8	10.8	296	1.81
min	0.25	0.00	0.00	0.00	0.00	0.1	2.5	9.0	219	
Hypolimnetic outflow										
max	1.52	0.02	8.96	0.15	0.43	7.8	8.1	6.8	482	
mean	0.56	0.01	4.00	0.06	0.13	5.0	4.3	2.1	379	
min	0.25	0.00	0.24	0.00	0.01	1.8	2.1	0.0	251	
SAVA BOHINJKA										
The Sava Bohinjka above the inflow of the Jezernica and the hypolimnetic outflow										
max	2.9	0.01	0.9	0.01	0.27	1.5	6.0	16.1	236	
mean	2.2	0.01	0.2	0.00	0.05	0.6	3.0	12.3	206	1.66
min	1.3	0.00	0.0	0.00	0.00	0.0	0.9	10.2	159	
The Sava Bohinjka below the inflow of the Jezernica and hypolimnetic outflow										
max	3.1	0.02	0.9	0.01	0.05	1.8	6.2	15.4	286	
mean	2.2	0.01	0.21	0.00	0.02	0.8	3.0	11.9	214	1.99
min	1.2	0.00	0.0	0.00	0.0	0.0	1.6	9.8	165	

4.4.4. CONCLUSIONS

4.4.4.1. Lake Bled

Particularly in the spring of 1992, cianobacteria were the most important phytoplankton group. Among them, *Oscillatoria rubescens* predominated, «algal bloom» in the layer between the surface and the depth of 8 meters in both lake basins in April. There was no typical metalimnion «algal bloom» of Oscillatoria in the summer months. As for other algae, the predominating species were cryptophytes, pyrrhophytes, green algae, yellow-brown algae or chrisophytes as well as diatoms, the latter reappearing after several years in the summer-autumn peak.

Average contents of chlorophyll **a** place Lake Bled into mesosaprobic level, while maximum contents place it into eutrophic level.

Species composition of Copepoda, Cladocera and dipterous larvae, which represent the majority of zooplankton population, saw no significant change compared to 1991. The species *Daphnia hyalina* predominated in zooplankton during the entire year. Other Cladocera and Copepoda were present in a similar temporal and depth distribution as in 1991. During the winter, on the bottom of the lake the dipterous larva *Chaoborus fluvicans* was present, which serves as an indicator of the mesosaprobic level.

The lake was covered with ice from the beginning of January till the end of February. Homothermal conditions prevailed in both lake basins till April, when the temperature stratification set in. Winter mixing of the layers began in the end of November. Water transparency in 1992 was slightly higher than in 1991, placing the lake both according to maximum as well as mean water transparency into the mesosaprobic levels.

Oxygen conditions during the summer period were more favourable than in 1991. Oxygen concentration of approx. 1 mg/l was measured in both lake basins from June to August, rising up from the bottom to a depth of 20 m.

The contents of total phosphorous remained for the major part of 1992 below the values of the previous year, while the contents of maximum concentrations were higher. The contents of inorganic forms of nitrogen, particularly of nitrite and ammonium exceeded those of 1991.

The mean contents of total phosphorous and the contents of inorganic nitrogen place this lake into the mesoeutrophic level.

In all influents, except in the Ribčev Graben, lower cation contents were measured in 1992 than in 1991. The contents of nutrients in the influents differ, but more nutrients entered the lake by way of individual influents than in 1991. The conditions deteriorated badly in the Ribčev Graben, where the content of total inorganic nitrogen compared to 1991 increased by a factor of 40, and of total phosphorous by a factor of 88; that being caused by intensive liquid manuring of adjacent surfaces. Saprobiological analyses of the influents showed a deterioration of the conditions of the Krivica and the Mišca.

The inflow of the Radovna was in the spring period increased to 700 l/s, the aim of that measure being to flood the huge mass of phytoplankton off the surface of the lake. For most of the year, the inflow of the Radovna was from 200 to 500 l/s. The flow from hypolimnetic outflow oscillated from 200 to 370 l/s and consequently twice the amount of total inorganic nitrogen and 1.5 times more total phosphorous were conducted through the hypolimnetic outflow from the lake than in 1991.

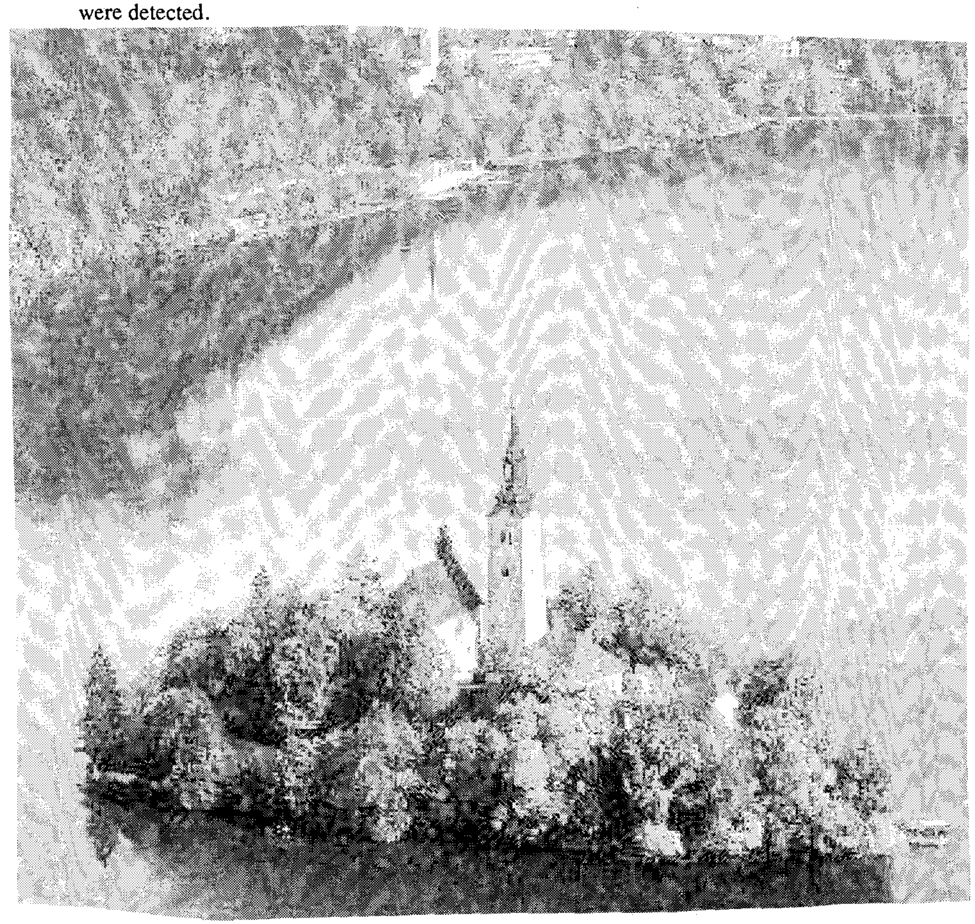
In the Sava Bohinjka the difference between the point above and the point below the inflow of the Jezernica and the hypolimnetic outflow is greatest according to saprobiological analyses, which show deteriorated conditions at the point below the inflow of the Jezernica, the hypolimnetic outflow, and the sewage. According to measured physical and chemical parameters the differences were less conspicuous in 1992.

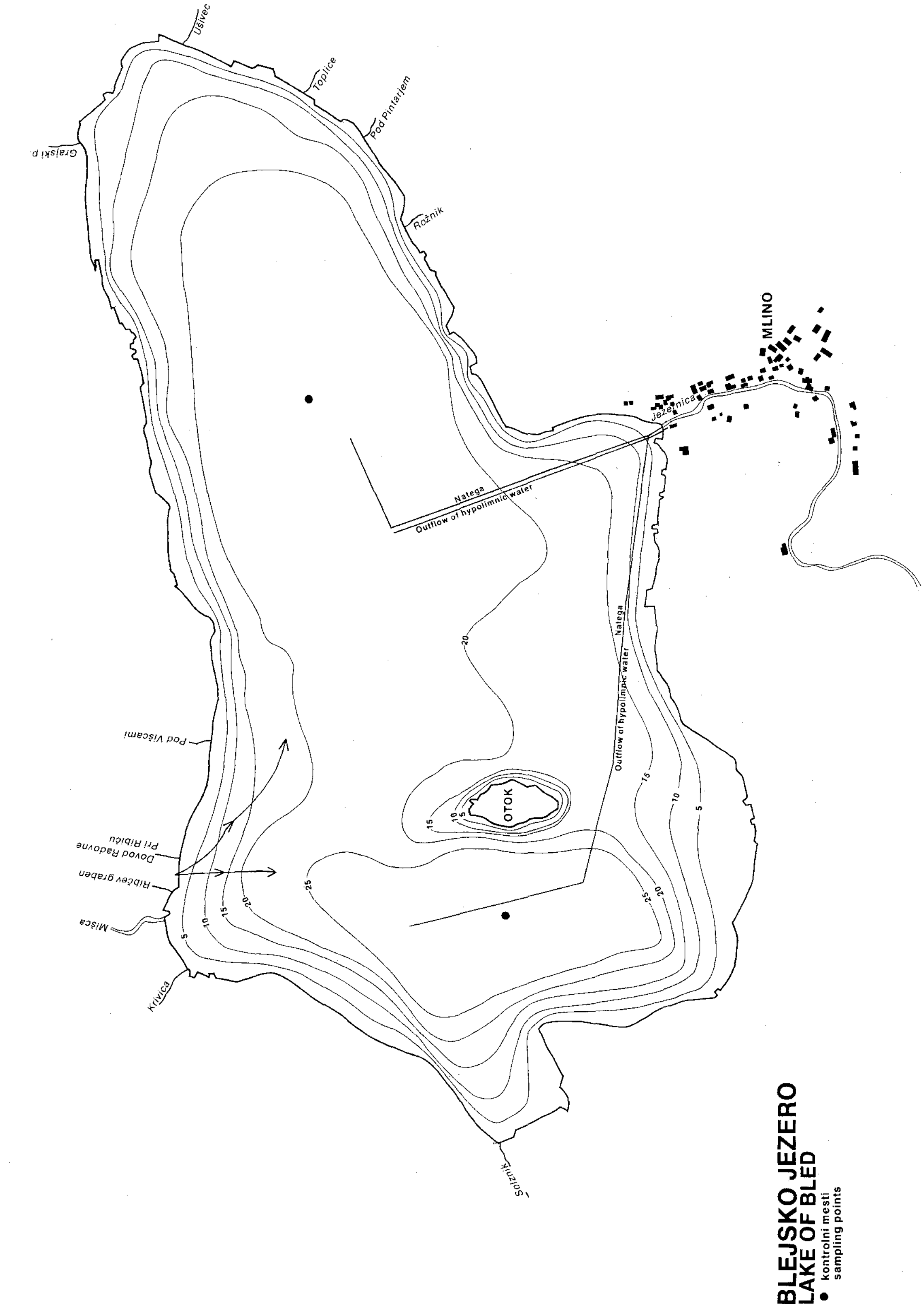
4.4.4.2. Lake Bohinj

The representatives of the algae, which are normally found in more polluted lakes, were in 1992 in the phytoplankton biocoenosis detected mostly in early spring and late autumn, while in the summer the situation was somewhat more favourable. Also detected in the phytoplankton biocoenoses, cianobacteria, although in very small numbers. The diatoms population was numerous in spring and autumn. In summer, besides the green algae of the following species *Gloeococcus schroeteri*, *Ankistrodesmus braunii* as well as various species of the genus *Staurastrum*, there also appeared chrysophytes, notably the species *Dinobryon divergens*. At any time of the year, phytoplankton populations consisted of few members only.

Species composition of Copepoda and Cladocera demonstrated that Lake Bohinj features psychrophilic species as well as species that cannot stand an eutrophised environment. Although *Daphnia hyalina* prospers there, other species, such as *Diaphanosoma brachyurum* or *Eubosmina longispina* in particular, are more strong in numbers. Among Copepoda, *Cyclops abyssorum praealpinus*, typical of oligotrophic lakes, predominated. In summer, the lake was stratified from May till the end of September. The lake was well aerated during the entire year all the way to the bottom. Occasional pollutions of the lake with nutrients were demonstrated by the values of COD, total phosphorous as well as by other parameters. On the basis of OECD recommendations (1982), Lake Bohinj is characterized as an oligotrophic lake.

Physical and chemical parameters in the influents show that the lake was receiving nutrients in increased quantities. Most polluted were the influents in the area around Skalca as well as the outflow from the fish-farm. Occasionally, increased inflows of total phosphorous in various influents and in different seasons of the year were detected.

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LAKE OF BLED
● kontrolni mesti
sampling points
MLINO
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Natega
Outflow of hypolimnic water
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Toplice
Pod Pintarjem
Rožnik
Grajski p.
Pod Viščami
Pri Ribiču
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Ribčev graben
Mišca
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Matija Drovenik, Mario Pleničar & Franc Drovenik

The origin of Slovenian ore deposits

Summary

An attempt has been made to interpret the multistage origin of the ore deposits of Slovenia in chronological order in relation to the geological history of the country.

Early Paleozoic era

The oldest ore bearing beds in Slovenia are the metamorphic rocks of Pohorje and Kozjak which belong to the Eastern Central Alps. They were derived from the sediments and products of the initial volcanism which filled during the Early Paleozoic era the large geosyncline in the region of the Alpides. During the subsidence of the geosyncline the deeper buried rocks were folded and metamorphosed. The progressive regional metamorphism terminated with the retrograde metamorphism. The problem of stratigraphy of our metamorphic rocks and the age of their metamorphism has not been solved completely yet. Metamorphism probably started already in the Baikalian orogeny, and continued during the Caledonian-Variscan orogeny. The metamorphic rocks overlain by quartz-sericite phyllite are probably Pre-Ordovician, and perhaps even of Precambrian age. The Magdalensberg beds which overlie the mentioned phyllite were deposited probably during the period of Middle Ordovician-Lower Devonian.

Already during the Early Silurian period the influence of the Periadriatic lineament became apparent. In the territory of Slovenia it is represented by several parallel faults which had different functions in different geological ages. During the Middle Triassic period the Periadriatic lineament might have been a subduction zone. At the boundary between Cretaceous and Tertiary periods it was represented by a system of right transcurrent faults, and during the Oligocene epoch and at the end of Miocene epoch it was the root region of overthrusts; north of the lineament the overthrusting was directed towards the north, and south of it southwards.

In metamorphic rocks are interesting the lead-zinc-copper deposit Okoška gora in the southern foothills of Pohorje, and the polymetallic ore deposit Remšnik in the southern slopes of Kozjak. At Okoška gora occurs mostly an ore-bearing breccia in which ore minerals represent crystalloblasts due to the influence of regional metamorphism (fig. 1). This is the oldest lead-zinc-copper ore deposit of Slovenia. Spectral analyses of ore minerals indicate a heterogeneous geochemical association, and mass-spectrometric analyses the juvenile origin of sulfur. Possibly, the ore-bearing solutions were derived from the same magma chamber as the keratophyre which was later metamorphosed.

Of more economic importance was the polymetallic ore deposit Remšnik in which lenticular concordant ore bodies were mined. In total, several hundred tons of lead, zinc, and copper were mined. According to trace elements and the isotopic composition of sulfur the Remšnik ore is nearest to that of Okoška gora. It should be mentioned, however, that it is highest in silver and bismuth among all lead-zinc ores in Slovenia. The genesis of Remšnik is still questionable. Some authors support its magmatic-metasomatic, and others the volcanogenic-sedimentary origin (figs. 2, 3).

The Magdalensberg beds are mineralized with lead and zinc in the Velunja valley. According to the mineral composition and geochemical paragenesis, the occurrences in the Velunja valley approach the veinlike lead-zinc deposits in Carboniferous-Permian beds of the Sava folds. On Hamunov vrh there were prospects and some mining of iron ore in Magdalensberg beds. Three diabase lenses contained magnetite bodies which were formed during the separation of liquid basic magma.

Lower Devonian beds outcrop in the Karavanke Alps in the surroundings of Jezersko. Upper Devonian beds are also exposed, but only locally.

Late Paleozoic era

At Stegovnik ore occurs at the contact of Upper Devonian reef limestone and Lower Carboniferous clastic beds. Devonian and Carboniferous rocks are silicified along the contact (fig. 4), and they contain ore minerals, mostly sphalerite, tetrahedrite, and galena (fig. 5). Spectral analyses of tetrahedrite show enrichment, especially of silver and nickel contents. Similar deposits were found along the contact of Devonian and Carboniferous beds also in the Carnian Alps; where they were explained by extrusive-sedimentary ore associated with the Carboniferous spilite-keratophyric volcanism. The total length of the zone of ore occurrences along the contact of Devonian and Carboniferous beds amounts to almost 140 km.

In the Upper Carboniferous beds of the Orenburgian stage occur small deposits of iron ore. They were mined in two belts, one between Jesenice and Tržič, and the other near Vitanje. In both belts ore bodies were mostly lenticular embedded in limestone or in clastic beds. In the first belt about 250,000 tons of sideritic ore were mined in Savske jame, Belščica, and Lepena. In the Vitanje belt iron ore was mined at Bric, Brdce, Felicijan, and in the surroundings of Gloše, Češnjice, and Kamna Gorica. To these deposits the hydrothermal-metasomatic origin was ascribed. However, considering that ore bodies occurred in both belts in the same stratigraphical-lithological horizon, and taking into account certain ore textures in Savske jame and Vitanje belt, sedimentary origin of iron ore in both belts seems more probable.

In the Sava folds the oldest rocks consist of a sequence of dark gray slate, light gray fine grained quartz sandstone, and quartz conglomerate. These beds were ranged first into the Carboniferous period. Later some ranged them into the Carboniferous-Permian, and others into the Lower Permian, i. e. into the Trogkofel stage. Evidence for a faultless classification of the sequence is stil insufficient. Until the age of these beds has been well determined, we shall range them into Carboniferous-Permian.

In the wider surroundings of Ljubljana in Carboniferous-Permian beds copper, iron, and lead ores were mined and melted already in prehistoric times. In the New Ages Litija was the mining center with one of the most important ore potentials in the Eastern Alps. Locally lead and zinc ore contained cinnabar and barite in economical quantities. It occurred in concordant and discordant veins. Between Hrastnica near Medvode in the west, and Pecelj at Sevnica in the east, more than 40 deposits occur at a length of about 80 km, most of them in the Litija anticline.

They are meso-epithermal ore deposits which are not exactly dated yet. We consider that their age determination should be performed primarily on the basis of their position in the geological setup of the Sava folds. These deposits are closely related to the Carboniferous-Permian beds. Ore veins of this kind were not found in the Middle Permian beds, although they overlie often the ore-bearing Carboniferous-Permian beds. They occur neither in Triassic nor in younger beds, with the exception of Pleše, where Triassic carbonate rocks are mineralized with barite — but only along the contact with ore-bearing Carboniferous-Permian beds. Ore at Pleše could be explained by mobilization of barite from Carboniferous-Permiam beds into the Triassic ones.

Ore veins were filled before the deposition of Middle Permian beds, and they are genetically associated with the Lower Permian magmatism, which furnished in Eeastern Alps quartz porphyry and keratophyre. True, outcrops of these rocks have not been found in Slovenia yet, but their pebbles and fragments are a frequent component of the Permian Val Gardena beds.

According to mineral composition four groups of ore deposits can be distinguished. To the first group can be ranged the mesothermal deposits Češnjice, Zlatenek, and Ponoviče; their characteristics is a simple paragenesis, and the principal ore mineral is sphalerite (fig. 6). The second group comprises most of the ore veins. They contain lead-zinc ore with prevailing galena. Typical representatives of this group are Zavrstnik, Maljek, and Zagorica. Ore minerals crystallized in the sequence sphalerite-chalcopyrite-tetrahedrite-galena. Veins often contain barite and also some quartz. Their country rock is in places silicified (figs. 7 and 8).

Economically most important was the third group of ore deposits characterized by ore veins with a heterogeneous paragenesis. Next to galena and sphalerite they contained also chalcopyrite and cinnabar, as well as locally barite in economical quantities. Such ore was mined especially at Litija, Knapovže, and Pleše. The highest ore reserves existed at Litija, where about 50,000 tons of Pb, 1 ton of Ag, 42.5 ton of Hg, and about 30,000 tons of barite were extracted. Vertically in veins the ore and the gangue minerals were zonally distributed. In the upper parts barite prevailed, accompanied by galena and cinnabar. Below, first an abundance of barite diminished, and then also of galena. At the same time sphalerite appeared. Its abundance increased with depth, and it became the main ore mineral accompanied by quartz. Veins then terminated downwards in barren quartz roots.

Into the fourth group only one ore deposit was placed, the Marija Reka mercury ore deposit. The main ore mineral is cinnabar. In lesser quantities occur also other ore minerals characteristic for Pb-Zn ore deposits of the Sava folds, as discussed above.

Typical for the vein deposits of the Sava folds is a slight enrichment of sphalerite in cadmium, cobalt, copper, and gallium, as well as enrichment of galena in silver, copper, and antimony. The isotopic composition of sulfur in sulfides from various ore deposits is rather similar. The main characteristic are close ranges of the δS^{34} value around 0.0 ‰, which is an indication of the juvenile origin of sulfur.

In the Carboniferous-Permian beds of the Sava folds also antimony ore was mined. Ore veins and lenses occurred only in the Trojane anticline between Trojane and Znojile in an about nine kilometers long belt. In the Kralj and Zinka adits, at Perhavec and Znojile, about 4,000 tons of antimony were extracted in total. Next to stibnite (figs. 9 to 12) the ore contains also other ore minerals, but in small quantities only. Considering the geochemical paragenesis and the isotopic composition of sulfur, these antimony vein deposits can be logically associated with other vein deposits in Carboniferous-Permian beds of the Sava folds.

South of the Periadriatic lineament the Permian beds occur in carbonate and clastic development, and north of it only in clastic one. Above the clastic Carboniferous beds in the Karavanke Alps the Trogkofel Pseudoschwagerina limestone was deposited. In the Trogkofel limestone occurs the lead-zinc deposit Korošica with the ore displaying pronounced colloidal structures and textures (fig. 13 a, b). In this respect it differs from other lead-zinc deposits in Slovenia.

From the metallogenic point of view the Permian clastic Val Gardena beds are of an essentially higher importance, since they contain the uranium ore deposit Žirovski Vrh and the copper ore deposit Škofje. The Val Gardena beds attain their maximum thickness in the Žirovski Vrh area. In their lower part, which is 200 to 250 m thick, prevail gray and green coarse and medium grained sandstone along with conglomerate and conglomeratic sandstone. Sheets and beds of red rocks are rare. In the upper part, 350 to 400 m thick, predominate red medium and fine grained sandstone and siltstone. In this part of the lithological sequence occur also beds of gray and green varieties. Geological evidence indicates that the Val Gardena beds were deposited in an arid climate on land: their lower part represents deposits of river bed, and the upper part deposits of flood plain. Especially the red clastic beds occur also in the Škofja Loka and Polhov Gradec hills, and in the Karavanke Alps. Fragments and pebbles of the clastic beds are derived from igneous, sedimentary, and metamorphic rocks. The gray and green Val Gardena sandstone shows evidence of diagenetic, epigenetic, and retrograde-epigenetic alteration. Under the microscope growth of detritic quartz, plagioclase and orthoclase grains, authigenic albite grains, and also several generations of quartz and carbonate minerals can be seen among others. Alterations occurred at temperatures attaining 200° C.

The uranium ore deposit Žirovski vrh lies in gray-green clastic rocks which contain intercalations of red varieties. In this part of the lithological sequence four rhythms can be distinguished. The lower rhythm lies unconformably on Carboniferous-Permian beds. It consists largely of obscurely bedded basal conglomerate and of conglomeratic sandstone. Sandstone and conglomerate of the second rhythm are locally well bedded, and they contain traces of uranium ore and of sulfides. In the third, ore-bearing rhythm sandstone predominates above conglomerate; it is characterized by cross bedding. The fourth rhythm consists of medium and coarse grained sandstone which in places contains also pitchblende and various sulfides (fig. 14).

The ore-bearing horizon of the third rhythm is 30 to 60 m thick. It is devided by lenticular intercalations of red shaly sandstone into the lower and upper part. Until now above 100 lenticular ore bodies have been found which are very irregulary distributed.

The most important ore mineral is pitchblende. It occurs in grains in the cement of sandstone. On the average these grains are about 10 μm thick, and they occur individually, or appear associated into small, irregular lenses (figs. 15, 16, 18, 19, and 20). In very rich ore pitchblende forms most of the cement, and detric grains "float" in it (fig. 17). It is accompanied by sulfides which in several ore bodies achieve even 5 %. Pyrite prevails which is characterized by "mineralized bacteria" (fig. 21). Also pseudomorphs of pitchblende and pyrite after plant remains have been found. In smaller quantities occur as primary minerals also galena, sphalerite, chalcopyrite, arsenopyrite (fig. 22), and tennantite.

Žirovski vrh is a sedimentary ore deposit. Pitchblende and sulfides precipitated in the reducing environment which was generated by decomposition of organic remains and metabolism of anaerobic bacteria. A part of uranium and a large part of sulfide grains were later remobilizied (figs. 23 to 26). The geochemical paragenesis comprises beside uranium also arsenic, copper, lead, zinc and vanadium. The mass-spectrometic analysis of the sulfur isotopic composition shows a strong enrichment in S^{32} with a very wide variation of δS^{34} which attains almost 40 ‰. This is regarded as evidence of biogenic origin of sulfur.

In the surroundings of Škofja Loka there are occurrences of uranium ore in Selca Valley at Sv. Tomaž and Sv. Valentin, as well as in Poljane Valley at Bodovlje ravine.

In the upper part of Val Gardena beds copper occurrences were deposited during diagenesis. There red siltstone, sandstone and shale predominate, however, mineralized are always only their gray and green varieties. Outcrops of copper occurrences are arranged in an almost 90 km long belt which extends from the Cerkno area into the eastern part of Sava folds. The mineralized clastic rocks are hydrothermally unaltered. Authigenic albite rims and authigenic albite grains are entirely fresh also in cases when they border directly on primary ore minerals. Ore beds contain anthracite lenses and very fine dispersed organic matter in clastic rocks. Ore minerals occur mainly in cement (figs. 27 and 28). The most important ore minerals are chalcopyrite and bornite (figs. 29, 32 and 33). In lesser quantities occur also pyrite, tennantite, chalcocite (fig. 30 a), sphalerite, and galena, while in traces enargite, linneite, and α domeykite are present. Characteristic are pseudomorphs of copper sulfides and pyrite after plant remains; the original cellular texture is often very well preserved (figs. 30 b, 34, 35 and 36).

At Škofje lenticular ore bodies occur in an about 15 m thick ore-bearing horizon which is in an inverse position due to post-ore tectonic. Most of the ore was found in dark gray, tough medium grained sandstone. According to mineral composition the bornite-chalcopyrite, bornite-chalcocite, and chalcopyrite-pyrite ore can be distinguished: they were formed in slightly different physical-chemical conditions. Along with copper the Škofje ore contains also some arsenic, lead and zinc, and is enriched in silver. Mass-spectrometric analysis gave evidence of high enrichment of sulfide sulfur with S^{32}; δS^{34} value varies in the range of about 29 ‰. Considering the sulfide sulfur from the surrounding occurrences Šebrelje, Masore, and Sovodenj, this arange is well above 40 ‰. Enrichment in S^{32} and the very broad range of δS^{34} favor the biogenic origin of sulfur in copper deposits of Val Gardena beds.

In the arid climate conditions of Middle Permian stage a small iron ore deposit was formed in the clastic beds at Hrastno near Mokronog. In various periods hematite ore was mined there.

In Upper Permian carbonate rocks no uranium, copper, or iron deposits occur but locally there are minor concentrations of lead-zinc ore. About three centuries ago at Skorno in Šalek Valley Pb-Zn ore was prospected and mined in Upper Permian carbonate rock. In total about 500 tons of zinc and 100 tons of lead were extracted. Mining workings of some importance were in the ore deposit Puharje where the Upper Permian beds exceed 400 metres. The larger part of the lithological sequence belongs to gray and dark gray dolomite. Mineralized with lead and zinc is the upper part of dolomite beds, while the underlying and the overlying limestones are completely barren. Several irregular ore bodies of moderate dimensions showing epigenetic ore structures and textures have been found in the recently driven adit in the gray and dark gray dolomite. In spite of the simple paragenesis, the succession of crystallization of sphalerite and galena which prevail in ore, is very complex (figs. 37 to 42). In dark, very finely grained bituminous variety of dolomite also sedimentary textures and structures appear. They were preserved due to the fact, that the ore bed was insulated by sheets of slaty bituminous dolomite. According to our opinion, the ore minerals of Puharje were deposited during diagenesis of the more or less bituminous carbonate rock, but were later redistributed. By spectral analysis enrichment of sphalerite with cadmium, and of galena with arsenic has been determined. Sulfur of sphalerite and of galena is moderately enriched in S^{34}. It has been released most probably during bacterial reduction of repeatedly reduced sulfates.

Mesozoic era

During the Scythian stage the Alpidic orogenic cycle started with the formation of a shallow geosyncline, which differentiated during the Lower Anisian stage into an eugeosyncline and a miogeosyncline, with an interoceanic high inbetween. The same arrangement lasted also throughout the Ladinian stage. Starting with the Cordevolian substage, however, in the eugeosynclinal area developments in two regions can be distinguished. In the western part of Sava folds the deep marine sedimentation lasted without interruption through the end of Jurassic period. In the other areas of the Southern Alps the eugeosynclinal deposition became interrrupted in the Cordevolian substage and in the Norian and Rhaetian stages with an unique shallow marine carbonate deposition. During the Julian and Tuvalian substages narrow and shallow miogeosynclinal trougs with intermediate carbonate shallow marine deposition were formed. The miogeosyncline, i.e. the region of Dinarides, was periodically interrupted by carbonate shallow marine deposition in the Cordevolian substage, and in the Norian and Rhaetian stages. The total thickness of Scythian, Anisian, Ladinian, Carnian, Norian, and Rhaetian beds amounts to 1900 metres.

Although sedimentary beds deposited in various conditions, the Triassic system is characterized by carbonate rocks. Considering that these beds were deposited in shallow sea, and that their thickness is considerable, it is understandable that the depositional basin had to subside gradually.

Along the dislocations which cut the lithosphere the ascension of the basic basalt magma of the upper mantle started already during the Scythian stage. Due to ist differentiation, and due to the assimilation of the rocks of the lithosphere during its way towards the surface, various volcanic rocks were formed. Mentioned should be especially porphyrite, quartz porphyry, quartz porphyrite, quartz keratophyre, and diabase. Several varieties are albitized and chloritized, so that some rocks have characteristics of typical spilites. During volcanic eruptions pyroclastic rocks were deposited. They exist nowadays in larger outcrop areas than proper volcanic rocks.

The dynamic geological evolution resulted in the formation of various ore deposits. In Triassic carbonate rocks occur lead-zinc deposits without any apparent association with the igneous activity. In Scythian beds there is a number of deposits between Mokronog in the west and Bohor in the east, in Anisian beds occurs the Topla zinc-lead deposit, and in Ladinian, as well as partly in Carnian strata the Mežica lead-zinc deposit.

With deep faults, which cut into the lithosphere, the mercury deposit Idria is associated in which Upper Paleozoic, Scythian, Anisian, and Ladinian beds are mineralized. At the same time as Idria, the mercury deposit Podljubelj was probably formed as well; here, Anisian beds contain ore. Directly connected with the Middle Triassic igneous activity are the deposits of pyrite, as well as lead and zinc which occur in keratophyre and its pyroclastites in the Pirešica area, and iron deposits in the Rudnica area, where Anisian beds are mineralized. During the emersion and weathering of older beds also deposits with varying quantities of aluminum monohydrates and iron hydroxides were formed locally.

Lead-zinc deposits in Triassic carbonate beds differ from vein-type lead and zinc deposits in Carboniferous-Permian beds by the shape of ore bodies, mineral composition, and geochemical properties. The ore deposits in Triassic limestones and dolomites are characterized especially by the following:

— Ore deposits are often roughly concordant with the bedding of the carbonate country rock. In Scythian and Anisian strata they are not associated with faults. However, in Ladinian beds numerous ore bodies are situated at discordant fault systems. These ore bodies were probably deposited in post-Triassic times.

— Ore usualy shows textures and structures indicating metasomatic processes. It should be mentioned that very often also sedimentary textures and structures can be seen.

— The mineral paragenesis of the ore is very simple. Besides galena and sphalerite, whose abundance in different deposits is variable, only pyrite and marcasite occur in noteworthy quantities. Other sulfides are present in traces. The ore contains only those gangue minerals which form the carbonate country rock.

— In the carbonate country rock there are no traces of hydrothermal alteration.

— Spectral analyses show that sphalerite and galena contain only a few trace elements, and even those mainly in small quantities. An exception is only cadmium in sphalerite.

Follows a review of Triassic ore deposits, according to the stratigraphical succession.

In the past in the Lower Scythian beds of the southeastern part of the Sava folds ores were mined which variably contained in some places more lead, and in others more zinc. Deposits are mainly situated in medium grained dolomite (fig. 45) which was deposited in the supratidal environment, and contains locally also gypsum intercalations. These deposits are distributed between Mokronog and Bohor, at a distance of almost 30 km. The most important mining works were at Bohor, while ores were mined also at Ledina, Mokronog, and Škovec.

Most data exist from Bohor, where mainly smaller ore bodies were mined. They were distributed in a distinct horizon, and they consisted of lenses, veinlets, and impregnations of medium and coarse grained galena, cerussite, smithsonite, and also sphalerite (fig. 46). It should be emphasized that at Ledina also ore with layered texture and indications of sedimentary structures was found. The mass-spectrometric analysis of sulfur of galena from Bohor showed a slight enrichment in S^{34} and a very homogeneous isotopic composition.

Considering the fact that the ore deposits in Scythian beds occur in a relatively large area in the same stratigraphical-lithological horizon, that the ore is of very simple mineral and geochemical paragenesis, and that there are no indications of hydrothermal alteration of the enclosing rock, it should be concluded that mineralization is most probably diagenetic. In epigenetic processes ore minerals were recrystallized and partly also remobilized. In this manner epigenetic structures were formed, and they are highly predominant in the ore now. At the first glance the isotopic composition of sulfur does not support its biogenic origin. However, we permit the possibility of its more heterogeneous original composition which was homogenized during remobilization of ore minerals. According to the nature of ore occurrence, paragenesis and the isotopic composition of sulfur, the lead-zinc deposits in Scythian beds are most of all similar to the lead-zinc deposit Puharje.

In Anisian beds Topla zinc-lead deposit only occurs in the northern Karavanke Alps. In its environs appear three horizons of carbonate Anisian beds. The lower and the upper horizon consist of limestone, and the middle of dolomite. Economically important is the dolomitic horizon which contains relatively abundant organic detritus. In this horizon occur interstratified ore bodies of irregular shapes and moderate dimensions. In their lower parts prevails the zinc ore, and in the upper ones the lead, or the lead-zinc ore.

The ore of this deposit is characterized by very abundant sedimentary structures and textures, and especially by rhythmic alternation of ore and gangue minerals. In the ore occur several generations of sphalerite and galena. There prevail irregular sphalerite grainlets with diameters chiefly below 60 microns (fig. 51). Especially interesting is an early diagenetic variety of sphalerite forming globules up to several tens of microns in diameter (fig. 52). To a lesser degree ore contains also pyrite and marcasite. From the geochemical point of view it may be of interest that in Topla zinc prevails above lead; their ratio is about 5 : 1.

Topla is doubtlessly one of those lead-zinc ore deposits in the Eastern Alps in which primary sedimentary textures and structures are well preserved; therefore, the diagenetic origin of the ore in the Anisian dolomite is beyond doubt. This origin is favored also by mass-spectrometric analysis of sulfur; the sulfide sulfur is enriched with S^{32}, whereas values of δS^{34} vary in a very wide range which attains about 32 ‰. Sulfur consequently went through the biogenic reduction of sulfates.

The most important concentrations of lead and zinc occur in Ladinian and partly also in Carnian carbonate rocks of the northern Karavanke Alps, in the Mežica deposit. Mežica comprises the Central deposit with numerous workings, and deposits Graben and Mučevo. Ore occurrences are distributed also at Naravske Ledine, on Peca mountain, at Suhi dol, and Kotlje.

By the volume of metals produced during three centuries, Mežica may be ranged among the most important lead-zinc ore deposits of the Alpine area.

Ore bodies occur in the carbonate beds of the upper part of the Ladinian sequence. There prevails the Wetterstein limestone in the lagoonal development, passing laterally into reef limestone; however, also the Wetterstein dolomite occurs there. Ladinian carbonate rocks are overlain by Carnian beds which are characterized by three horizons of the Rabelj slate. The first horizon of Rabelj slate is the direct hanging wall of the Ladinian beds in the Central deposits. In the Graben deposit the stratigraphical relations are more complex.

A peculiarity of Mežica consists in mining the ore in various types of ore bodies which also occupy various positions in the Wetterstein carbonate beds. They are concordant and discordant ore bodies, deposits of very irregular shapes and disposed in the rock without apparent geological control, and the ore deposits in reefs. The heterogeneity of ore bodies, as well as the structures and textures of the ore indicate that mineralization in Mežica was not formed by an unique, single process, but is a result of the action of distinct and temporally separated processes. However, all ore bodies occur over an area of almost 30 km^2 in the same stratigraphic unit, which permits to attribute Mežica to the group of stratabound ore deposits. Such explanation is supported also by the fact that in the Eastern Alps numerous other deposits are associated with Ladinian beds, especially the two related ore deposits — Rabelj in Italy and Bleiberg in Austria. This is an indication that in the Middle Triassic period favorable conditions for the formation of lead-zinc ores existed in a larger area.

The original mineral composition of the Mežica ore is very simple. Besides galena and granular as well as botryoidal sphalerite (figs. 57, 58, 59, 60 and 62) the unweathered ore contains only pyrite and marcasite in minor and variable quantities. Wurtzite, arsenopyrite, and molybdenite represent only the mineralogic curiosity. Recent investigations have shown that in individual ore bodies several generations of both principal ore minerals appear. Beside calcite and dolomite ore contains in minor quantities also fluorite (figs. 61 and 63).

In spite of many years of research the most probable explanation of the genesis of the Mežica ore deposit is still questionable. The source of lead and zinc is not known, either. By assuming the Middle Triassic age both metals might be supergeneous, as well as hypogeneous. By all means, it should always be considered that the deposit was formed probably during the times of the most violent igneous activity in Slovenia. However, it must be mentioned that those lead-zinc deposits which in Slovenia are provenly asssociated with the Middle Triassic magmatism have much more complicated mineral parageneses which are characterized by larger abundances of pyrite and the presence of copper sulfides. Besides, sphalerite and galena from those deposits contain more trace elements, and in higher quantities than the sulfides from Mežica. Sphalerite from Mežica is namely very low in them. The analyzed samples were enriched only in cadmium, and some of them in germanium. Only the botryoidal variety contains also higher arsenic. As for galena, it is especially interesting that samples from discordant ores are even lower in trace elements than those from concordant bodies. Results of spectral analyses of galena and sphalerite, then, do not favor a magmatic-hydrothermal origin of the Mežica deposit. Even by admitting the volcanogenic-sedimentary genesis we consider it more probable that both principal elements were derived from older beds, and were only remobilized by the Middle Triassic igneous and tectonic activity.

A further possibility exists that Mežica is not directly associated with the activity of magmatogenic hydrothermal solutions, but was formed, on the contrary, by supergeneous processes. This possibility is favored, among others, also by sedimentary structures and textures which are preserved in many concordant ore bodies in the Central deposits and especially in ore bodies of the Graben deposit. In this connection it should also be mentioned that the sulfide sulfur is enriched with the light isotope, and there is a wide variation of the δS^{34} value. Both indicates a biogenic origin of sulfur. The mentioned problems show there are still no convincing answers to many questions on the origin of the Mežica ore deposit.

A typical example of an ore deposit which was formed along faults is the world known Idrija, where starting in 1492 until now at least 144,000 tons of quicksilver were mined. The ore-bearing solutions circulated along subvertical faults which formed the Idrija graben. In the top part they cut the Carboniferous--Permian, Permian and Lower Triassic, as well as partly the Middle Triassic beds.

The ore from Idrija is practically of monomineral composition. In numerous ore bodies cinnabar is namely the only ore mineral, and in rich ore it is accompanied locally by droplets of native mercury. The native mercury is an economically important ore component only in Carboniferous-Permian beds. Pyrite and marcasite are rather rare. Both were formed chiefly already during the diagenesis of Late Paleozoic and Triassic beds. Exceptionally, metacinnabar, sphalerite, and orpiment could be found in the ore. In veinlets cinnabar is accompanied by dolomite, calcite, and quartz. During mobilization they precipitated from the country rock under the influence of hydrothermal solutions, and later of pore waters.

There are, consequently, two mineralization stages. During the first stage the epigenetic ore originated, and during the second the syngenetic ore. The ore-bearing hydrothermal solutions arrived into the deposit area before the culmination of the Middle Triassic igneous activity. During the first stage cinnabar crystallized in Late Paleozoic, Scythian, and Anisian beds from low-tempera-

ture solutions (figs. 68 to 74). Subsequently, the Idrija graben was formed in the Langobardian substage. The ore-bearing solutions of the second stage repeatedly flowed through the mentioned strata, and then discharged on the bottom of the shallow sedimentary basin in which cinnabar deposited (figs. 75 to 78).
In this manner, in the Langobardian Skonca beds and in hanging wall tuffs as well as in tuffites lenticular and layered syngenetic ore bodies were formed. Locally, cinnabar occurs also in Cordevolian beds; however, all other Upper Triassic and younger beds in the area of the Idrija deposit are completely barren.

Contrary to expectations, the mass-spectrometric analysis indicated a very heterogeneous isotopic composition of sulfur. It is not sufficiently clear yet from where sulfur was derived. Igneous origin is certainly also possible. The observed fractionation of sulfur isotopes must be explained, in this case, by changing physico-chemical conditions during the formation of the ore.

More or less at the same time as Idrija was formed also the mercury deposit Podljubelj in the Karavanke Alps. Here, only Anisian beds were mineralized. Smaller, irregular ore bodies are situated in two parallel zones in the recrystallized and slightly silicified micritic limestone. They are formed by numerous irregular and interlaced cinnabar-calcite veinlets, by fine cinnabar impregnations (figs. 53 and 54), and to a lesser degree also by botryoidal cinnabar (figs. 54 and 55).

The ore from Idrija and Podljubelj is, consequently characterized by a very similar mineral composition. Practically, the only ore component occurring in either ore deposit, is the cinnabar. Its regular trace element is copper which is probably of the same origin as the mercury. Higher contents of lead in some samples of the »steel ore« in Idrija, and the presence of uranium in the Skonca beds are attributed to their syngenetic concentrations in the organic matter. All this indicates that the Idrija and the Podljubelj ores have been formed from similar, highly differentiated hydrothermal solutions. Considering the fact that in Idrija solutions followed deep faults, it may be supposed that mercury was derived from the upper mantle.

From highly differentiated low-temperature hydrothermal solutions also the antimony ore deposit Lepa Njiva originated. It is situated in Upper Permian limestone. The question of its origin — associated with the Triassic, or with Tertiary magmatic activity — is not solved yet. Solutions arrived along a strong tectonical zone, and they resulted also in an intense silicification of limestone. The mineral composition of the ore is very simple: next to stibnite (figs. 43 and 44) practically no other minerals are present. The isotopic composition of sulfur favors its juvenile origin.

A separate group is formed by ore deposits which are directly connected with the Triassic igneous activity. In the past large metallogenic importance was attributed to this volcanic activity, which is the strongest in the geologic history of Slovenia. According to our views, this emphasis was exaggerated. It is true that there are no important concentrations of ore minerals in the very abundant outcrops of Triassic volcanic and pyroclastic rocks. Besides, these rocks were never, with a few exceptions, hydrothermally altered to any appreciable degree. Also in older rocks, which directly surround the Triassic volcanics, occur no ore deposits of any degree of importance, and hydrothermal alterations in them are again only weakly developed.

It would not be justified to deny the Triassic igneous activity all its metallogenic importance. There is no doubt that the deposits in the Pirešica keratophyric area are directly associated with it. All are situated in the hydrothermally altered biotite quartz keratophyre. These deposits never had any greater economic importance. However, in the past numerous smaller pyrite bodies were mined at Studenci, Železno, and Galicija. Pyrite (fig. 79) was accompanied by marcasite (figs. 80 and 81) and in lesser quantities probably also by arsenopyrite. The question whether these bodies are of volcanogenic-sedimentary, ore of hydrothermally-metasomatic origin, has so far not been solved.

In the eastern part of the keratophyre area lead-zinc ore was mined at Zavrh. Ore occured in the silicified and recrystallized Ladinian reef limestone which is enclosed by keratophyre tuff; the latter, too, was hydrothermally altered, and to a slight extent mineralized. Exsolutions of ZnS-$CuFeS_2$ and of emulsion textures (figs. 78 to 89) characteristic for this process indicate relatively high temperatures of the genesis of this deposit. The concentrate of sphalerite is enriched in arsenic, cadmium, copper, gallium, indium, manganese, antimony, and tin. Next to silver and arsenic the galena concentrate contains also copper, antimony, and tin. Minor occurrences of lead-zinc ores occur also at Galicija, Lebič, and Šuperger. In one of the drillings at Šuperger also lead-zinc ore with layered structures and texture (figs. 85 and 86) was found; they are characteristic for a volcanogenic-sedimentary origin.

According to mineral composition, ore structures and textures, as well as geochemical association, the Zavrh ore differs from all the other lead-zinc ores of Slovenia. It is close to some Montenegrin lead-zinc ores which are also associated with the Middle Triassic igneous activity.

Other ore occurrences, which are probably also connected with the Middle Triassic igneous activity, appear on Rudnica, in the eastern extension of the Sava folds. In anisian beds between Olimje and Podčetrtek iron ore was mined; it was prospected also to the west of Olimje. The primary mineralization was deposited by hydrothermal solutions, which were derived most probably from the same magmatic source as the augite porphyrite. During metasomatic processes dolomite was altered chiefly into ankerite and partly also into siderite. As a result of their oxidation iron hydroxides were formed, and they were mined in the past. In the volcanogenic-sedimentary processes in the Pseudozilian beds of Rudnica chert with hematite was formed, while in the southern slope of Žusem there were occurrences of iron and manganese minerals in beds overlying the Pseudozilian strata.

The Rabelj beds, which were deposited during the Carnian stage, contain in the region Turjak-Podlipa ferruginous-bauxitic rocks, mainly rich in silica. Locally, oolitic textures occur; in places they contained enough iron to be mined in the past. At Podlipa near Vrhnika an about four kilometres long lens was found, being, however, relatively thin. A geographically discrete succession of rock units and oolitic lenses in clastic development indicate that aluminum and iron were redeposited.

The Jurassic beds are represented with Liassic, Doggerian, and Malmian beds. They were deposited in shallow and deep marine conditions. Characteristic for the shallow marine development are carbonate rocks of the shelf environment, and for the deep marine development platy limestone and slates. On the

Dobrovlje plateau the Liassic beds are associated with porphyry, porphyrite, keratophyre, and their tuffs. These rocks are evidence of eugeosynclinal Jurassic volcanism. In Liassic beds of the deep marine development the only manganese deposits in Slovenia are located. Concentrations of any interest occurred only on Begunjščica. From the ore bearing bed which was enclosed in slates about 130,000 tons of ore with 30 % Mn were mined. Also at Vancovec, Počenska Gora, and between Kobla and Črna Prst occurred manganese ore enclosed in slaty beds. In all cases deposits are sedimentary. After the local emersion of Jurassic beds in Malmian strata deposits of low-quality bauxite were formed, among others also at Železni Klanci and Rjavi Grič.

In Cretaceous period continued a similar sedimentary environment as in the Jurassic. Deposited were Valanginian, Hauterivian, Barremian, Aptian, Cenomanian, Turonian, and Senonian beds. Deposits of the shallow marine facies are much more abundant than those of the pelagic. During the Upper Cretaceous in Central Slovenia the flysch miogeosynclinal trough started forming, and it kept gradually spreading towards the south and the north until Eocene epoch. During this period the shallow marine carbonate deposition continued south of this trough. In places orogenetic movements uplifted younger Mesozoic beds into the weathering zone. As a consequence, three horizons with lenses of moderate quality bauxite were formed. The first horizon is intercalated between the Lower Cretaceous and Upper Cretaceous beds, the second lies along the contact of Turonian and Senonian beds, and the third is underlain by the Turonian and Senonian strata, and is overlain by Paleocene beds.

During the deposition of Jurassic and Cretaceous beds the ore deposits, which existed in Permian and Triassic beds, were brought by subsidence into deeper parts of the lithosphere. When investigating the copper deposit Škofje, we observed that, due to higher temperature and pressure, ore and gangue minerals were partly mobilized and redistributed. Most probably similar phenomena occurred also in other ore deposits, since similar conditions existed in them.

Cenozoic era

Up to now the origin of numerous Slovenian ore deposits was attributed to their association with the Tertiary igneous activity. However, the more the Tertiary igneous rocks and the environment of their emplacement became known, the more convincing became the concept that Tertiary igneous phases were of reduced metallogenetic importance. In the temporal sequence of the emplacement of Tertiary igneous rocks, first the Oligocene andesite appeared accompanied locally by dacite. Andesite was derived from the quartz dioritic magma. It extruded to the surface mainly along the Smrekovec fault; and from there eastwards it occurs also along the Šoštanj and Donat faults. Tuffs associating andesite occur in the Oligocene beds in a very wide area.

Along the system of faults which form the Periadriatic lineament plutonic rocks with prevailing hornblende-quartz diorite intruded in the Karavanke area during Oligocene. It was derived from the quartz-dioritic magma, and is characterized by parallel structure. Radiometric dating revealed an age of about 29 million years. Since both rocks were formed from the quartz-dioritic magma, and coincide in the age of their emplacement, it is believed that the Smrekovec andesite represents the extrusive rock of the same magma which yielded the Karavanke diorite.

Close to the Periadriatic lineament also biotite-quartz diorite and granodiorite, which solidified from a magma of palingenic origin occur on Pohorje. Rocks are probably more or less synchronous with the Karavanke diorite. Both diorites, that of the Karavanke Alps and that of Pohorje, may be considered synorogenic intrusives.

To all appearance, the Oligocene magmatism was a barren one. This concept is supported by the absence of hydrothermal alteration of Oligocene plutonic and volcanic rocks. Until now no concentrations of ore minerals have been found in them. In the same line, no ore deposits are known along the contacts of Oligocene igneous rocks and older adjacent rocks.

The igneous activity on Pohorje, which started in Oligocene with the intrusion of biotite-quartz diorite and granodiorite, terminated during the Helvetian stage with the extrusion of dacitic magma. Dacite prevails in the western part of Pohorje. Along its contact in the area of Mala Kopa by contact metamorphism mainly Upper Cretaceous sedimentary rocks were altered, especially limestone and marl. Skarns were formed with contact silicates which contain chiefly magnetite, accompanied in lesser abundance by pyrrhotite, chalcopyrite, and pyrite. In the past centuries iron ore was mined here. Mala Kopa is the only deposit which can be reliably connected with the Tertiary magmatism.

The very dynamic tectonic erosion of older beds and heterogenous sedimentary environments in individual depositional basins resulted during Tertiary period into the deposition of very heterogeneous sedimentary rocks. However, these rocks lack concentrations of ore minerals of any importance.

On the other hand, Quaternary fluvial deposits of Drava and Mura contain some gold that was locally washed in the past. With the increasing prices of this metal on the world market due attention should be given in the future to these placers.

During the Quaternary period also small deposits of pisolitic bog iron ore were formed. It was melted already in prehistoric times. Pisoliths composed ore provided the basis of iron industry, which starting with the 14th century principally of limonite were collected especially in the Triglav foothills. Bog iron developed in Železniki, Kropa, Kamna gorica, and Bohinj.

Of considerable importance for the ore deposits of Slovenia were the Tertiary tectonic phases. The paroxysm of the Alpidic orogeny coincided in these regions most probably with the Rhodanian orogenic phase at the end of the Miocene epoch. At that time the ore-bearing Carboniferous-Permian, Permian, and Triassic beds were brought to higher levels by folding, and were thrust up over younger beds. In this thrust faulting the Periadriatic lineament appears to have had an important part being the root zone of overthrusts with the vergence southwards, as well as northwards. Thus, the ore-bearing beds of the Idrija ore deposit were uplifted from a depth exceeding 4,000 m; they were folded and thrust forward from northeast to southwest. Nowadays, the Idrija deposit is situated in a schuppen structure within the Žiri-Trnovo nappe. A part of the deposit, approximately a quarter of it, was "lost" during thrusting somewhere between the Jelovica high plain and Idrija.

With the lower part of the Val Gardena beds in the Žiri-Trnovo nappe also the uranium deposit of Žirovski Vrh rised to the surface. Orogenic movements folded and deformed the ore-bearing beds, and affected also the ore bodies lying in the so called double "S" structure (fig. 14). In the same nappe lies also the copper deposit Škofje, as well as numerous ore occurrences in its environs. The ore bearing Val Gardena beds were folded together with Carboniferous--Permian and Triassic strata. In one of the Škofje overthrust sheets the ore-bearing horizon is located, however, in the overturned position. During the orogeny in Žirovski Vrh and Škofje besides quartz also carbonate minerals were mobilized into quartz-, carbonate- and quartz-carbonate veins and veinlets with characteristic striped texture (fig. 24).

The lead-zinc ore deposits in Scythian beds, among others also Bohor, are located in the Dolsko overthrust which was moved from the north in the Outer Dinarides. Distance of overthrusting amounts to about 10 km.

North of the Periadriatic lineament in the northern Karavanke Alps the Triassic and Jurassic beds were moved towards the north. Here, the Jazbine, the Central, and the Northern overthrust zones are distinguished. The Mežica ore deposit is located in the Central zone; the central underground workings of this deposit are in the tectonic graben delimited by the Naveršnik, Godec, Šumah, and Peca faults. Also beds in the graben itself are cut by numerous faults; some of them were probably repeatedly active. Along faults and in fractured zones crystallized ore minerals, as well as calcite and dolomite. In this way were probably formed the discordant ore bodies, among them also the bodies of the Union system (fig. 91).

Deformation of ore deposits continued also into the neotectonic time. The Idrija deposit was cut by subvertical faults striking NW-SE with a horizontal right movement of flanks. Along the Idrija fault a part of the deposit was moved for about 2.5 km towards the southeast; several years ago it was discovered by deep drilling at Ljubevč. The ore bodies were fractured, and in fissures superinduced cinnabar, calcite, and dolomite crystallized. In the copper deposit Škofje, and in the uranium deposit Žirovski Vrh gangue minerals were reworked. In veins quartz, carbonate, quartz-carbonate, and even albite veinlets were formed, which contain in ore beds even sulfides (fig. 31). In the Mežica deposit old faults were rejuvenated. Due to movements, the ore was fractured. In rich lead ore the "lead mirrors" were formed, and during recrystallization of galena often also the "lead tail". In youngest faults crystallized well developed calcite crystals.

During Pliocene epoch and Quaternary period many ore deposits appeared at land surface; the overlying beds having been wholly or partly removed by denudation. Due to the penetration of surface waters rich in oxygen the physico--chemical conditions changed. The primary ore minerals became unstable and they started to decompose. Unstable sulfides passed mainly into carbonates, oxides, hydroxides, and sulfates. Very probably the surface waters brought from overlying Carnian beds also molybdenum into the Mežica ore deposit. In this manner wulfenite was precipitated, especially in the upper parts of some ore bodies.

Geologie und Vererzung der Quecksilberlagerstätte Idrija

Ivan Mlakar und *Matija Drovenik*

Zusammenfassung

Das geologische Profil des Idrija-Gebietes charakterisiert eine mehrere 1000 m mächtige Serie karbonatischer und klastischer Gesteine des jüngeren Paläozoikum, der Trias, der Kreide und des Eozän. Die mitteltriassischen radialen Verschiebungen der Blöcke begleitete eine magmatische Tätigkeit; Diabase und Keratophyre, sowie ihre Tuffe werden als Produkt des initialen geosynklinalen Vulkanismus betrachtet.

Eine viel intensivere und bedeutsamere alttertiäre Tektonik hat einen Deckenbau zur Folge gehabt, welcher aus vier Decken besteht. Dieser Deckenbau stellt das Endstadium der Deformierung einer großen liegenden Falte dar. Die Überschiebungslänge beträgt 25 bis 30 km. Autochtone und allochthone Schichten wurden sehr wahrscheinlich im Pliozän mit einem System dinarisch gerichteter Verwerfungen mit horizontalen rechten Blockbewegungen bis 2,5 km durchgeschnitten.

Die Quecksilberlagerstätte Idrija befindet sich in der dritten Decke. Im Hangenden und im Liegenden ist sie mit den Überschiebungsflächen begrenzt; im Nordosten und im Südwesten ist die Lagerstätte dagegen mit jüngeren dinarisch gerichteten Verwerfungen abgeschnitten. Den unteren Teil der Lagerstätte bilden jungpaläozoische sowie unter- und teilweise noch mitteltriassische Schichten, welche gewöhnlich subvertikal oder invers liegen. Im oberen Teil finden wir aber anisische, cordevole und vor allem langobardische Gesteine. Beide Strukturen, die wir als unteren und oberen Bau der Lagerstätte bezeichnet haben, scheidet ein mitteltriassischer Bruch, welcher nach der Umdrehung der Schichten eine subhorizontale Lage eingenommen hat.

Systematische Grubenaufnahme und in den letzten Jahren durchgeführte mikroskopische Untersuchungen haben unzweifelhaft das triassische Alter der Lagerstätte bewiesen. Es wurde sogar festgestellt, das die Vererzung im Ladin stattgefunden hat. Der mineralogische Bestand des Erzes ist sehr einfach. Das Haupterzmineral ist der Zinnober, welcher in kleinerer Menge von Pyrit und in einigen Erzkörpern auch von gediegenem Quecksilber begleitet ist. Metacinnabarit, Markasit, Zinkblende und Auripigment sind nur sporadisch vertreten. Als Gangmineralien sollen Dolomit, Calcit, Quarz und Chalcedon erwähnt werden.

Die Erzkörper kommen in allen Horizonten vom Jungpaläozoikum bis zu dem oberen Teil der Mitteltrias vor. In den älteren Schichten, die vorwiegend aus Perm-, Skyth- und Anisgesteinen bestehen, handelt es sich um epigenetische Vererzung. Für die Langobard-Schichten, insbesondere für Skonca-Schichten und für die jüngste wirtschaftlich vererzte stratigraphische Einheit, die aus Tuffit, Tuff und Radiolarit bestehen, ist hingegen die syngenetische Vererzung kennzeichnend.

Geologie

In der umfangreichen geologischen Literatur über die Lagerstättenverhältnisse des Bergbaues Idrija nehmen die Interpretationen von Kossmat (1899, 1911), Kropač (1912) und Berce (1958) eine sichtliche Stelle ein. Die Angaben, gesammelt in den letzten Jahren, öffnen aber neue Ansichten über den Aufbau und die Entstehung der Idrija-Lagerstätte (Mlakar, 1967, 1969).

Das geologische Profil des Idrija-Gebietes charakterisiert eine mehrere 1000 m mächtige Serie karbonatischer und klastischer Gesteine des jüngeren Paläozoikum, der Trias, der Kreide und des Eozän (Abb. 1). Jura-Schichten kommen erst in weiterer Umgebung von Idrija vor.

Der schwarze Tonschiefer ist zweifellos das älteste Gestein im Gebiete von Idrija. Nach der alten Auffassung sollte er zu Karbon gehören, es fehlen aber paläontologische Beweise.

Auch das Alter des grauen und roten Schiefers, der Sandsteine und Konglomerate ist paläontologisch nicht bewiesen. Diese Schichten von einer Mächtigkeit bis 40 m reihen wir in die Sosio-Stufe des permischen System ein, die im Idrija-Gebiet in der Grödener Fazies entwickelt ist. Oberpermische Schichten sind dagegen der älteste paläontologisch bewiesene stratigraphische Horizont. In diese Schichten reihen wir den grauen Dolomit und den schwarzen bituminösen Dolomit mit schiefrigen Einlagen ein. Die Gesamtmächtigkeit beträgt höchstens 60 m.

Im unteren Teil der unterskythischen Schichten wechselt sandiger Dolomit mit Dolomit ab, im oberen Teil finden wir aber kalkglimmerige Schiefer und Aleurolith mit Linsen von Oolithkalk. Oberskythische Schichten sind im unteren Teil dolomitisch entwickelt, im oberen Teil aber kalkmergelig. Die Mächtigkeit der Skyth-Schichten in der Lagerstätte beträgt etwa 400 m.

Anisisches Alter hat der hellgraue Dolomit; seine Mächtigkeit erreicht ungefähr 60 m.

Die Sedimente der Ladiner Stufe liegen auf dem anisischen Dolomit diskordant. Es fehlen nähmlich die Schichten der Fassaner Unterstufe. Langobardische Schichten beginnen mit basalem Sandstein, gewöhnlich nur einige Meter mächtig. Es folgt ein Konglomerat, vorwiegend aus Geröllen anisischen Dolomites, darauf schwarzer bituminöser Schiefer und Skonca-Sandstein. Langobardische Schichten enden mit graugrünem Tuffit, Tuff und Radiolarit mit Hornstein. Die Mächtigkeit der langobardischen Schichten in der Lagerstätte beträgt etwa 200 m. Die Cordevol Schichten stellen weißer Dolomit und schwarzer Kalkstein mit Hornstein, in gesamter Mächtigkeit von ungefähr 180 m vor.

Die Schichten der karnischen Stufe sind im Idrija-Gebiet vorwiegend klastisch entwickelt, die Gesteine der norischen und rhätischen Stufe aber karbonatisch. Die Schichten der Obertrias besitzen eine Mächtigkeit von annähernd 1600 m.

Die Schichten der Jura und Kreide sind karbonatisch entwickelt in einer Gesamtmächtigkeit von etwa 2800 m.

Mit den Eozän-Schichten, die auf Senon-Kalken diskordant liegen, endet im Idrija-Gebiet die geosynklinale Sedimentation. Diese Schichten umfassen Flyschmergel, Sandsteine und Kalkbreccien; sie sind nur einige

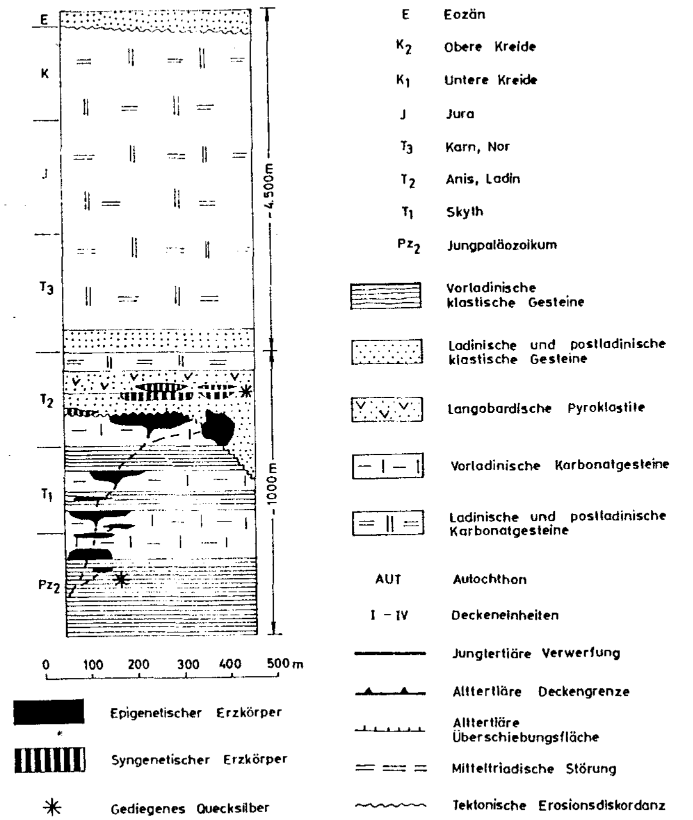

Abb. 1. Schematisches Säulenprofil durch das Idrija Gebiet

Hunderte Meter mächtig. Die Gesamtmächtigkeit der geosynklinalen Sedimenten beträgt aber ungefähr 5500 m.

Im Gebiete von Idrija ist eine intensive mitteltriassische Tektonik festgestellt, die der labinischen tektonischen Phase entspricht. An den Brüchen entlang, mit Richtung Nord-Süd und vor allem Ost-West, haben sich die Blöcke radial für mehrere Hunderte Meter verschoben. Langobardische Schichten liegen daher diskordant auf verschiedenen anisischen und skythischen stratigraphischen Gliedern. Vorlangobardische Gesteine sind gegen die mitteltriassische Diskordanzfläche höchstens um 15° bis 20° geneigt. Faltungen die nur im unteren Teil der Struktur zum Ausdruck kämen, konnten wir bisher nicht feststellen.

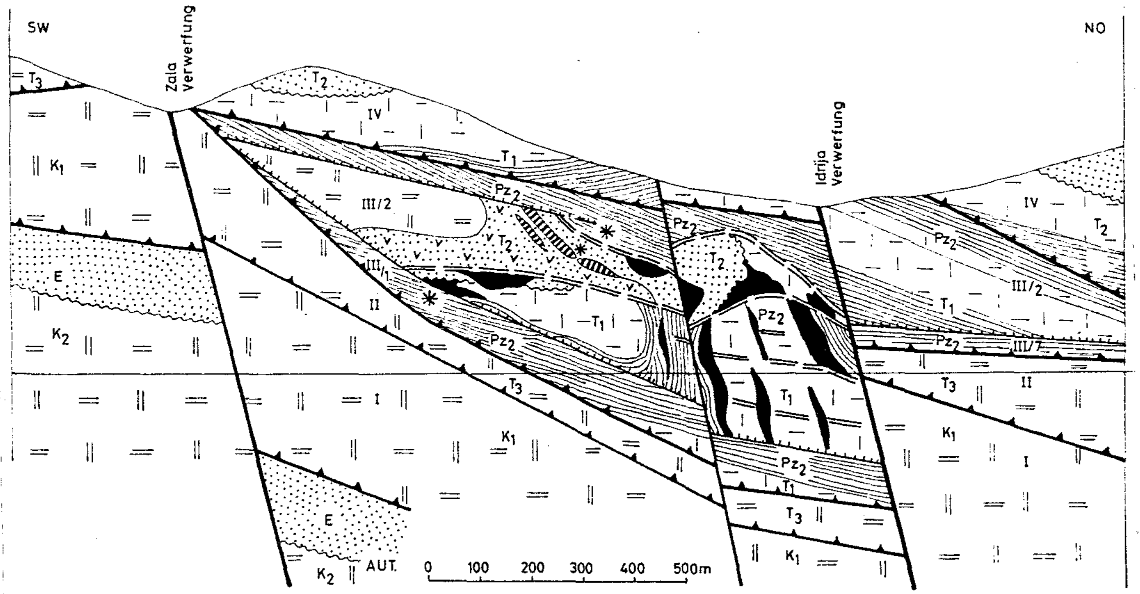

Abb. 2. Schematisches Querprofil durch die Quecksilberlagerstätte Idrija
Legende in Abb. 1

Die radialen Verschiebungen der Blöcke begleitete eine magmatische Tätigkeit. Diabase und Keratophyre, sowie ihre Tuffe, betrachten wir als Produkte des geosynklinalen initialen Vulkanismus. Magmatische Gesteine finden wir ungefähr 13 km nordwestlich von Idrija im Bereich von Stopnik und Cerkno.

Nach bisher gesammelten Angaben haben die erwähnten mitteltriassischen tektonischen Linien die Quecksilbervererzung im Raum von Idrija kontrolliert.

Eine viel intensivere alttertiäre Tektonik hat nachher die Folgen der mitteltriassischen tektonischen Phase verwischt und überprägt. In dieser Zeit entstand der Deckenbau, in welchem alle Schichten vom jüngeren Paläozoikum bis zum älteren Tertiär teilnehmen (Abb. 2).

Den alttertiären Deckenbau des Idrija-Gebietes haben wir in vier Decken unterteilt (Mlakar, 1964, 1969). Die autochthone Unterlage bilden mesozoische und alttertiäre Schichten in normaler Superposition. Die erste Decke, die Koševnik Decke genannt, die wir auch als parautochthon bezeichnen können, besteht aus Kreidegesteine in normaler Lage. Die Schichten der Obertrias und stellenweise noch Jura- und Kreideschichten in inverser stratigraphischer Lage bilden die zweite, die Čekovnik Decke. Die dritte, die Idrija Decke, besteht aus paläozoischen und triassischen Schichten in normaler und inverser stratigraphischen Reihenfolge. Im Bau der vierten, Žiri-Trnovo Decke, nehmen alle Schichten von jüngerem Paläozoikum bis Eozän in normaler stratigraphischer Lage teil.

Der Deckenbau, enstanden unter dem Einfluß tangentialer Kräfte gerichtet von Nord und Nordosten, ist das Endstadium der Deformierung einer großen liegenden Falte. Die autochthone Unterlage, die Koševnik Decke und ein Teil der Idrija Decke mit normaler Schichtenfolge stellen den unteren Flügel der liegenden Falte dar. Die Čekovnik Decke und der inverse Teil der Idrija Decke gehören zum Mittelflügel, der obere Teil der Falte ist aber in der Žiri-Trnovo Decke erhalten. Alle Deckeneinheiten sind unten mit einem basalen und oben mit einem Hangendschrägzuschnitt begrenzt.

Einzelne Decken haben gewöhnlich eine Mächtigkeit von einigen 100 m, nur die vierte ist bedeutend mächtiger. Die Überschiebungslänge beträgt 25 bis 30 km. Die mitteltriassische labile Zone ist eine embryonale Struktur des alttertiären Deckenbaues. Das Alter des Deckenbaues können wir nicht genauer feststellen, doch der größere Teil der Deformationen entstammt der posteozänen Periode.

Im Endstadium der alpinen Orogenese war der Deckenbau noch mit einem System dinarisch gerichteter Verwerfungen mit horizontalen rechten Blockbewegungen bis 2,5 km durchschnitten (Mlakar, 1964). Der bedeutendste ist die Idrija Verwerfung, die steil gegen Nordost abfällt. Die Verwerfungen sind sehr wahrscheinlich pliozänen Alters.

Die Schichten der dritten Decke wiederholen sich zweimal (Abb. 2). Die Deformation hat einen Schuppungscharakter. Die Idrija-Lagerstätte liegt im zweiten Teil der dritten Decke. Im Liegenden ist sie mit einer Überschiebungsfläche des ersten Teiles der dritten Decke begrenzt. Im Hangenden begrenzt sie die Überschiebungsfläche der vierten Decke. Im Nordosten schneidet die Idrija-Verwerfung die Lagerstätte ab, und im Südwesten die Verwerfung Zala. Die Brüche verlaufen subparallel. Die Idrija-Lagerstätte ist also ein Ausschnitt des Deckenbaues und hat sich im tektonischen Graben zwischen zwei jungtertiären Brüchen erhalten.

Den unteren Teil der Lagerstätte bilden jungpaläozoische sowie unter- und teilweise noch mitteltriassische Schichten. Die Schichten liegen gewöhnlich subvertikal oder invers. Nur im Teil der Grube, welchen wir »Talnina« nennen, und im südöstlichen Teil der Lagerstätte, sind unter- und mitteltriassische Schichten in normaler stratigraphischer Lage erhalten. Von Nordosten gegen Südwesten sind die Schichten immer jünger.

Im oberen Teil der Grube finden wir anisische, cordevole und vor allem langobardische Gesteine. Beide Strukturen, die wir als unteren und oberen Bau der Lagerstätte bezeichnet haben, scheidet ein mitteltriassischer, seinerzeit subvertikaler Bruch, welcher nach Umdrehung der Schichten im älteren Tertiär eine subhorizontale Lage eingenommen hat. Auch der Kontakt der oberpaläozoischen und langobardischen Schichten im Hangenden der Lagerstätte ist mitteltriassischen Alters. Der Block zwischen den Brüchen ist in der Mitteltrias gesunken. Auf beiden Seiten der Brüche liegen die langobardischen Gesteine verschiedenen älteren stratigraphischen Gliedern an.

Vererzung

Im Laufe der bergmännischen Arbeiten und Tiefbohrungen wurde festgestellt, daß die Quecksilbervererzung in den Schichten des unteren Teiles der stratigraphischen Säule vorkommt, daher nur an die Horizonte zwischen Jungpaläozoikum und dem oberen Teil der Mitteltrias beschränkt ist. Die Obertrias-, Jura-, Kreide- und Tertiär-Formationen sind durchaus erzleer. Diese Feststellung und die Tatsache, daß sich auch in anderen Lagerstätten und Vorkommen Sloweniens Quecksilber nie in Jura-, Kreide- und Tertiärschichten befindet, präjudiziert im gewissen Sinne das triassische Alter der Vererzung. Dieses Alter haben tatsächlich auch viele, in Idrija tätige Forscher vermutet (Gröger, 1876; Schrauf, 1891; Kropač, 1912; Berce, 1958; Mlakar, 1967). Andere haben sich für das tertiäre Alter der Vererzung ausgesprochen (Lipold, 1874; Nikitin, 1934; Schneiderhöhn, 1941; di Colbertaldo-Slavik, 1961).

Systematische Grubenaufnahmen und mikroskopische Untersuchungen sowohl des Erzes als auch des Nebengesteines, die in den letzten Jahren durchgeführt wurden, haben schließlich unzweifelhaft das triassische Alter dieser Lagerstätte bewiesen. Es wurde weiter festgestellt, daß die Quecksilbervererzung in das Ladin, genauer noch in die langobardische Unterstufe einzureihen ist (Mlakar, Drovenik, 1971).

Wie schon oben erwähnt, kommt die Vererzung in allen lithostratigraphischen Horizonten vom Jungpaläozoikum bis zum oberen Teil der Mitteltrias vor. Sowohl die Intensität der Vererzung als auch die Entstehungsweise sind jedoch verschieden. Wir müssen hier auf die von Meier bereits vor 100 Jahren (1868) geäußerte Ansicht aufmerksam machen, nach welcher der nordwestliche Teil der Lagerstätte (wo vorwiegend Ladin-Schichten mit bekanntem Skoncaschiefer vorkommen) als eine lagerartige, und der südliche (mit älteren Schichten) hingegen als eine gangartige Vererzung zu bezeichnen sei. Derselben Meinung waren auch andere ältere Forscher. Wir wollen nur die diesbezügliche Meinung von Kropač (1912) zitieren: »Die Anreicherungen in den nicht mächtigen Skoncaschiefern sind lagerartig, während die Imprägnationen in den Dolomiten, Breccien und Konglomeraten in Stockwerken oder in Klüften vorkommen.« Unlängst hat man diesen Angaben nicht genügend Aufmerksamkeit geschenkt. Heutzutage wurde bestätigt, daß es sich in den älteren Schichten, die vorwiegend aus Perm-, Skyth- und Anis-Karbonatgesteinen bestehen, wirklich um epigenetische Vererzung handelt. Gleichzeitig wurde jedoch nachgewiesen, daß in den jüngeren, ladinischen Schichten auch die syngenetische Vererzung vorkommt.

In den Jungpaläozoikum-, Skyth- und Anis-Schichten finden wir also einen Fall von typischer epigenetischer Vererzung. Klastische Sedimente haben in der Regel einen kleineren Vererzungskoeffizient als die karbonatischen. Außerdem befinden sich in den klastischen Sedimenten kleinere Erzkörper und auch ärmeres Erz, in den karbonatischen hingegen größere Erzkörper und reicheres Erz. Die Erzkörper sind vor allem an die Kontakte zwischen einzelnen lithostratigraphischen Horizonten und an die mitteltriassische Erosionsdiskordanz gebunden. Sie befinden sich vorzugsweise dort, wo die mitteltriassischen Verwerfungen und Klüfte wenig permeable Schichten durchgeschnitten haben, die zur Zeit der Erzbildung Barrieren darstellten. Eine plattenartige Gestalt vieler Erzkörper in den skythischen und anisischen Schichten wurde also durch lithologische Verschiedenheit verursacht. Während der Aufschiebung der Lagerstätte auf die kretazische und tertiäre Grundlage sind viele Erzkörper in vertikale und subvertikale Lage geraten.

In diesen Schichten ist Zinnober das dominierende und in vielen Erzkörpern sogar das einzige Erzmineral. Er hat nicht nur viele Risse und Klüfte, sondern auch Poren ausgefüllt und das Nebengestein metasomatisch verdrängt. Bei der Metasomatose und der Vererzung mußten allerdings hydrothermale Lösungen teilgenommen haben.

Die Skyth- und Anisschichten führen manchmal reiche Anhäufungen von Zinnober, die man der Farbe wegen als Stahlerz benannt hat. Diese Art des Zinnobererzes zeichnet sich durch hohe Quecksilbergehalte aus, die 70 % und darüber erreichen können. Sie ist durch eine sehr intensive Verdrängung des Nebengesteines mit Zinnober, oder noch häufiger, durch eine Ausfüllung von Klüften mit diesem Mineral enstanden. Für das, in den Gängen vorkommende Stahlerz sind kolloidale Strukturen von nachträglich sehr feinkörnig auskristallisiertem Zinnober charakteristisch. Gewöhnlich sind auch organische Verbindungen anwesend, von welchen jedoch nur Idrijalin mit Sicherheit festgestellt wurde.

Das gediegene Quecksilber ist zwar das zweithäufigste Quecksilbermineral, tritt aber in relativ größerer Menge nur im karbonischen Schiefer und in einigen reicheren Erzkörpern der triassischen Schichten auf. Seine Entstehung ist noch nicht hinreichend erklärt. Es soll in einigen Erzkörpern den primären, und in anderen den sekundären Bestandteil darstellen. Im letzten Falle wird das gediegene Quecksilber wohl als Umsetzungsprodukt von Zinnober angesehen. Sehr sporadisch kommt auch Metacinnabarit vor, der sehr wahrscheinlich aus hydrothermalen Lösungen kristallisierte. Das Erz enthält gewöhnlich 1—2 % Pyrit; er ist in der Regel als eine diagenetische Komponente zu bezeichnen. Ausnahmsweise hat sich Pyrit von den Erzlösungen ausgeschieden. Markasit, Zinkblende und Auripigment sind recht selten (di Colbertaldo-Slavik, 1961).

Zinnober wird von wenigen Gangarten begleitet. Erwähnenswert sind nur Quarz, Dolomit und Calcit. Zuallererst soll auf die Tatsache hingewiesen werden, daß in den klastischen Sedimenten, wo der Quarz die häufigste Komponente ist, nur er als Gangmineral vorkommt. In Karbonatgesteinen hingegen ist Zinnober vorzugsweise mit Dolomit (in Dolomiten) oder mit Calcit (in Kalksteinen) vergesellschaftet. Baryt stellt eine mineralogische Seltenheit dar. Kaolinit soll nach einigen Angaben sogar ein charakteristisches Mineral für Idrija sein; in den jungpaläozoischen, skythischen und anisischen Schichten kommt er jedoch als Gangart überhaupt nicht vor. Dasselbe gilt für Fluorit. Daraus folgt, daß in einzelnen Schichten Zinnober vorzugsweise von denjenigen Gangarten begleitet wird, die im Nebengestein die wichtigste Komponente darstellen. Diese Feststellung erlaubt zwei Erklärungen: nach der einen hätten die hydrothermalen Lösungen während der Metasomatose und der Vererzung die Nebengesteinskomponenten ausgelaugt und gleich wieder ausgeschieden, nach der anderen könnte es sich um eine spätere Mobilisation (lateralsekretionäre Vorgänge) von Nebengesteinsbestandtteilen, und natürlich auch von Zinnober handeln. Mit Erzlösungen wurde sehr wahrscheinlich nur wenig Kieselsäure zugeführt.

Die Einwirkung der Erzlösungen auf das Nebengestein ist im allgemeinen sehr gering. Sie äußert sich nur in schwacher Silifizierung der Karbonatgesteine, die stellenweise nachgewiesen wurde. Weiter soll betont werden, daß im mikroskopischen Bilde keine Sprossung von Calcitkörnern in Kalksteinen erkennbar ist. Diese Gesteine sind also überhaupt nicht rekristallisiert. Daraus kann man auf eine Teilnahme der relativ tieftemperierten hydrothermalen Lösungen schließen. Leider verfügen wir mit keinen genaueren Angaben über die Bildungstemperatur der Erzmineralien in Idrija. Aus den neuesten Forschungsergebnissen der amerikanischen (Tunell, 1970) und sowjetischen Forscher (Fedorčuk und andere, 1963; Merlič, 1963) betreffs der Bildungstemperatur von Zinnober und Metacinnabarit kann man jedoch den Schluß ziehen, Idrija habe sich sehr wahrscheinlich in einem Temperaturinterval von 100° bis 200° C gebildet.

Hydrothermale Lösungen folgten den mitteltriassischen Verwerfungen und Klüften, die als Aufstiegswege dienten. Berücksichtigt man die ursprüngliche Schichtfolge, dann läßt sich nachweisen, daß diese zuerst die karbonischen Schiefer mit Sandsteinlinsen erreicht haben. In diesen Schichten ist diagenetischer Pyrit eine relativ häufige Komponente. Er bildet entweder kleine idiomorphe Kristalle und sogenannte »vererzte Bakterien« oder Knollen, wo er oft Pseudomorphosen nach den Pflanzenresten bildet. Während der Quecksilbervererzung kam es bei günstigen physikalisch-chemischen Verhältnissen zur Kristallisierung des Zinnobers. Er tritt in feinen Imprägnationen auf, die oft parallel mit der Schichtung liegen, sowie in Äderchen zusammen mit Quarz. Es kam auch zu einer Verdrängung des Pyrits durch Zinnober. Sulfidische Knollen wurden sogar gefunden, die mehr Zinnober als Pyrit führen. Als nächsthäufiges Mineral ist das gediegene Quecksilber anzusehen; hie und da ist der Schiefer mit winzigen Quecksilberkugelchen stark imprägniert.

Im mittelpermischen Grödener Sandstein befindet sich Zinnober vor allem in tektonisch durchbewegten Teilen, wo er in Rissen und Poren kristallisierte. Im reicheren Erze hat er auch den Zement verdrängt, welcher mehr karbonatischen Anteil aufweist als die oben erwähnte Varietät. Außerdem wird unter dem Mikroskop intensive Korrosion der Quarzkörner beobachtet, was eine relativ größere Aktivität der Erzlösungen in tieferen Teilen der Lagerstätte zuzumuten gestattet. Vererzter Aleurolith führt auch Zinnoberidioblasten. Es handelt sich keineswegs um Pseudomorphosen nach Calcit, der zwar sonst in diesem Gestein auch vorkommt, jedoch in viel kleineren Körnern und nie idiomorph.

Für den schwarzen bituminösen oberpermischen Dolomit ist ein großer Vererzungskoeffizient kennzeichnend. Die Ursache für die intensive Vererzung soll zuerst in einer stärkeren tektonischen Zerrüttering des Gesteines gesucht werden. Sehr wahrscheinlich wirkte außerdem die feinverteilte organische Substanz als Katalysator. In den Rissen und Klüften kristallisierten als Frühausscheidungen Dolomit und Calcit, ihnen folgten stellenweise Quarz und zuletzt Zinnober, welcher ältere Gangmineralien und das Nebengestein verdrängte. Für das reiche Erz ist die Breccientextur, für das arme hingegen die Netztextur und Imprägnationstextur charakteristisch.

Der darüberliegende unterskythische Dolomit war sehr wahrscheinlich so tektonisch beansprucht wie der oberpermische, trotzdem ist sein Vererzungskoeffizient kleiner. Daß kann man durch die Anwesenheit von klastischen Komponenten, vor allem von Quarz und Tonmineralien erklären, welche die Metasomatose verhinderten. Die Schichten des sandigen Dolomits bildeten sogar Barrieren. Bemerkenswert ist die Tatsache, daß sich die subvertikalen plattenförmigen Erzkörper stets an der NE Seite der sandigen Dolomitschichten befinden, also unter den Schichten, welche offensichtlich während der Vererzung als Aufstauhorizonte für die Erzlösungen wirkten. Die Nebengesteinsveränderungen äußern sich durch schwache Silifizierung; der hydrothermale Quarz, in Form von winzigen Xeno- und Idioblasten, erscheint im Erz höchstens mit 15 %.

Mit scharfer Grenze foglt eine heterogene Serie, die aus Schiefer und Aleurolith besteht, in welcher konkordant eingelagerte Linsen des Oolithkalksteines vorkommen. Die petrographische Zusammensetzung des Schiefers und Aleurolithes erlaubte keine metasomatischen Verdrängungen, weswegen Zinnober nur als Ausfüllung von Rissen und Klüften vorkommt. Intensive metasomatische Prozesse haben sich hingegen in den Linsen des Oolithkalksteines entwickelt, was zur Bildung des reichen Erzes führte. An mehreren Stellen ist sogar das Stahlerz mit wenigstens 70 % Hg entstanden. Bei der Metasomatose sind oft auch Zinnoberidioblasten gebildet worden, die Einschlüsse von Karbonaten und Quarz aufweisen. Das reiche Erz enthält in Klüften und Rissen feine Tropfen von gediegenem Quecksilber; in einigen Erzkörpern tritt auch Metacinnabarit auf.

In der Schichtfolge beobachten wir nacheinander oberskythischen Dolomit, oberskythischen mergeligen Kalkstein und anisischen Dolomit. In den Dolomiten herrschten während der Vererzung gleich günstige Bedingungen; beide haben nämlich einen ziemlich hohen Vererzungskoeffizient. Der mergelige Kalkstein enthält jedoch nur unbauwürdige Imprägnationen von HgS.

Zu der Zeit der mitteltriassischen tektonischen Bewegungen verhielt sich der oberskythische Dolomit spröde, und bildete Feinklüfte und Klüfte, die mit Zinnober ausgefüllt wurden. Das Erz hat gewöhnlich eine Breccientextur. Längst der Klüfte wurde Dolomit stark durch Zinnober verdrängt; im Quecksilbersulfid »schwimmen« korrodierte Dolomitkörner. Dann folgt eine Zone, in welcher der Zinnober Intergranularfilme bildet; abschließend sind nur noch sehr feine Zinnoberimprägnationen an den Grenzen einzelner Dolomitkörner zu finden. Einige Erzkörper führen auch Metacinnabarit. Zusammen mit Zinnober bildet er kleine halbkugelige und nierenartige Aggregate, die oft einen schaligen Aufbau aufweisen. Im Kern befindet sich gewöhnlich Metacinnabarit, dann folgen abwechselnd einige Schalen aus Zinnober und Metacinnabarit. Die äußere Schale gehört in der Regel dem Metacinnabarit. Beide Sulfide sind am wahrscheinlichsten hypogen. Hie und da kann man auch gediegenes Quecksilber feststellen. Als mineralogische Seltenheiten sollen ferner noch hydrothermaler Pyrit und Baryt erwähnt werden.

Im anisischen Dolomit überwiegt ärmeres Erz mit Netz- und Imprägnationstextur. Karbonatgangarten und Zinnober füllen feine Risse und Klüftchen. sowie auch Poren aus. Mikroskopisch wurde festgestellt, daß die Karbonate im Kontakt mit Zinnober öfters überhaupt keine Korosion aufweisen, woraus man eine Kristallisation von Zinnober aus kälteren, wenig reaktiosfähigen Erzlösungen vermuten kann.

Die darauffolgenden Ladin-Schichten beginnen mit basalem langobardischen Sandstein. In diesem Gesteine bildet Kaolinit häufig den Hauptgemengteil. Nebenbei treten sowohl andere klastische, wie auch pyroklastische Komponenten auf. Kleine Erzkörper haben eine unregelmäßige oder linsenartige Form. Zinnober befindet sich fast ausnahmslos in den

veränderten Plagioklasen und Tuffkörnern. Allem Anschein nach wurde vererzter Tuff oder vererzter Vulkanit mechanisch desintegriert. Zinnoberführende Plagioklase und lithoide Körner sedimentierten zusammen mit tauben detritischen und pyroklastischen Komponenten. Seltene Zinnoberimprägnationen, die im Zement vorkommen, sind sehr wahrscheinlich während der späteren Mobilisation entstanden. Dieser Prozeß hat auch zur Bildung der Kaolinitäderchen geführt. Plagioklase und Tuffkörner, die im basalen Sandstein vorkommen, sind als erster Beweis der mitteltriassischen vulkanischen Tätigkeit in diesem Raum anzusehen.

Hydrothermale Lösungen haben zwar mit dem basalen Sandstein sehr wahrscheinlich überhaupt nicht reagiert, mußten aber entlang der Verwerfungen und Klüften in das hangende Konglomerat eingedrungen sein. Dieses Gestein besteht hauptsächlich aus Geröllen von anisischem und oberskythischem Dolomit, sowie aus karbonatischem Bindemittel. Das Konglomerat war von zahlreichen Klüften und Rissen durchgesetzt, welche manchmal die gesamte Mächtigkeit erfaßt haben. Nachfolgende Erzlösungen konnten leichter zirkulieren und deswegen hat das Konglomerat einen höheren Vererzungskoeffizient. Eine ganz besondere Bedeutung wird den reich vererzten Geröllen aus oberskythischen Dolomit beigemessen, die in fast taubem Konglomerat gefunden wurden. Nach der Art und Weise der Vererzung und nach ihrer Lage im Konglomerat könnte man entnehmen, daß bereits vererzte Dolomitgerölle sedimentierten. Wenn diese Vermutung stimmt, dann müßen wir eine Vererzungsphase vor der Konglomeratbildung anerkennen.

Mit scharfer Grenze liegen über dem Konglomerat Skoncaschichten, die den größten Vererzungskoeffizient aufweisen. Diese Schichten bestehen aus schwarzem bituminösen Tonschiefer, welcher öfters zahlreiche Radiolarien enthält, so daß es sich manchmal um einen Übergang zum Radiolarit handelt, und aus bituminösem Sandstein, der auch pyroklastische Komponenten führt. Allem Anschein nach wurden die Skoncaschichten syngenetisch vererzt. Die Zufuhr der Erzlösungen erfolgte durch starke, am Meeresboden austretende Thermalquellen. Nach epigenetischer Deutung müßten die Zufuhrspalten wenigstens gelegentlich erhalten geblieben sein. Bei syngenetisch-sedimentärer Deutung werden die Zufuhrkanäle jedoch im weichen Schlamm des Meeresbodens zugedrückt. In Skoncaschichten konnte man sie tatsächlich nirgends nachweisen.

Die chemische Zusammensetzung der Erzthermen war nicht immer die gleiche. Einige brachten in nennenswerten Mengen nur das Quecksilber, sehr wahrscheinlich in Form von Komplexion HgS_2^{2-}. Veränderte physikalisch-chemische Verhältnisse führten zur Bildung hochdisperser Lösungen, die zinnoberreiche kolloidale Ausfällungen gefördert haben, welche oft zusammen mit Sapropel sedimentierten. Auf diese Weise sind konkordante Stahlerzlagen und Linsen enstanden. Reiche Stahlerzarten bestehen vorwiegend nur aus feinkörnigem rekristallisierten Zinnober, der unter dem Mikroskop kolloidale Strukturen aufweist. Ärmere Arten führen nebst Sapropelit sehr feinkörnigen Zinnober, klastische Komponenten, »vererzte Bakterien« und Reste von Lebewesen.

Andere Thermen haben außer dem Komplexion HgS_2^{2-} auch beträchtliche Mengen von Kieselsäure mitgebracht. Hochdisperse Zinnober- und Opalniederschläge sedimentierten auf dem Meeresboden; Opal wandelte sich später in Chalcedon um. Auf diese Weise hat sich Hg-SiO_2-reiches Erzsediment gebildet, das auch vererzte Radiolarien, sowie klastische und pyroklastische Komponenten enthielt. Es wird vermutet, daß eine gleichzeitige tektonisch-vulkanische Aktivität Erdbebenunruhe verursachte und trübe Strömungen (turbidity currents) auslöste, die halbkonsolidiertes Erzsediment mechanisch desintegriert haben. Die Erzkörner wurden auf kleinere und größere Distanzen transportiert. Nach ihrer Konzentration und Verteilung im bituminösen Tonschiefer oder bituminösen Radiolarit unterscheidet man mehrere Erzabarten.

Konkordante Erzlagen und Erzlinsen mit zahlreichen Erzkörnern, die sich öfters berühren, wurden wegen der roten Farbe Ziegelerz benannt. Unter dem Mikroskop sind gewöhnlich 50 Mikronen bis 1 Millimeter große Chalcedonkörner erkennbar, die Zinnoberimprägnationen in Größen von der Grenze der Auflöslichkeit bis zu 30 Mikronen aufweisen. Es ist zu betonen, daß die Quarz- und Plagioklaskörner überhaupt keine Zinnoberimprägnationen führen.

Eine sehr häufige Erzart kommt als Lebererz vor. Es handelt sich um bituminösen Tonschiefer oder bituminösen Radiolarit mit mehr oder weniger gleichmäßig verteilten Erzkörnern. Während der tektonischen Bewegungen entstandene glänzende Rutschflächen sind mit Bitumen und Zinnober überzogen, weshalb sie eine leberartige Färbung haben.

Wenn sich die Erzkörnerkonzentration von Lage zu Lage ändert, dann zeigen einzelne Lagen verschiedene graurötliche Abtönungen. Taube Lagen sind dagegen grau oder schwarz. Verschiedene Färbung verursachte gebänderte Textur, weswegen diese Erzart Banderz genannt wird. Hie und da kann man in einzelnen Erzlagen Seigerungsschichtung (graded bedding) und Schrägschichtung (cross bedding) beobachten.

In den jüngsten langobardischen Schichten, die aus Tuffit, Tuff und Radiolarit bestehen, befindet sich das Zinnobererz in zwei konkordanten Horizonten. Der untere Horizont, dessen Mächtigkeit bis 1,5 m beträgt, liegt unmittelbar auf den Skoncaschichten; er ist aus reichem Banderz aufgebaut. Erzlagen zeigen sehr oft Seigerungsschichtung, manchmal auch Schweredeformationen, die ihrer Form wegen als »flammende« Texturen bezeichnet werden können. Ungefähr 1 m höher befindet sich der zweite Erzhorizont, der eine Mächtigkeit von 0,5 m erreicht und aus ärmerem Banderz zusammengesetzt ist. In beiden Erzhorizonten befindet sich Zinnober fast ausschließlich in Chalcedonkörnern und in Radiolarien. In einigen Lagen sind vererzte Radiolarien sogar häufiger als Chalcedon-Zinnoberkörner. Eine stärkere Vergrößerung zeigt öfters, daß Zinnober-imprägnationen genau die Struktur der Radiolarien folgen. Es sei nicht unerwähnt, daß auch in diesem Erz die Plagioklas- und Quarzkörner frei von Zinnoberimprägnationen sind, obwohl diese Körner manchmal vom vererzten Chalcedon umgeben sind.

Während der lateralsekretionären Prozesse waren in den Tuffiten Zinnober und Kieselsäure, in den Skoncaschichten aber auch organische Verbindungen in den Rissen und Klüften abgelagert.

Schließlich sollte bemerkt werden, daß Zinnoberimprägnationen und Äderchen auch in Cordevolschichten vorkommen, jedoch sehr untergeordnet und nie in abbauwürdigen Mengen. Am wahrscheinlichsten sind sie während der späteren Mobilisationsprozesse enstanden.

Zusammenfassend läßt sich über die Vererzung der Lagerstätte Idrija folgendes sagen:

Das einzige bedeutende Quecksilbermineral ist Zinnober. Er hat sich in zwei Vererzungphasen gebildet. Die erste koinzidierte mit dem Beginn der mitteltriassischen vulkanischen Tätigkeit. Die Vererzung erfaßte karbonische, permische, skythische und anisische Schichten. In dieser Phase wurden auch langobardische Tuffe (Vulkanite?) vererzt, die nachher mechanisch desintegriert wurden, was zur Bildung von syngenetischen Erzkörpern in basalem langobardischen Sandstein geführt hat. In der zweiten Phase ergossen sich Erzlösungen auch als Thermen in das Meer, wobei synsedimentäre Erzkörper in Skoncaschichten und Tuffiten entstanden.

The Middle Triassic Structure of the Idrija Region

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Detailed studies were carried out to reveal the geologic structure of the Idrija region, and the features exposed at the surface during the Middle Triassic time. First a vertical cross section is drawn to show the recent structure and interrelations between the Idrija and Ljubevč mercury deposits, the later being displaced from the former for some 2500 meters towards south-east. Another section is constructed to show the same ore deposits joined into a whole as existed at the time before the beginning of neotectonic movements. Finally a Middle Triassic cross section is given for the time of the sedimentation of Langobardian beds together with the syngenetic cinnabar. In conclusion the question is discussed, how the geologic movements from the Idria region suit the tectonic sequence of the wider South Alpine area.

Preliminary discussion and the method used

The geological structure of the Idrija region has been formed by movements that occurred during three tectonic phases. Taking into account the origin of cinnabar in Langobardian time, a Middle Triassic premineral phase and an old Tertiary postmineral phase followed by neotectonic movements are recognized.

The cross section of the Idrija ore deposit contains all basic elements of the whole Idrija-Žiri region showing a nappe structure. The most important feature of this region is the Idrija schuppe enclosed within the uppermost nappe. There the Idrija mercury deposit occurs. The Idrija schuppe is overlain by the Tičnica overthrust. Therefore the study of the Middle Triassic beds is essentially based on the study of the position of the Idrija schuppe.

The restoration of the original Middle Triassic conditions of the ore deposits is shown in figure 1. A cross section of the old Idrija mine, and that of the recently discovered Ljubevč ore deposit is given (fig. 1 a). The main neotectonic, old Tertiary, and Middle Triassic faults are drawn in. The horizontal distance between both ore deposits is 2500 meters (I. Mlakar, 1964).

In figure *1 b* there the Tertiary profile of the deposit before the neotectonic faulting is presented. Both deposits are joined in one cross section, that shows the Idrija schuppe as a whole. The geological features of the Idrija schuppe correspond to those in the Tičnica overthrust.

In figure 1 c there are the overturned syncline of the Idrija ore deposit, and the recumbent anticline of the Ljubevč deposit, both levelled out to a horizontal position of the beds. Thereby a fairly clear distribution of faults and ore bodies is revealed. According to this sheme, the mineralized Triassic beds are situated in a fault trough. The upper part of the trough belongs to the Idrija ore deposit, and the lower northern part to the Ljubevč ore deposit. But no one of the recent structural units could be derived from the southern part of the fault trough. It is believed that a corresponding sheet-block had been broken off and remained behind during thrusting.

The displacement between the Idrija schuppe and the Tičnica overthrust amounts to several hundreds of meters; for this reason in the section 1 c the unit of Tičnica cannot be seen.

At the same time paleoenvironmental conditions were studied to explain the origin of the Middle Triassic sedimentary sequence (plate 1). In this way the results were checked by two different methods.

Paleostructure of the Idrija Region at Middle Triassic time

Up to now the Idrija Middle Triassic fault trough is reconstructed in a lenght of 19 km from Vojsko to Zaplana, and in a width of about 6 km. In the north and in the south the trough is closed by fault ridges; behind them extend the northern and the southern sedimentary basins respectively (plate 1).

The trough is bounded by the Urbanovec-Zovčan fault on its northern long side, and by the Veharše fault on its southern long side. The longitudinal faults hade 70°—80° northwards and southwards. In the Idrija ore deposit at the Urbanovec-Zovčan fault the vertical displacement amounts to at least 750 meters (plate 2).

A system of transverse faults cutting the trough in N—S direction is very distinctive. The most important are the Filipič fault and the »O« fault, that divide the ore deposit into the western, middle, and eastern zones. The vertical displacement at the »O« fault varies from 80 through 150 meters. Of importance is also the horizontal component of the displacement, but up to now it has not yet been determined.

In the region of the Idrija ore deposit the trough is cut by longitudinal faults into structural units Zorc, Uršič, Čemernik, and Karoli. Upwards these units are confined by the Middle Triassic angular unconformity, with exception of the unit Uršič, that thins out in upward direction somewhat earlier. In horizontal direction the structural units either thin out, or are not known totally.

Origin of the Idrija fault trough

The Idrija Middle Triassic fault trough originated in the apical part of an anticline whose origin is described forthwith (plate 3).

In that part of the sea basin, where later originated the Idrija Middle Triassic trough with the mercury ore deposit, the folding started at about the end of Lower Scythian stage. At first only a relatively slower subsidence of the northern and southern fault ridges and of the trough can be remarked in comparison with the northern and southern sedimentary basins. The result of this movement of the bottom is an essentially greater thickness of the Lower Scythian sediments in the northern and southern sedimentary basins. Up to Upper Scythian only the differences in thickness of the sediments can be recognized; but in the Campilean beds already facial differentiation set in.

During the sedimentation of the Upper Campilean beds a pronounced flexuring developed at a right angle to the anticline. The amount of downthrow was about 40 meters. Interesting is the intraformational breccia developed within the flexure. From this flexure resulted the transverse fault »O«, one of the two most important transverse dislocations. The growth of the flexure as well as further formation of breccia continued in the lower part of Anisian stage as well. During this period, simultaneously with N—S faults, E—W faults originated as well.

The further growth of the faulted anticline caused the forming of a somewhat larger mainland on the whole Idrija region already in the end of the Anisian stage or in the Fassan substage (plate 3, fig. 1). The erosional period was however short. The northern sedimentary basin started soon to subside. The transgression advanced gradually over tectonic blocks in this area. These blocks also haded slightly.

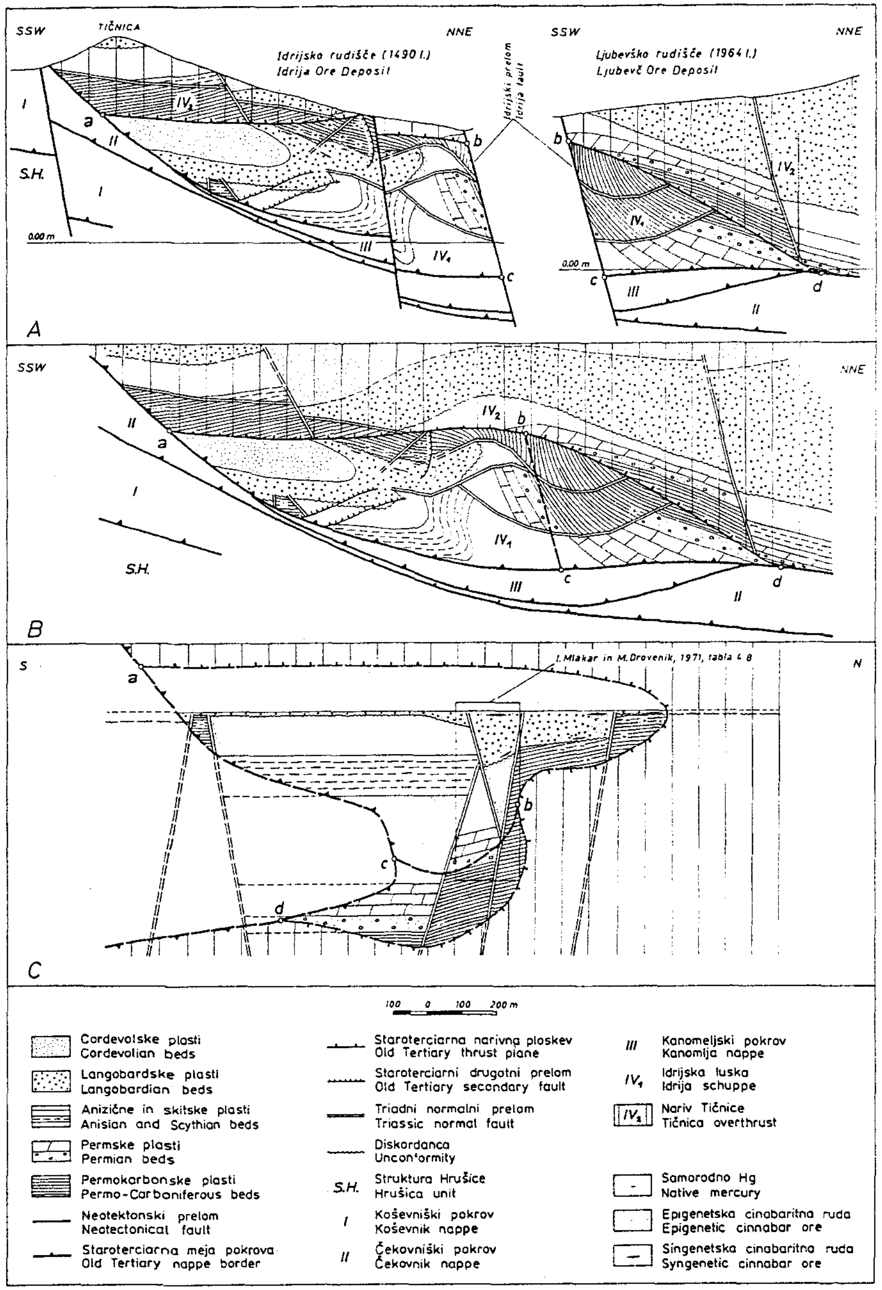
The Idrija fault trough, as well as the northern and the southern fault ridges were still on mainland (plate 3, fig. 2). From both fault ridges erosion removed in the course of time all rocks down to Permo-Carboniferous. The removed material filled the northern sedimentary basin.

A period of stronger tectonic movements followed simultaneously with volcanic activity that yielded material for different magmatic and pyroclastic rocks. For the first time parts of the fault trough and of the southern margin of the northern fault ridge were flooded. Unconformably on the Anisian and Permo-Carboniferous beds there variegated basal sediments accumulated. It is well to point out, that in these sediments the lower horizon of syngenetic cinnabar occurs (plate 3, fig. 3).

During this stage larger displacements took place along the longitudinal and the transverse faults. Also a stronger hading of some uplifted blocks can be connected with these processes. In the northern sedimentary basin the sedimentation of conglomerate continued into the beginning of this stage, while olistostrome and dolomite conglomerate have been amassed in the fault trough. At the end of this stage the trough got gradually shallow as evidenced by sandstone in both areas.

At the end of Langobardian, the sea spread over the northern and the southern fault ridges. The trough area was covered by a bog; some belts of dry land rose above the bog level. Along the faults there hydrotherms were tending to come to the surface. They accumulated in the bog sediments where the upper level of rich syngenetic ore originated.

The bog sedimentation was abruptly discontinued by a strong volcanic activity giving keratophyre and diabase associated with tuffs. At last the sea transgressed also over the remaining dry land parts, and therefore tuffites have been laid down unconformably over the Permo-Carboniferous beds of the



northern and southern fault ridges (plate 3, fig. 4). The highest part of the upper horizon of the syngenetic cinnabar occurs in the lowest pyroclastic layers.

Distribution of the epigenetic and syngenetic mercury ores

The Idrija Middle Triassic trough is considered to have been a structure favourable for the ore formation in the Mediterranean mercury metallogene province. Between the Vojsko High Plain and Rovte there are four mercury ore occurrences (plate 1). At Kočevše on the Vojsko High Plain only low geochemical concentrations are found. In the Idrija and Ljubevč mines there is the mercury ore of economic importance. At Zovčan in the west of Veharše high geochemical concentrations occur. In the surroundings of Kurja Vas, there the ore is indeed of high mercury content, but of no economic importance.

The distribution of the epigenetic and the syngenetic ore bodies in the Idrija Middle Triassic tectonic trough is shown in Plate 2. The cross section through the ore deposit is adjusted for the time of sedimentation of the lowest level of Langobardian pyroclastites. There the highest stratigraphic horizon of syngenetic cinnabar is recognized. All cinnabar in the trough is controlled by normal longitudinal and transverse faults, along which the ore-forming fluids moved to the surface.

Unsolved questions

The stratigraphical features and structural relations of the Idrija region during the Triassic period are well known. The question arises now, how the corresponding movement suit to the succession of geologic events in the wider south Alpine area. But the tectonic development of wider Slovenia and South Alpine areas are not closely defined as to make possible to recognize individual phases and even subphases during which proper systems were formed. Figure 2 shows a review of the Triassic tectonics relative to Slovenia as comprehended in the works of F. Kossmat, B. Berce, I. Mlakar, J. Čar, L. Placer, and U. Premru as well as in the compiled reports of I. Rakovec, A. Tollman, and A. Ramovš. Diversities in the data show, that none unambigous interpretation of the tectonic movements is done as to their temporal and spatial interrelations. Unsolved is the question of the forces involving the rock deformation as well as their regional or local importance.

In the Idrija area today there are two problems important for better understanding of the Triassic structural events.

1. The Middle Triassic structure of the Idrija region could have been the result of a general dilatation of the Earth's crust, or of a local folding caused by suborogene processes during the period of general dilatation. The answer requires a detailed study of the origin of tectonic deformations in the Idria region in Middle Triassic time as well as a correlation with some other regions.

2. Of importance is the time of origin of the Middle Triassic faults. As to the transverse fault »O« it was developed from an flexure. The vertical displacement was estimated to be 40 meters in late Campilean. The longitudinal faults trending E—W existed in Middle Anisian. These conclusions are made, however, without sedimentological investigations of the rocks lying below the Middle Triassic angular unconformity.

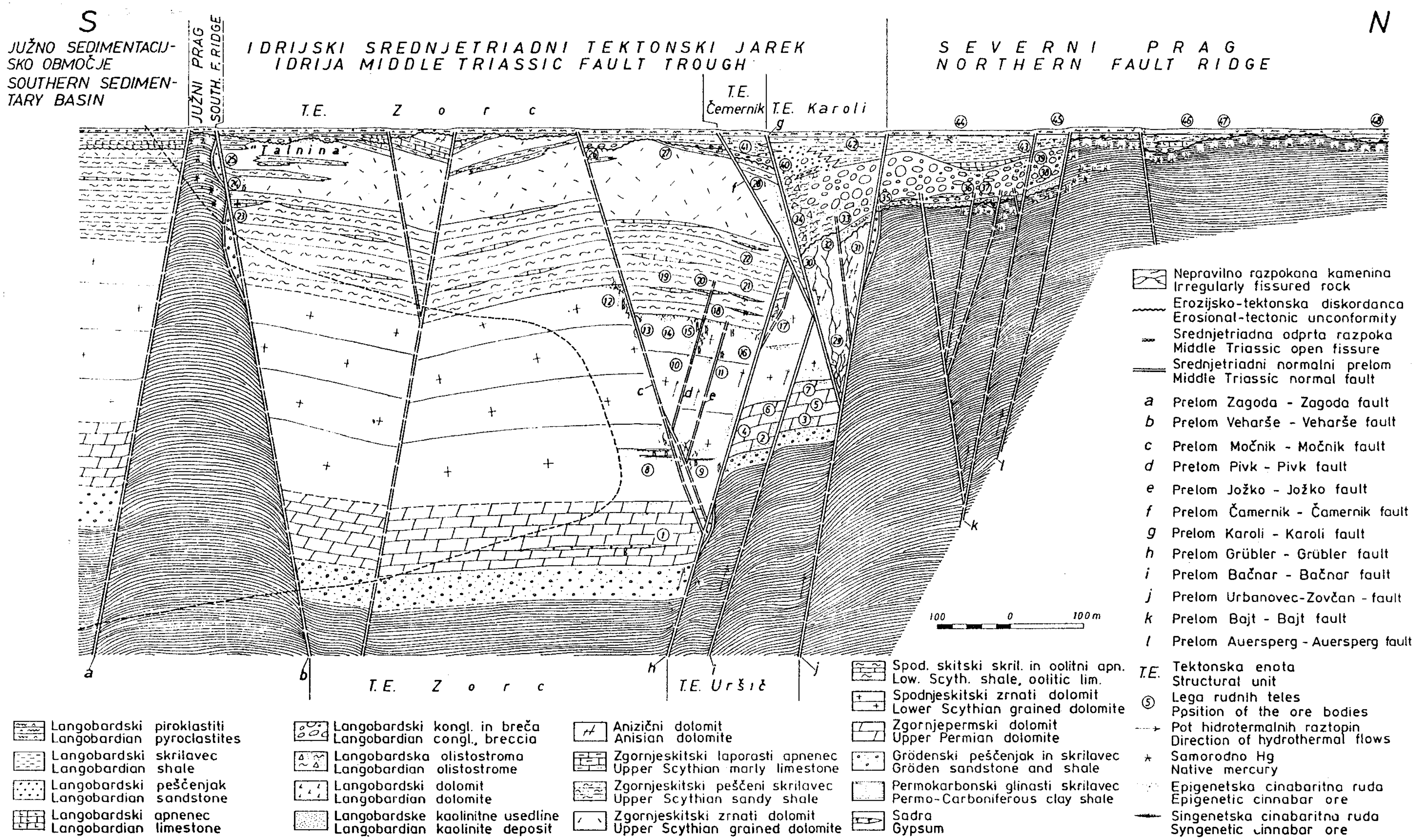


Tabla 2 PROFIL IDRIJSKEGA RUDIŠČA V ČASU USEDANJA LANGOBARDSKEGA TUFA

Plate 2 SECTION OF THE IDRIJA ORE DEPOSIT DURING THE LANGOBARDIAN TUFF SEDIMENTATION

Škojanske jame

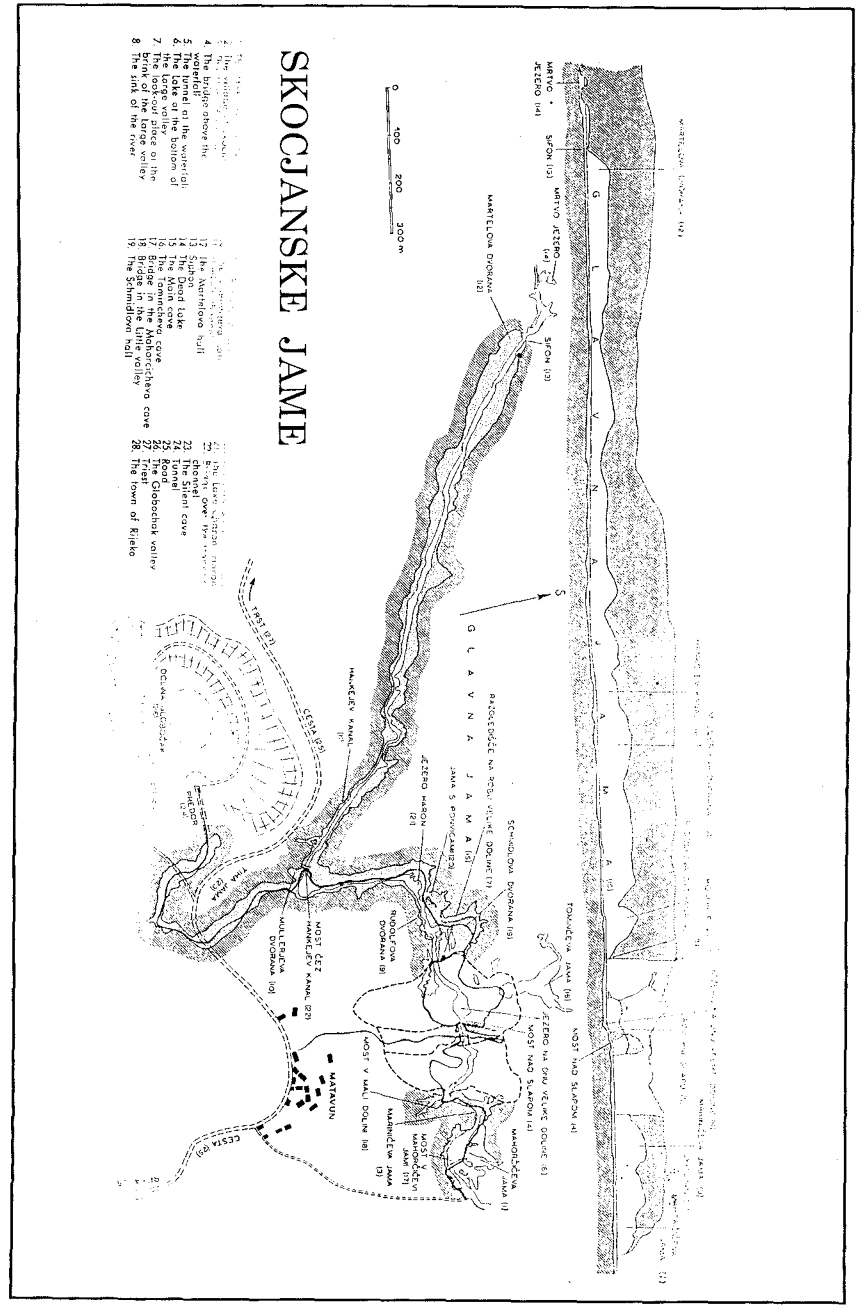
Cadastral No 735
Gauss-Kruger
Map Ref 5421980/5058350
Length 5800m
Depth 250m
Approximately:
Lat N4539', 878'
LongE1359'.422'

Showcave, but caving trips possible by prior agreement.

To get there head south past **Postojna** to Divača, turn off left following the signs to **Škocjanske jame**. The tourist trip starts a short walk away, in a large doline, the guide takes you into a manmade tunnel dug to connect with the "silent cave". This is a high level side passage. The route follows down amongst some very well decorated passage into a large chamber with several stalagmites of huge size. Eventually the rumble of powerful water can be heard in the distance. The passage ends at a balcony overlooking the huge chasm 100m high and up to 30m wide that is the main passage. A plaque on the wall marks a record flood level some 63m above normal water level. The path follows a ledge carved out of the left-hand wall and takes you to the "Hankes Bridge" over the river. Far below the water of the Reka rushes on towards the sump over 1200m further down the passage. Near the ceiling can be seen the remains of a slender catwalk erected by early cavers. As you carry on towards where the water enters the cave, there are other signs of their efforts all along the walls. The trip ends with a walk through the collapsed doline and with a funicular railway to the surface. The village of Škocjan sits on top of the huge rock bridge on the other side of the doline.

Caving trips to **Škocjanske jame** are possible in summer, at times of low water. Contact the Sezana Caving Club:

c/o Viktor Saksida
Pod Gozdom1
SI6210
Sežana
Slovenia
Tel: 067 73 128
Fax: 067 72 292



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APPENDIX

MAP: Coastal Sea - Sampling points for the Alps-Adriatic Monitoring Programme, National Monitoring and Sanitary Quality of Sea-water

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4.5.2. Contents of crude oil and dissolved crude oil remnants (μg/l) in the seawater at the sampling points in the Bay of Koper and Bay of Piran in 1992.
4.5.3. Results of chemical and bacteriological analyses of wastewaters and the tributaries of the sea in 1992.
4.5.4. Results of analyses of heavy metals in the tributaries of the sea and treatment-plant outflows in 1992.

4.5.1. INTRODUCTION

The natural properties of the Gulf of Trieste (shallowness, freshwater tributaries, surface drain, meteorological influences, dynamics of water masses) all combine to give the Gulf of Trieste its character of a vulnerable marine environment. Increased urbanization and industrialization put an ever growing pressure on the coastal sea in terms of municipal and industrial wastewaters. Rivers increasingly act as recipients of untreated municipal and industrial wastewaters, which are an important source of suspended solids and dissolved compounds, influencing chemical and biological processes in the coastal sea.

In spite of its coastline being short, Slovenia's development is closely connected with its utilisation. The problem of utilisation of the coast and the ecologically fragile coastal sea is a burning issue due to conflicting activities (municipal, industrial, wastewaters from ships, fishing, tourism, pisciculture), therefore the protection of marine environment and the care to improve its quality ought to play an active role in the planning of economy and infrastructure.

Monitoring the quality of the coastal sea was done in monthly intervals and the existing data cover the last twenty years. This paper brings results of physicochemical, sanitary as well as bioproduction analyses of the Slovenian sea in 1992, as collected by the associates of the Institute of Biology at the University of Ljubljana, The Piran Marine Biological Station, within the framework of the sea quality monitoring programme. According to the coastal sea monitoring programme, two investigations of the pollution of tributaries and the sea in immediate vicinity of the outflows of municipal as well as of some industrial wastewaters were carried out in 1992.

4.5.2. REGIONAL AND SEASONAL DISTRIBUTION OF SAMPLING POINTS

Sampling points for monitoring physical, chemical, bioproduction and pollution conditions in the wider belt of the Slovenian coastal waters in the Gulf of Trieste are presented in the enclosed map. Numbers from 1 to 37 denote sampling points for microbiological analyses. These sampling points are distributed along the coast in such a way as to include all major areas important to determine the sanitary quality of the sea. Particularly important the sampling points in areas designated for pisciculture and bathing sites. Seawater samples were analysed twice monthly during the bathing season and bimonthly for the rest of the year.

For sampling points designated on the map by capital letters, the programme of physical, chemical, and bioproduction measurements was implemented. Locations of sampling points were determined on the basis of long-term observations and estimation of specific characteristics of individual areas of the investigated environment. Based on this, these sampling points were considered as having specific differences among themselves and yet posses a characteristic quality. The information gathered permits an assessment of the developments for the entire monitored area.

Table 4.5.1: Sampling points in the coastal waters of Slovenia and in other pollution sources in 1992.

S. point	Latitude (N)	Longitude (E)	Location description
K	45°33'36"	13°43'12"	entrance of the Koper Bay
KK	45°35'70"	13°40'40"	influenced by the outflow of the Rižana
F	45°32'43"	13°33'13"	Cape Madona in Piran
MA	45°30'10"	13°34'31"	Central part of the Piran Bay
35	45°29'39"	13°34'75"	Piran Bay, pisciculture area
M*	45°31'59"	13°28'36"	entry of waters from the direction of Istria
G	45°35'97"	13°31'69"	influenced by the outflow of the Soča
CZ	45°37'26"	13°38'07"	Centre of the Gulf of Trieste
M1*	45°32'59"	13°26'75"	Italian/Croatian border
F1	45°34'23"	13°32'05"	influenced by the outflow of the Soča
14+			Port of Koper
PM+			Portorož Marina
Pa, Pb, Ia, Kb			municipal wastewater outflows from Piran, Izola and Koper
DE			wastewater release from the "Delamaris" plant, Izola
RI, BA, DN, DR			The Rižana, the Badaševica, the Drnica and the Dragonja

* no samples could be taken in 1992 (see explanation below)
\+ analyses of mineral oils only

Up to and including September 1991, the monitoring program was implemented on 10 sampling points at sea, but following the uncertain situation along the as yet undefined sea border with the neighbouring Republic of Croatia, sampling was omitted at sampling points M and M1, which were assumed to lie within Croatian territorial waters. As a rule, samplings were performed on a monthly basis.

The content of dissolved oil and its remnants was measured at five sampling points (KK, K, 14, MA and PM) six times in 1992: once in winter, spring and autumn, and thrice in summer.

Twice yearly (in January and August) samples were taken at the outflow of rivers into the sea. Pollution originates in agriculture, industry and urbanized areas. Sampling points were situated at the outflow from treatment plants in Koper (Kb), Izola (Ia), Piran (Pa and Pb), Delamaris in Izola (DE), and outflows of the following rivers the Rižana, the Badaševica, the Drnica, as well as the Dragonja.

4.5.3. SAMPLING METHODS AND ANALYSES

Samples for the analysis of physical, chemical, and bioproduction parameters in the water body were taken at five different depths for each sampling point: on the surface, at depths of 5, 10, and 15 m as well as approx. 0.5 m above the bottom, high enough to prevent the Niskin sampler to stir up the silt on the sea bottom. Water samples just above the sea bottom were taken by means of a Rutner sampler.

Water temperature at individual depths was measured by means of a standard oceanographic tilting thermometer (Richter-Wiese). Water transparency was measured by means of Secchi disc.

pH-value of samples was determined with an Iskra laboratory pH-meter, salinity (chloride) according to the Mohr-Knudsen titration method with silver nitrate.

Oxygen was determined according to Winkler method, BOD in five days (BOD_5) according to the Grasshoff procedure of the Winkler method (1). COD was determined according to the standard bichromate method.

Contents of nutrients were determined colorimetrically as follows: phosphate (Murphy and Riley, 1962 and modified by Koroleff, 1968), total phosphorus (Nydahl, 1978), ammonia (Grasshoff, 1967), nitrite (Bendscheider and Robinson, 1952), nitrate (Grasshoff, 1970), silicon (Mullin and Rilley, modified by Strickland, 1968), detergents (2) as MBAS.

The content of dissolved crude oil and its remnants was measured according to UNESCO directives (3), in samples taken at a depth of 1 meter.

Faecal coliforms were determined according to the membrane filtration method and 24-hour incubation on plate m-FC agar (4) (UNEP/WHO, 1983).

Chlorophyll **a** (Chla) quantity was measured at six sampling points (F, CZ, G, KK, K and 35). Chlorophyll **a** was determined fluorimetrically (Holm-Hansen, 1965) by means of a Turner fluorimeter, while its content was expressed either in μg Chla/l or mg Chla/m^3.

The density of phytoplankton cells in water samples was determined at sampling points F and CZ, in monthly intervals. Cells were counted under inverted microscope (Utermohl, 1958).

Microzooplankton, sized from 20 to 200 μm, was sampled according to two methods, the standard Utermohl method with Niskin sampler at depths of 0, 5, 10 and 20 m at sampling points CZ and F, as well as by means of a special microzooplankton net, with 50 μm net mesh aperture radius.

Physical and chemical parameters of wastewaters (salinity, pH, dissolved oxygen, BOD^5 and COD) as well as in river tributaries were measured according to standard methods (5). Nutritious salts (compounds of nitrogen, phosphorus and silicon) were determined colorimetrically (Grasshoff, 1967), total nitrogen and total phosphorus also colorimetrically (Koroleff, 1977). Contents of detergents were analysed according to the methylene-blue method, total suspended solids gravimetrically (6) on glass fibre filters (Whatman GF/C 1.2 μm).

Heavy metals in rivers and outflows from wastewater-treatment-plants (Hg, Cd, Pb, Cr, Zn, Ni, Cu, Fe, Mn) were analysed according to UNEP/FAO (7, 8) instructions and recommendations with wet acid degradation at increased temperatures and pressure (PTFE-autoclave). Samples were measured by AAS Varian (Spectr AA-10BQ and Varian model 1250A), using GTA, FL and VGA modules.

4.5.4. RESULTS OF RESEARCH IN 1992

Fourteen samplings were conducted within the monitoring framework in the January - December period of 1992, as follows:

January 14 - 15
February 12 - 13
March 4 - 5
April 6 - 7
May 7 - 8
May 27 - 28
June 15 - 16
July 13 - 14
August 19 - 20
September 15 - 16
October 20 - 21
November 17
November 24 - 25
December 21 - 22

4.5.4.1. Physical and Chemical Conditions in Water Body

The results of the analyses are summarized in figures 4.5.1 - 4.5.5. Figure 4.5.1 shows annual temperature variations in the water body of the Slovene coastal sea, taken as a whole. This includes total average of temperatures measured at all sampling points at individual depths. The lowest temperature on the water surface was reached in January, the highest in August. In February, water temperature was uniform along the entire depth profile. Isothermal conditions lasted till the beginning of March, when the entire water body started warming up and a gradual stratification set in. The highest annual sea temperature measured in 1992 amounted to 26.7 °C (F1). In October the period of autumn isothermal conditions set in, from then on the entire water body cooled down with constant speed, while the top layer was at all times somewhat cooler than the deeper layers.

Figure 4.5.2 shows salinity oscillation in 1992 as an average of all measured values at all sampling points for individual depths. There were three minimums to be noted here: April, June, and November, particularly marked on the surface. These changes in salinity of the surface layers were brought about by mixing with freshwater influents, notably the Soča River. April and November saw heavy precipitation, with the result that large quantities of fresh water entered the sea, flooding a substantial part of the Gulf of Trieste in very short time. In November 1992, the Soča reached its highest discharge for the last hundred years. The June salinity minimum was likewise connected to a slower, but as to its quantity an even more pronounced inflow of freshwater from the Soča, and also from the Rižana and the Dragonja. This effect was also noted in deeper layers, which the freshwater entered gradually, mixing with seawater. Here the sampling point G deserves a special mention, since in November 1992 an all-time low salinity value in the open waters of the Gulf of Trieste was measured, the lowest since the Piran Marine Biological Station conducts its oceanographic monitoring in this area.

Figure 4.5.3 shows density variation in water layers during the year as mean values for the entire research area and individual depths. Seawater density is dependent on temperature and salinity. The April and June penetration of fresh water into the interior of the Bay of Piran and Bay of Koper (on the surface), will be noted.

Figure 4.5.4 shows the annual dynamics of the content of dissolved oxygen as a mean value of all measured values for all sampling points and individual depths. The lowest oxygen content (2.6 ml/l) was measured in September just above the sea bottom. The highest oxygen content was measured in March at a depth of 5 m, amounting to 8.1 ml/l. Oxygen contents are, as a rule, lowest in the bottom layer. In the period from January to December 1992, oxygen contents never fell bellow the limit contents for sea bottom fauna to remain alive. This means that there were no occurrences of anoxia in 1992, such as was often the case in previous years.

The rivers which flow into the Gulf of Trieste (The Soča, the Dragonja, the Rižana, the Drnica etc.) bring with them huge quantities of most varied matter, organic as well as inorganic. These include nutrients, mostly nitrogen and phosphorus compounds.

Figure 4.5.5 shows variations in content and depth distribution of total phosphorus in the water body of the area under investigation in 1992. There were most pronounced maximums in March, May, and July, and to a lesser extent in December. Differences in contents of total phosphorus as to the depth distribution were only slight and showed an almost parallel course.

Results of analyses of contents of oil and dissolved oil remnants in the seawater in 1992 are compiled in table 4.5.2.

Oil contents at sampling points KK, K and MA was low as expected, since there are no pollution sources near these sampling points. Table 4.5.2 also brings data for sampling points 14 and PM, where measurements are being carried out within the

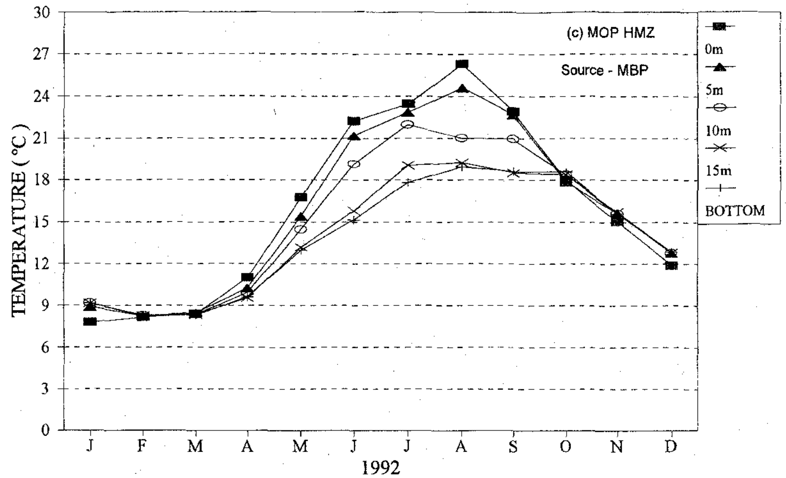

Figure 4.5.1: Temperature in the Slovene coastal waters in 1992.

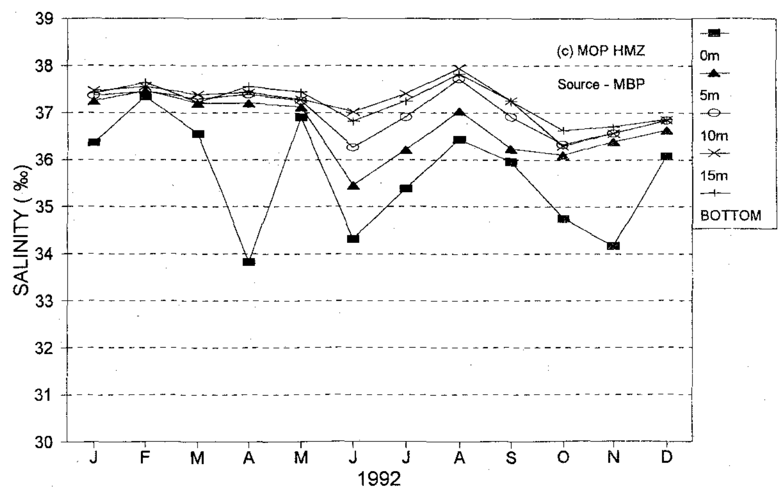

Figure 4.5.2: Mean salinity for all sampling points in 1992.

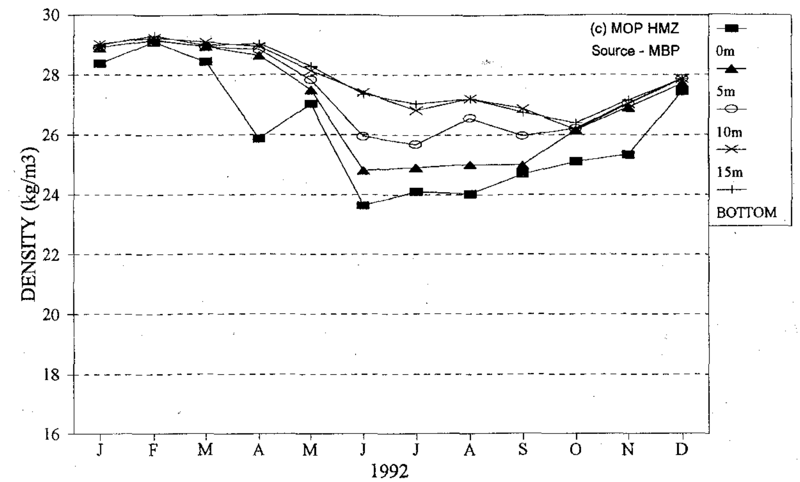

Figure 4.5.3: Water layer density in the Slovene coastal waters in 1992.

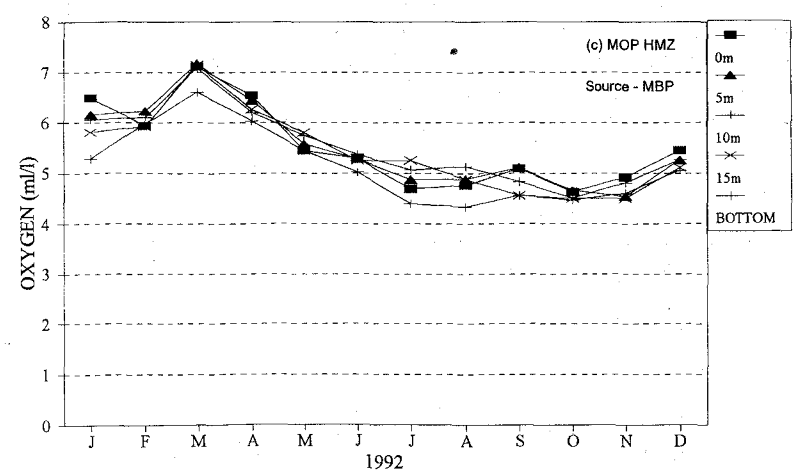

Figure 4.5.4: Dissolved oxygen contents in Slovene coastal waters in 1992.

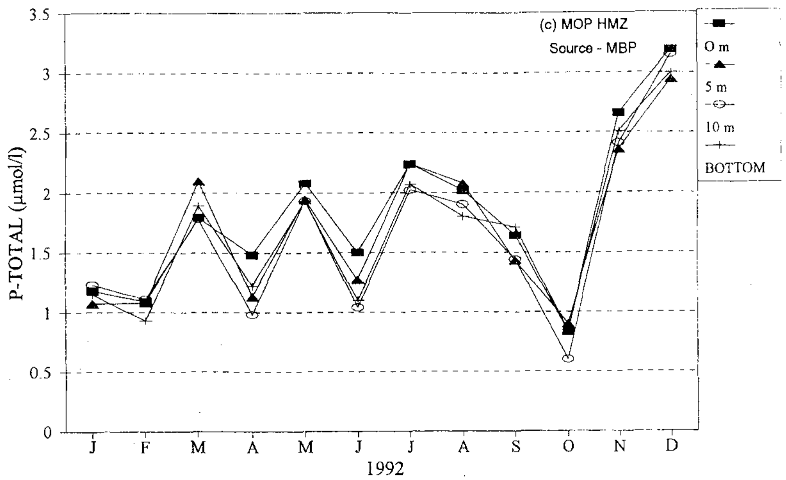

Figure 4.5.5: Contents of total phosphorus in the Slovene coastal waters in 1992.

framework of other monitoring programmes. These two sampling points showed the highest values, by no means a surprise, considering their location. The PM sampling point showed an increase in the oil contents mostly during the summer months, when nautical traffic was most dense. Concentrations did not surpass the limit of 50 µg/l as set for the 1st quality class of the coastal sea (Official Journal of the SFRY No. 6/1978).

Table 4.5.2: Contents of crude oil and dissolved crude oil remnants (µg/l) in the seawater at the sampling points in the Bay of Koper and the Bay of Piran in 1992.

Sampling point Date	KK	K	14 (µg/l)	MA	PM
Mar. 17	0.2	0.2	6.3	0.1	12.5
Jun. 26	0.1	0.1	19.5	<0.1	19.1
Jul. 22	<0.1	0.1	39.2	<0.1	30.5
Aug. 18	0.1	0.1	11.6	0.1	33.5
Nov. 26	0.1	0.2	19.1	0.1	20.8
Jan. 12,1993	0.4	0.1	10.3	0.1	5.5

4.5.4.2. Sanitary Conditions of the Coastal Sea

In 1992, 331 analyses of seawater were performed in the coastal sea from Debeli Rtič to Kanegra at 22 sampling points at bathing sites, around the area dedicated to shell rearing in the Bay of Piran (sampling point No. 26), further in the estuary of the Rižana (13 in 14), at the cross section towards the middle of the Bay of Koper (15, K1) as well as at the reference sampling point in the middle of the Bay of Piran (MA).

Seawater samples were analysed twice weekly during the bathing season, bimonthly during the rest of the year. The extent of faecal pollution was determined by means of indicator bacteria for fecal pollution (fecal coliforms), applying the membrane filtration culture method as recommended by WHO (UNEP/WHO, 1983).

Sanitary analysis of the samples taken at bathing sites from Debeli Rtič to Kanegra have in most cases satisfied the WHO criteria regarding suitability of the sea for recreational purposes, with the exception of seawater samples taken at bathing sites in Ankaran, Koper, and Izola, which contained less than 100 fecal coliforms in 100 ml only in 75 % of analysed samples, but did not exceed 2000 fecal coliforms in 100 ml, since these seawater samples contained less than 100 fecal coliforms/100 ml.

4.5.4.3. Chemical and Sanitary Conditions in the Tributaries of the Sea and Wastewaters

The results of chemical and bacteriological analyses of wastewaters and the tributaries of the sea in 1992 are compiled in tables 4.5.3 and 4.5.4.

Concentrations of individual parameters did not markedly depart from the results of previous years. Outflows from all treatment plants exceeded limit concentrations of biochemical oxygen demand (BOD^5), fecal coliforms, and in some cases even concentrations of Fe (Ia, Kb), as allowed for releasing of wastewaters into the rivers or coastal seawater (Official Journal of the Republic of Slovenia 18/85).

The contents of heavy metals such as *Mn*, *Ni*, *Pb*, *Zn* and *Cr* as well as of *Cu* and *Fe* in one sample in the rivers were highest in the Badaševica, where some concentrations were even higher than in the outflows from treatment plants. Slightly lower were the concentrations in the Drnica. The Dragonja was the least polluted river, with the exception for mercury content. Concentrations of individual metals do not substantially differ from the results in the previous years, however the concentrations measured for some metals exceed the permitted values as allowed for releasing of waters into the coastal sea (Fe, Pb, and Zn in the Drnica and in the Badaševica, (Official Journal of the Republic of Slovenia No. 18/85).

Table 4.5.3: Results of chemical and bacteriological analyses of wastewaters and the tributaries of the sea in 1992.

	Date	BOD5 mg/l	COD mg/l	TSS mg/l	TN mg/l	TP mg/l	det µg/l	FC No./100ml
Pa	Jan/22	240.3		227	51.5	4.3		7.20E+06
	Aug/26	115.7		85	21.8	4.8	2872	1.40E+07
Pb	Jan/22	115.4		40	23.7	2.1	5.	70E+06
Ia	Jan/22	340.6		201	73.9	6.9	4252	1.26E+07
	Aug/26	203.1		172	39.2	7.6	4677	3.50E+07
Kb	Jan/22	112.2		311	14.7	2.4	2105	1.20E+06
	Aug/26	85.7		10	20.4	4.3	3725	2.84E+07
DE	Jan/22	1724.3		1285	196.3	25.4	488	
	Aug/26	1472.6		1110	75.0	18.3	717	
Riž.	Jan/22	3.7	285	3.3	0.9	0.2	31	910
	Aug/26	15.8	322	16.3	3.5	0.6	1124	38000
Bad.	Jan/22	3.6	312	3.3	3.0	0.2	1	31000
	Aug/26	4.2	921	10.8	0.7	0.1	40	3080
Drn.	Jan/22	3.1	53	1.4	3.7	0.3	26	900
	Aug/26	6.6	859	12.0	1.5	0.2	109	350
Dra.	Jan/22	2.4	36	1.9	2.8	0.2	144	256
	Aug/26	1.2	65	11.9	2.2	0.1	23	550

TSS - suspended solids
TN - total nitrogen
TP - total phosphorus
det - detergents
FC - fecal coliforms

The estuary of the Rižana remained in 1992 one the most polluted areas of the Slovene coastal waters. The extent of pollution diminished somewhat after the treatment plant in Koper went into operation, but concentrations of fecal coliforms in the estuary area (sampling point 15) remained high. The worst bacteriological conditions were found immediately below the municipal wastewater run-off from the town of Koper into the estuary of the Rižana (sampling points 13 and 14). Fecal pollution diminishes rapidly with growing distance from the pollution source, its level and distribution, however, depend on the hydrological and meteorological conditions, since the movement of the water body in the bay depends mostly on tide and wind.

The mentioned rivers receive untreated municipal and industrial wastewaters and are therefore an important source of compounds which influence chemical and biological processes in the coastal sea. The results of the implemented analyses demonstrate that in 1992 all coastal rivers were charged with nutrients, detergents, fecal and industrial wastewaters, while the most heavily polluted rivers were the Rižana and the Badaševica.

Table 4.5.4: Results of analyses of heavy metals in the tributaries of the sea and treatment-plant outflows in 1992.

	Date	Cd µg/l	Cr µg/l	Cu µg/l	Fe µg/l	Hg µg/l	Mn µg/l	Ni µg/l	Pb µg/l	Zn µg/l
Pa	Jan/22	1.0	2	108	2780	<0.020	214	77	108	512
	Aug/26	1.1	<0.5	106	598	<0.020	206	37	73	558
Pb	Jan/22	7.2	3	195	930	<0.020	389	67	303	884
Ia	Jan/22	1.2	15	36	688	<0.020	70	9	80	173
	Aug/26	8.9	3	201	5040	<0.020	388	144	370	860
Kb	Jan/22	2.0	5	142	545	<0.020	314	104	108	780
	Aug/26	1.0	7	95	1066	<0.020	213	23	83	474
DE	Jan/22	9.1	4	275	1080	0.060	503	40	463	896
	Aug/26	8.3	3	40	1835	0.191	768	68	670	1554
Riž.	Jan/22	1.8	5	109	695	0.027	318	28	132	814
	Aug/26	1.1	12	91	465	0.060	185	54	258	789
Bad.	Jan/22	0.9	6	120	865	0.060	360	54	329	875
	Aug/26	2.3	13	144	2080	0.109	775	72	751	1706
Drn.	Jan/22	0.2	1	36	410	<0.020	120	3	141	310
	Aug/26	0.7	12	150	2235	0.158	705	54	803	1775
Dra.	Jan/22	1.3	2	23	174	0.257	30	1	75	76
	Aug/26	0.1	1	22	308	0.152	95	14	129	237

4.5.5. BIOPRODUCTION

The monitoring programme for biological, physical and chemical parameters in the eastern part of the Gulf of Trieste encompasses both primary and secondary production.

4.5.5.1. Annual Dynamics of Phytoplankton and Chlorophyll a

The monitoring program for biological, physical and chemical parameters in the eastern part of the Gulf of Trieste covers also the temporal and regional distribution of phytoplankton biomass, expressed as the quantity of *chlorophyll a*, measured in all samples of the sea water.

The distribution of the phytoplankton biomass in 1992 followed the physical and chemical characteristics of the shallow Gulf of Trieste. Values of *chlorophyll a* at some sampling points were subject to great fluctuations, but they all reflected a similar dynamics of the biomass of algae.

In 1992 there were three maximums: in April, June, and November. The highest integrated values of the water column were reached in April (from 1.06 at sampling point M to 3.93 µg Chla/l at sampling point K). The exception here was the sampling point CZ, with the highest concentration, i.e. 3.44 μg Chla/l, reached in March. Following this spring peak, the values fell, but only to rise again in June. Again, they were higher in the Bay of Koper at sampling points KK and K (1.20 and 1.36 μg Chla/l). During the summer months, the biomass diminished again only to reach its third high in November, but that time, except for sampling point CZ, lower than on the two previous occasions. All three peaks coincided with salinity minima and nitrate maxima in the surface layer of the sea. Those months saw an increased inflow of fresh water, particularly April and June, but also November, when there was aboundant precipitation. Increased nitrate quantities caused a sharp rise of the phytoplankton biomass, notably in April on the surface, while values were considerably lower already at a depth of 5 meters. Sampling point G showed strong deviation, with 9.96 μg Chla/l on the surface, indicating a strong influence of the Soča River. November saw a sub-surface maximum due to lower surface temperatures. The maximum in bottom samples was observed at the sampling point CZ in March (8.79 μg Chla/l), while the situation was also similar in August and September, corresponding to high concentrations of nutrients.

The annual dynamics of cell density of individual taxonomic groups had all characteristics of phytoplankton biocoenoses of shallow or closed basins, receiving rivers and effluents from urbanized and developed catchment areas. Phytoplankton density at sampling points CZ and F showed a similar picture to that of its biomass. Markedly standing out the maximum at sampling point CZ in March (2.7 x 10^6cells/l), and sampling point F in April (1.7 x 10^6cells/l). March saw the biggest density at the bottom, that being also the highest cell density for the entire year (8.8 x 10^6cells/l). In April, cell density was highest on the surface (4.3 x 10^6cells/l). Significantly lower values of cell density were reached for both of the other two peaks in June and September. The number of cells was lowest in October at both sampling points (1.7 x 10^5cells/l at CZ and 1.6 x 10^5cells/l at F).

Microflagellates were the predominant group, i.e. 2 to 10 μm big flagellate algae of various taxonomic groups. As in previous years, microflagellates made for 80 to 90% of the entire number of cells, i.e. they were the predominant group for almost the entire year.

For all three peaks of cell density and chlorophyll **a**, there was strong predominance exerted over all other groups by diatoms: in April by *Skeletonema costatum* and *Nitzschia delicatissima comp.*, in June by *Chaetoceros spp.*, *Cyclotella sp.*, and *Nitzschia delicatissima comp.*, in November by *Cerataulina pelagica, Rhizosolenia delicatula, Rhizosolenia fragilissima* and *Nitzschia seriata comp.* Their share was biggest in April, amounting to 44 to 81%. In January and December, Cocolithinae predominated with species *Acanthoica aculeata*. Dinoflagellates were present all the year round, however, always in lesser numbers.

In 1992, no mucilage algae aggregates appeared in the Gulf of Trieste.

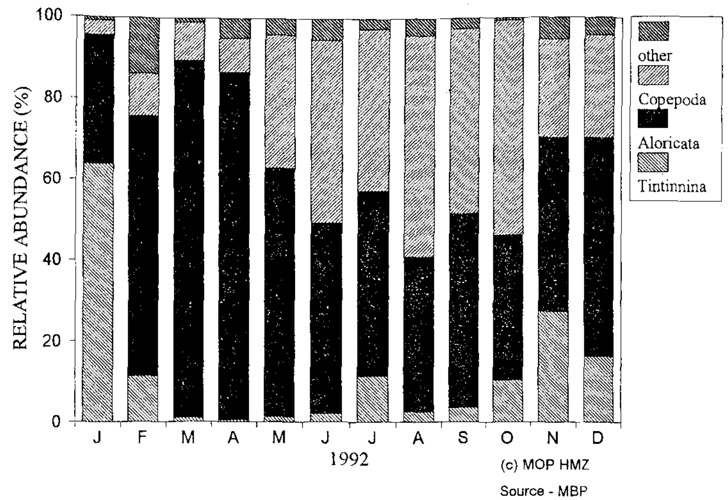

Figure 4.5.6: Relative abundance of microzooplankton at sampling point F.

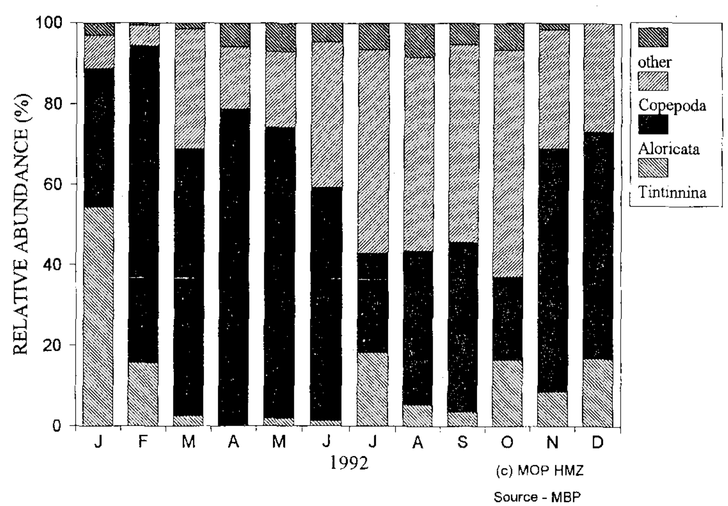

Figure 4.5.7: Relative abundance of microzooplankton at sampling point CZ.

4.5.5.2. Annual Dynamics of Microzooplankton

The seasonal dynamics of microzooplankton in 1992 roughly coincided with the dynamics of the previous years. The most important categories, such as aloricates, tintinides and nauplii of Copepoda all show a similar trend. Both groups of plankton ciliates had simultaneous abundance peaks, i.e. the winter-spring and the summer-autumn peaks. The first peak of tintinides was represented by the psychrophilic species *Stenosemella nivalis* in January, in June it was the turn for *Helicostomella subulata*, and in September for several other species, among which *Salpingella rotundata* predominated.

Figures 4.5.6 and 4.5.7 show relative abundance of microzooplankton at sampling points F and CZ. Aloricates presented the most important microzooplankton category, while both peaks were due to genera *Strombidium* and *Tontonia*. Only in summer months the nauplii of Copepoda were more numerous, and in January tintinides.

Copepoda nauplii marked only one distinct peak in 1992, i.e. in August at sampling point F and in September at sampling point CZ. Their abundance amounted to 200 individuals/dm^3.

In like manner as in 1989, 1992 saw increased numbers of some species, which are typical of southern Adriatic. Thus the abundance of species *Codonellopsis schabi* amounted to 179 individuals/dm^3. The appearance of this species, as well as other species from southern Adriatic in autumn 1992, is linked to the inflow of water masses from the southern Adriatic into the Gulf of Trieste. Similar phenomena were also detected in 1986 by the experts from Trieste.

4.5.6. CONCLUSIONS

The main characteristics of the phenomena in the Slovene sea in 1992 were as follows:

- water temperature was on the average by 1 °C lower than in previous years, with maximum temperatures setting in as late as August
- the open sea was subject to strong influence of the surface inflow of the fresh water from the Soča River, particularly in April, and to a lesser extent in June, and again very abundantly in November. The lowest measured salinity in open waters was measured in November (15.3 ‰)
- oxygen content in 1992 never fell below critical limit, and only once below 50% saturation, as was the case at the bottom in the open waters in mid September
- variation in the quantity of nutrients was to a considerable extent conditioned by the influence of freshwater tributaries, notably by nitrogen and phosphorus salts
- bioproduction and nutrients dynamics were in inverse proportion to each other and without any major peculiarities
- the chemical and sanitary quality of treated wastewaters were not satisfactory. Critical areas included Ankaran, Koper, Izola and Portorož
- sanitary quality of samples taken at the bathing sites from Cape Debeli Rtič to Kanegra satisfied the demands for recreational purposes in the majority of cases.

4.5.7. LITERATURE

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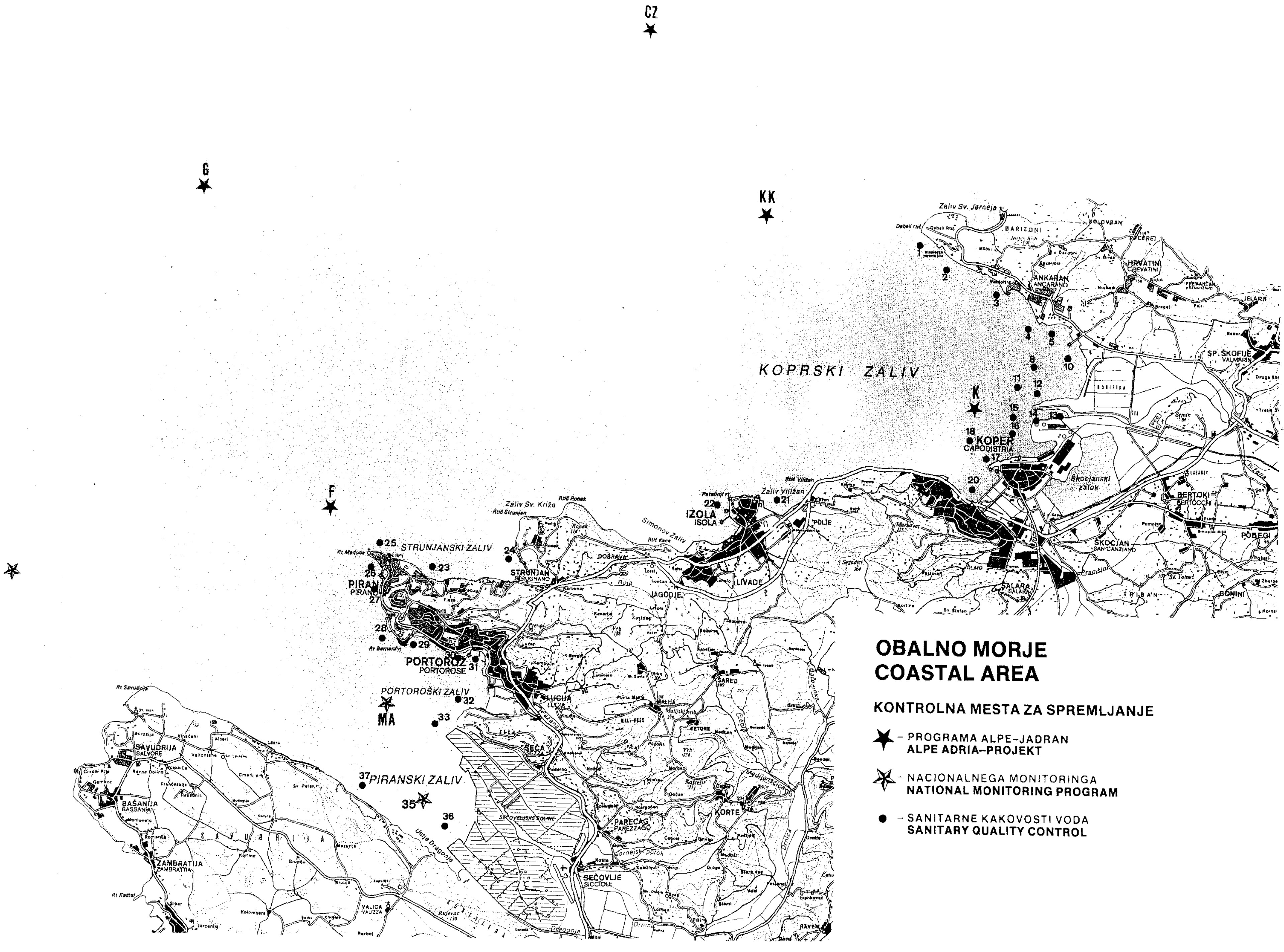
OBALNO MORJE
COASTAL AREA
KONTROLNA MESTA ZA SPREMLJANJE
- PROGRAMA ALPE-JADRAN
ALPE ADRIA-PROJEKT
- NACIONALNEGA MONITORINGA
NATIONAL MONITORING PROGRAM
- SANITARNE KAKOVOSTI VODA
SANITARY QUALITY CONTROL
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IZOLA
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PIRAN
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PORTOROŽ
PORTOROSE
STRUNJANSKI ZALIV
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LUCIJA
SEČOVLJE
SICCIOLE
SAVUDRIJA
SALVORE
BAŠANIJA
ZAMBRATIJA
ANKARAN
ANCARANO
HRVATINI
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SALARA
PAREČAG
KORTE
Škocjanski zatok
Zaliv Sv. Jerneja
Zaliv Sv. Križa
Zaliv Viližan
Simonov Zaliv

2. INVESTIGATIONS IN LJUBLJANICA RIVER BASIN

GOSPODARIČ R, BAUER F

2.1 DESCRIPTION OF INVESTIGATED AREA

2.1.1 GEOMORPHOLOGIC AND HYDROGRAPHIC CHARACTERISTICS
P. HABIČ

THE RIVER BASIN SITUATION

Beside Karst of Trieste also Ljubljanica karst river basin belongs to classical karst regions not only in Yugoslavia, but even in Europe (M. HERAK and T. V. STRINGFIELD 1972). Centuries ago this region had been already explained by numerous natural scientists (N. FRISCHLIN 1583, A. KIRCHER 1665, J. V. VALVASOR 1689, J. A. NAGEL 1748, F. A. STEINBERG 1761, B. HACQUET 1778, T. GRUBER 1781 and others). The pecularities of this area are presented also by sinking streams Pivka, Unica and Ljubljanica, by karst poljes and by numerous karst cavities, which had been among the first described by A. SCHMIDL (1854), W. PUTICK (1887), A. E. MARTEL (1893). The touristic attraction has augmented mostly by discovery of interesting cave of Postojna.

To reputation and investigations the favourable traffic position has added and beside general interest of natural scientists for karst also practical economical view has appeared. By the development of settlements, industry and communications at one side increases the need for drinking water, which had been always scarce in karst scenery, on the other side the periodical floods on karst poljes have retarded agricultural development and exploitation of relatively good soil in the karst (R. VICENTINI 1875, W. PUTICK 1888). Almost hundred years lasting efforts for abolition of floods on karst poljes did not attain the desired aims. All investigations and practical experiments have shown that without extensive and expensive intervention the karst nature cannot be satisfactory mastered. By opening and cleaning of swallow-holes on karst poljes the floods did not essentially diminished in rain periods, while by stuffing of swallow-holes and ponors also was not possible to retain the water in dry periods. In spite of by relief favourable karst depressions in the Ljubljanica river basin they are not yet changed into natural accumulation basins, suitable for energetic and other purposes (F. JENKO 1959, M. BREZNIK 1962, P. HABIČ 1974).

Ljubljanica river collects the water from extreme NW part of Dinaric karst and belongs as right Sava affluent to Danube part of Black Sea water basin. In the northern part superficial watershed with Sora affluents, which is collecting the waters from mostly non karstic promontory of Julian Alps, prevails. In the western part the watershed between Ljubljanica and Adriatic affluents as are Idrijca, Vipava, Notranjska Reka and Rečina, is situated on high karst plateaus from Hrušica to Javornik and Snežnik. The real watershed is placed somewhere in the underground, and the waters from karst plateaus are flowing to several parts. The same happens at the watershed with Kolpa and Krka rivers on southern and eastern basin's part (Fig. 1). Therefore Ljubljanica karst river basin cannot be precisely defined (Annex 1). In general the watershed line is supposed to be on the highest karst reefs. But it is known, that in karst the orographic watershed could be foundamentally different from the real one, that it can even change in different hydrologic situations.

All the incompatibilities between orographic and real watershed have not been yet even approximatively evaluated, although several works basing on geologic, geomorphologic and hydrologic data have been done by this purpo-

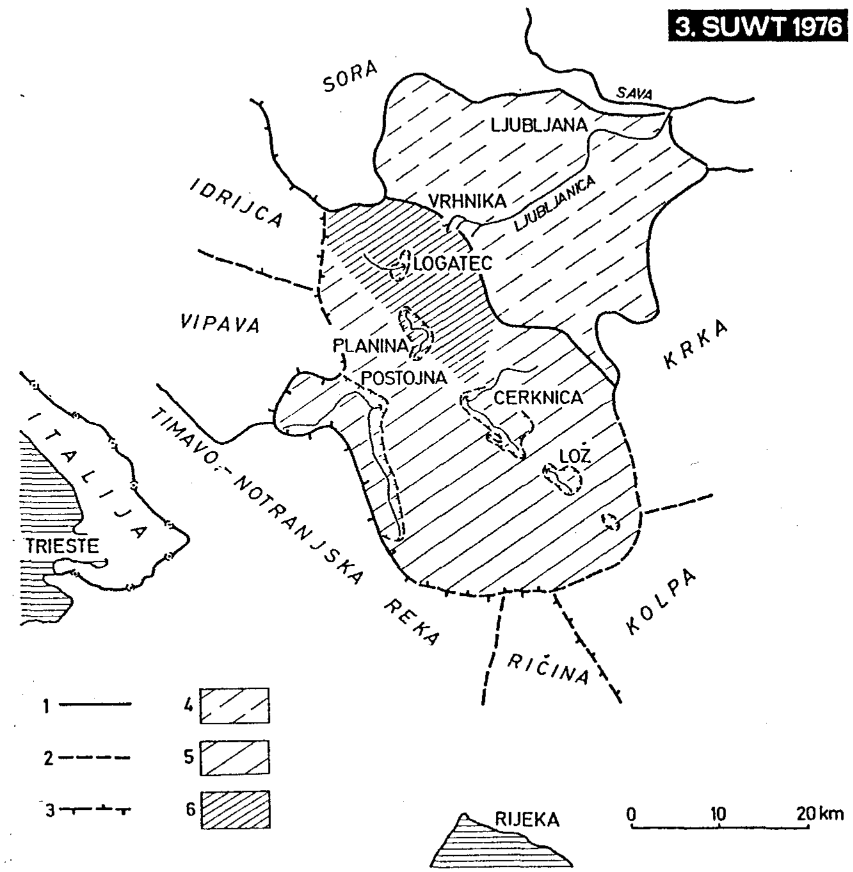

Fig. 1. *The situation of Ljubljanica river basin.* 1 — superficial watershed, 2 — karst watershed, 3 — Adriatic-Black Sea watershed, 4 — non karst river basin's part, 5 — karst river basin's part, 6 — restricted test area of combined water tracing test.

Sl. 1. *Položaj porečja Ljubljanice.* 1 — površinsko razvodje, 2 — kraško razvodje, 3 — jadransko-črnomorsko razvodje, 4 — nekraški del porečja, 5 — kraški del porečja, 6 — ožje raziskovalno območje kombiniranega sledilnega poskusa.

se. The unknown water basin extent causes the troubles by solving the practical economical questions.

The total Ljubljanica water basin up to its outlet to Sava is evaluated to 1900 km²; to restricted karst part, including the immediate hinterland of karst springs near Vrhnika about 1100—1200 km² belong to. Orographically the water basin is variegated, being the difference between the highest Snežnik Mt. (1796 m) and Ljubljanica outlet to Sava (266 m) even 1530 m; in restricted karst area up to Ljubljanica springs near Vrhnika (291 m) still remain 1505 m of altitude difference.

GEOMORPHOLOGIC CHARACTERISTICS

The Ljubljanica water basin relief characteristics are the easiest to be recognized after particular units, being conditioned by geologic structure on one side and by geomorphologic development at the contact of Alps and Dinarids Mt. on the other, between the Adriatic and Black Seea. In the southern Snežnik (1796) being the most dominant among them. Towards NW directed and several times interrupted reef of Javorniki follows, reaching with peaks up to 1260 m. The deepest gap in high karst plateaus is presented by Postojnska vrata in the altitudes between 600 and 700 m, having the important part of connection between the Adriatic and Pannonian basin. Towards NW wooded high plateaus continue, reaching the peaks of Hrušica and Trnovski gozd Mts. in the altitudes between 800 and 1200 m. On the SW part of this High karst to Ljubljanica water basin the well inhabited Postojna flysh basin belongs too, having the bottom mostly from 520 to 600 m. From all the parts it is surrounded by higher karst reefs, lower gaps being cut in only on the watershed towards Vipava river, in the altitude of 595 m, near Razdrto below Nanos Mt, and towards Notranjska Reka river near Pivka in the altitude of 590 m, and near Knežak 600 m above the sea level. Pivka river sinks near Postojna in the altitude of 511 m There is not the lowest basin's part, having the sinking stream Lokva near Predjama village, which is flowing towards Vipava springs under the Nanos karst plateau, cut more deeply into the flysh base (F. HABE 1973).

In the central Ljubljanica water basin's part on the NE side of high karst plateaus a wide belt of lower karst surface in so called Notranjsko podolje predomines in the altitudes between 450 to 600 m. There karst poljes are distributed in levels, presenting the deepest relief depressions and the sole planes of flattened area in the whole karst Ljubljanica water basin and therefore also the most inhabited.

At the watershed with Kolpa water basin the highest lying is the karst polje near Prezid (770 m), followed by Babno polje (750 m), Loško polje (580 m), Cerkniško polje (550 m), Rakov Škocjan und Unško polje (520 m), Planinsko polje (450 m), Logaško polje (470 m) and finally by Ljubljansko Barje (Ljubljana Moor) (285—300 m). On the eastern part the watershed reefs reach the altitudes between 800—1100 m and are little dissected and lowered only on Bloke plateau (720 m) and in the Cerkniščica river basin.

A special relief unit is presented by NW part, by Logatec—Rovte plateau, where the altitudes between 500 to 800 m predomine. This region is separated from Hrušica plateau by Hotensko podolje region, which is inclined from Godovič (600 m) near Idrijca waterhsed towards Hotedršica and Kalce (500) as enough uniform dry valley. In the region of Logatec—Rovte plateau the normal fluviatile and karst relief are varying, presenting gradual transition between completely Notranjsko podolje karst region and dominantly normal relief of nearby Idrijca and Sora river basins.

The former Ljubljanica river basin had been greater from today's. By karstification a part of its waters had been captured by adriatic affluents. mostly by Idrijca and Vipava and probably also Krka, as the southern Sava affluent had taken a part of former Ljubljanica river basin (F. KOSSMAT 1916, A. MELIK 1952, P. HABIČ 1968). After the principal relief forms the geologists and geomorphologists have tried to reconstruct the former superficial river net, which is now preserved only on impermeable flysh, shale and partly on dolomite and on karst poljes, while previously superficially flowing waters from the limestones have been displaced by gradual karstification into underground.

By morphological view the most in detail is described just the Pliocene Ljubljanica development, basing on these relief characteristics, which prove the former connected superficial streams (F. KOSSMAT 1916, A. MELIK 1952). Beside the Pliocene problematics also the Quaternary karst development, specially this of karst poljes (A. MELIK 1955) and karst caves (S. BRODAR 1952, I. GAMS 1963, F. OSOLE 1961, R. GOSPODARIČ & P. HABIČ 1966, R. GOSPODARIČ 1970, 1976) have been partly studied. The last mentioned studies are limited mostly to the region of Postojna basin and to Planinsko and Cerkniško poljes. Very important data about the morphological development in the Ljubljanica river basin have been given by geologic investigations of Ljubljana Moor and by palinologic analyses of the there lying sediments (A. ŠERCELJ 1966).

The recent perceptions about the development of young tectonic basin of Ljubljana Moor are presenting good initial point for the further karst investigations in Ljubljanica river basin. The Moor's basin origin is tightly joined to connection of Alps and Dinarids Mts (I. RAKOVEC 1955). At this contact mostly in Pleistocene up to 200 m deep tectonic depression had originated, being filled up mostly by Upper Pleistocene and Holocene sediments (A. ŠERCELJ 1966). Beside relatively punctual temporal definition of subsidence also the unproportionate process of deepening and filling up the basin can be seen from the sediments, because of gravel layers, lacustrine clay and peat alterings. By elevation of central Dinaric reef and by Moor's subsidence in the Ljubljanica water basin important change has occured, accelerating the displacement of superficial waters to the underground. Between the Moor flattening and former bottom of the superficial Ljubljanica in Notranjsko podolje, the tectonic movements have caused about 150 m of altitude difference, which rendered possible the further karst dissection of former fluviokarst valley.

THE KARST DEVELOPMENT

The principal characteristics in karst surface and underground development have been tried to be presented by schematic longitudinal section of central valley's part among Ljubljana Moor, Postojna basin and Cerknica polje

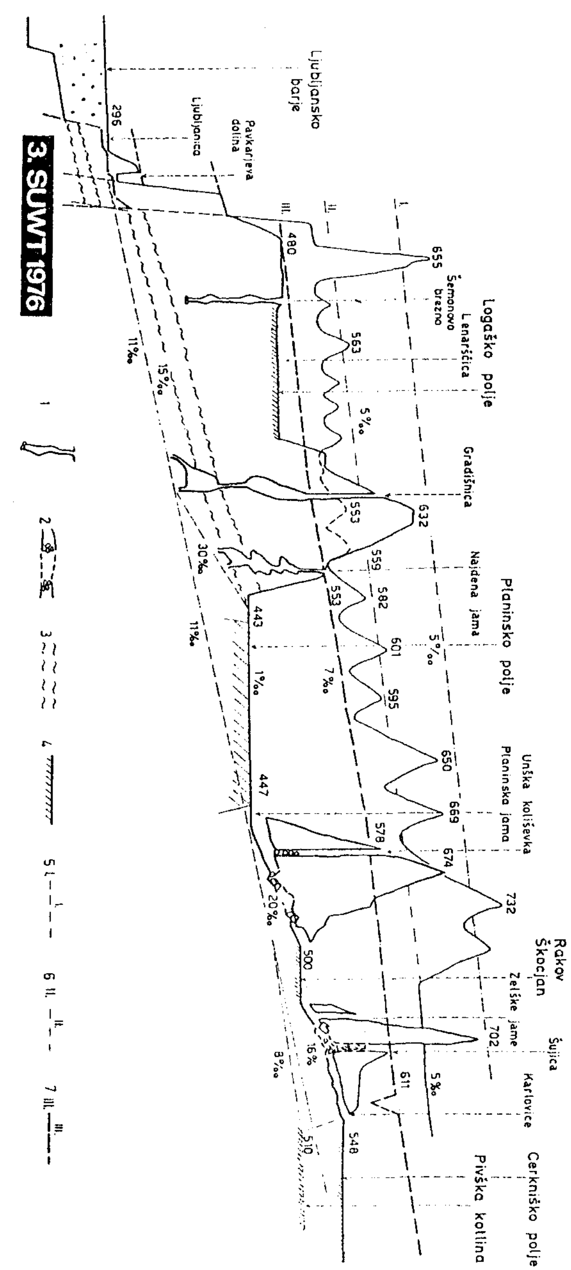

Fig. 2. *Longitudinal cross section of central part of Ljubljanica karst river basin.* 1 — active cave or pothole, 2 — unknown parts within known active caves, 3 — the supposed zone of former active caves between Planinsko polje and Ljubljansko barje (Ljubljana Moor), 4 — karst polje's bottom, 5 — Gradišče relief level, 6 — Bodiški vrh relief level, 7 — Dolina relief level.

Sl. 2. *Vzdolžni prerez osrednjega dela kraškega porečja Ljubljanice.* 1 — vodna jama ali brezno, 2 — neznani odseki v znanih vodnih jamah, 3 — predvidena cona nekdanjih vodnih jam med Planinskim poljem in Ljubljanskim barjem, 4 — dno kraškega polja, 5 — Gradiška reliefna stopnja, 6 — Bodiška reliefna stopnja, 7 — Dolinska reliefna stopnja.

(Fig. 2). The central part of Notranjsko podolje among Vrhnika, Postojna and Cerknica is not unitary dry valley, but composed by different relief units. Among higher karst plateaus as there are Hrušica, Javorniki and Pokojišče plateaus, it is difficult to follow the former bottom of Ljubljanica valley, being the surface by corrosional processes well dissected to singular ample summits and smaller remains in the form of shelves and levels. In fact karst transformation has changed the former relief shapes so much, that they can be recognized only by characteristic altitudes of particular elevations.

The characteristic higher and lower ample peaks mostly belong to two levels. The highest peaks belong to so-called Gradišče level, while lower ample summits to more expressive Bodiški vrh level. In longitudinal section the particular summits prove to be the remains of former valley with average inclination about 5 ‰. At different places of former valley the traces of fluvial sediments have been found (R. GOSPODARIČ 1968). A special value is presented by the clay sediment found on Bodiški vrh Mt. (558). After previous palinologic analyses it has been stated that it had originated from Lower Pleistocene or Upper Pliocene (A. ŠERCELJ 1968).

More than 5 m thick layer of carbonate clay can be sedimented only by waters flowing still on the surface in the Bodiški vrh level. But even if these clays present the remains of cave fills, they have a special importance on the isolated Bodiški vrh. After their age also the age of other, lower karst surface had been evaluated. Anyway the Dolina level is younger with superficial water flowing and forming the extensive erosional-solutional Logaški Ravnik. Till now this one had been inserted in Middle or at least in Upper Pliocene (I. RAKOVEC 1955). Thus all the karst depressions and karst poljes of this region are from Lower Pleistocene or even younger.

Karst dissection was not proportionate in whole water basin, but dependant in great rate from local geologic and geomorphologic conditions. Therefore beside common development characteristics at each polje also some specific features can be recognized.

In restricted hinterland of Ljubljanica springs mostly geomorphogenetic differences between Logaško and Planinsko poljes were observed. After the situation and levels distribution it would be expected that Logaško polje would be situated lower from Planinsko, but it is just opposite, being already remained by J. RUS (1925) and A. MELIK (1928). Logaško polje has been formed mostly by superficial streams from dolomite and shale hinterland, while the waters of Unica from Planinsko polje did not had any direct influence. After characteristic low margin levels on the eastern part of Logaško polje we conclude, that this polje has deepened slower than Planinsko one and had gradually narrowed. The deepening had been held back mostly because of extensive sediments of superficial streams, while the narrowing had been caused by karst dissection of water net in the polje's hinterland, where Rovte plateau is situated.

On Rovte plateau the ponors of todays sinking streams continue the dry valleys where formerly the waters have superficially flown to Logaško polje (Fig. 3). The actual superficial streams as are Petkovščica, Majerjeva grapa, Rovtarica and Ovčica, Pikeljščica, Žejski potok, Hlevišarka and Hotenka are sinking enough far away from polje, to which only Logaščica flows from only a quarter of former hinterland. At these sinking streams ponors the recent blind valleys with more or less expressive rocky border and flattened filled up bottom have originated. Mostly impassable swallow-holes are situated in the bottom of the valleys, or well at the foot of rocky border and only at Petkovščica, Ovčica, Pikeljščica and Žejski potok smaller ponor caves are known.

Essentially different had been the development of Planinsko polje, being formed and deepened by karst waters from Cerknica and Postojna regions. The waters have run off undergroundly directly to Ljubljanica springs near Vrhnika. In Planinsko polje development two principal phases can be distin-

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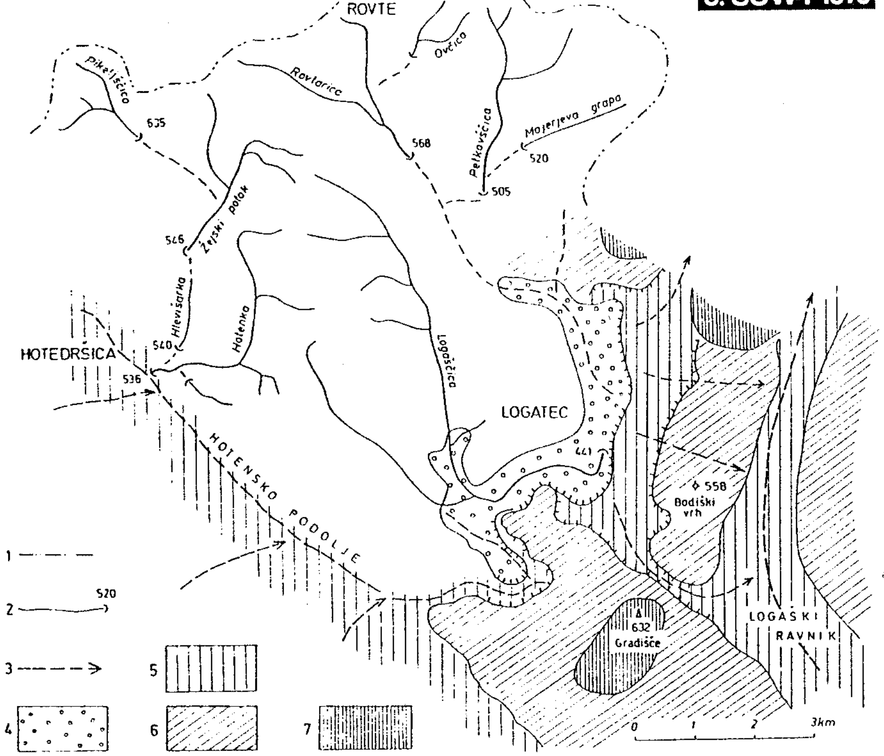


Fig. 3. *Sinking streams and dry valleys on Logatec—Rovte plateau.* 1 — superficial watershed, 2 — sinking stream with the ponor's sea level, 3 — dry valley, 4 — Quaternary sediments on marginal karst polje, 5 — Dolina or Ravnik relief level, 6 — Bodiški vrh level, 7 — Gradišče level.

Sl. 3. *Ponikalnice in suhe doline na Logaško-rovtarski planoti.* 1 — površinsko razvodje, 2 — ponikalnica z nadmorsko višino ponora, 3 — suha dolina, 4 — kvartarne naplavine na robnem kraškem polju, 5 — Dolinska ali Ravniška reliefna stopnja, 6 — Bodiška stopnja, 7 — Gradiška stopnja.

guished. The older polje's bottom had been in the altitude about 520 m, presenting together with actual ouvala near Unec—Rakek the uniform karst polje on the important Idrija wrench-fault and Predjama over-thrust. The abundant deepening of the polje's bottom to actual altitudes between 440 to 450 m follows, but in smaller extent, being Unec ouvala separated from the superficial confluence of Cerknica and Postojna waters. This confluence has taken its place in the area of Malni springs and Planinska jama (Planina Cave). Parallel to Planinsko polje bottom's deepening on the border underground inflow and outflow channels have been formed.

By detailed speleological investigations (W. PUTICK 1888, I. MICHLER 1955, I. GAMS 1963, M. PUC 1965, F. ŠUŠTERŠIČ & M. PUC 1972, R. GOSPODARIČ 1970, 1976) three more expressive levels of inflow and outflow channels have been stated. The lowest level is now active, the medium is the most extensive and in general dry, the highest one is preserved only in shorter cave passages, being much transformed by breakdowns. Similar statements can be done for the border of Postojna basin and Cerknica polje, smaller differences being conditioned by differences in geologic structure (flysch, dolomite) and by altering of superficial and karst hinterland.

The ponor regions of karst poljes are distinguished by well developed, but frequently interrupted net of runoff channels. Postojna, Cerknica and Planina cave systems are well known, while near springs much more uniform channels prevail. In the Planinska jama one channel of several levels exists and several erosional and accumulation phases can be distinguished, connected by general development of karst surface and underground in Upper Quaternary.

Karst poljes deepening as well inbetween underground channels deepening is tightly connected. It is dependant as much from erosional deepening in the area of superficial streams in headwater, as well in lower river basin's part and also from lowering of relatively less permeable barriers in the central river basin's part, where the karst poljes have developed. Beside the channels situation also their permeability is important. In general the channels have to be widened because of greater age, but such a development has been in retard because of different fills, being deposed by superficial waters in the underground. To lessened channels permeability also the breakdowns have influenced, impeding the underground streams and forcing them to search new ways.

The importance of breakdowns in unknown underground is shown also by several collapsed dolines. In Notranjsko Region there are more than 150 larger collapsed dolines, developed by roof collapse above the former water channels. The most frequent are the collapsed dolines just behind the ponor and on low plateaus surface directly above the Ljubljanica springs, but they are numerous also in the inbetween area (Fig. 4). After the shape, size and situation the collapsed dolines are very different (F. ŠUŠTERŠIČ 1973), although the majority of them can be connected to distribution of medium level of the underground channels. The collapsed dolines and steepheads of Močilnik and Retovje directly above the Ljubljanica springs have the curious situation. They are lying much lower than other allied forms. If they have originated above the same channels as other collapsed dolines, which is probable, then we have to connect their actual situation with allied channels to gradual tectonic subsidence of Ljubljana Moor and of its boundary. By such development also other relief characteristics on the passage from Notranjsko podolje to Ljubljana Moor marginal zones agree.

Under the Dolina level on the passage to rocky bottom of Ljubljana Moor there are still at least five levels, being till now explained mostly by erosional Ljubljanica influence (I. RAKOVEC 1955). About the great transformation capacity of waters nearby karst springs we have been persuaded at several places, but anyway the entire relief missing in levelled Moor's marginal zone near Vrhnika, cannot be ascribed only to erosional processes. For such origin of marginal zone there are not the real proofs, being the old steepheads missed, similar as these at Močilnik and Retovje near actual springs. A. MELIK (1952) has already missed them, but also the remains of former water caves of these levels have not been found till now.

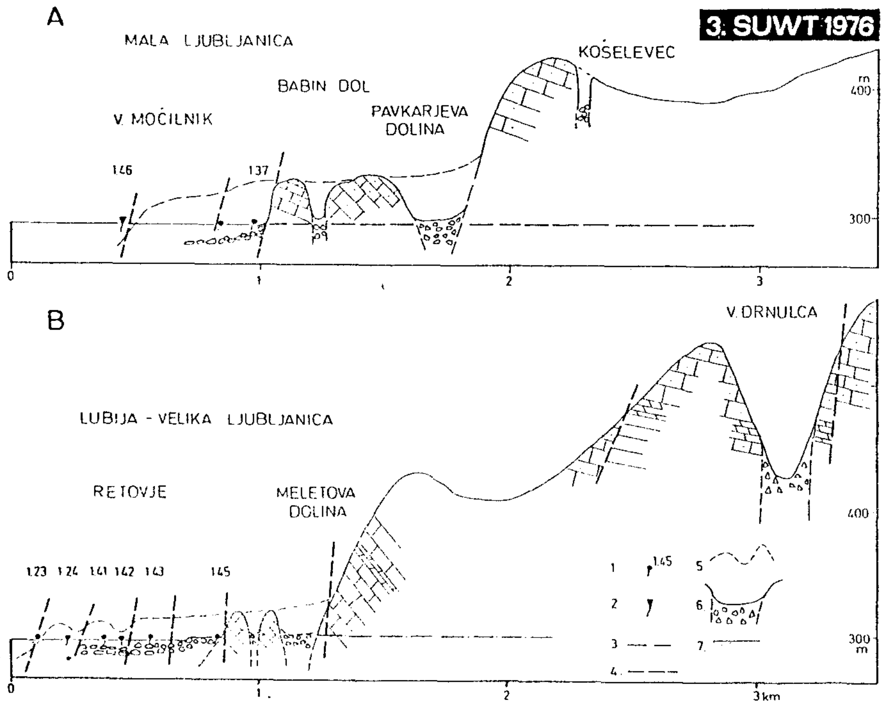


Fig. 4. *Ljubljanica springs restricted hinterland cross section, A-Močilnik, B-Retovje.* 1 — karst spring with number, 2 — thermal spring, 3 — karst water level, 4 — important fault, 5 — sketch of steephead, 6 — collapsed doline with breakdown rocks, 7 — Quaternary sediments on Ljubljansko barje.

Sl. 4. *Prerez ožjega zaledja izvirov Ljubljanice, A - Močilnik, B - Retovje.* 1 — kraški izvir z oznako, 2 — termalni izvir, 3 — nivo kraške vode, 4 — važnejši prelom, 5 — obris zatrepne doline, 6 — udornica s podornim skalovjem, 7 — kvartarne naplavine Ljubljanskega barja.

It seems, that simultaneously to Moor subsidence origin, the former cave channels together with surface and collapsed dolines have been lowered, partly also under the actual flooded flattening. The sediments have damed up the water runoff from former channels, which also have been interrupted on several places by tectonic movements and breakdowns and the karst waters have to search across the fissures new ways to the surface. Instead of united stream, as we know it from Planinska jama and from other great karst springs (Vaucluse, Aachtopf) the karst Ljubljanica has wide, delta like mouth. The waters are bubbling to the surface from several strait fissures and several impassable crevices. Only few channels giving the possibility to divers to penetrate deeper into the underground (A. PRAPROTNIK & P. KRIVIC 1973). Thus in morphological and hydrological conditions near the Ljubljanica springs the consequences of young tectonic subsidence are seen, while the influence of this subsidence is reaching still deeper into karst hinterland.

HYDROGEOGRAPHIC CHARACTERISTICS

The altering of permeable and impermeable rocks in Ljubljanica river basin render possible the superficial and underground discharges. The underground and superficial waters from headwater are flowing to karst poljes, sinking there and reapper on the surface on lower lying karst poljes. Finally all the waters after several sinks or after direct underground discharges appear in the springs near Vrhnika in relatively narrow belt at western Ljubljana Moor's border, flowing afterwards as Ljubljanica river superficialy to Sava.

Near Vrhnika (Annex 1) one good kilometer wide and up to 2 kilometers long steephead is situated, where the springs of Mala Ljubljanica (1.3), Velika Ljubljanica (1.4) and Lubija (1.2) are situated, while the Bistra springs (1.1) are lying 2 km towards east at the foot of Moor's border. West from Vrhnika the superficial Bela brook, affluent of Mala Ljubljanica, collects the waters from partly karstified dolomite, where two important springs Staje (1.38) and Lintvern (1.39) are situated. The latter had excited already J. V. VALVASOR (1689) attention, because the water is flowing out in unequal intervals. The superficial Bela sinks at low waters in her own river bed and flows undergroundly to Kožuhov izvir of Hribščica brook (1.32), which has, considering the abundance and the results of previous tracings a great hinterland in the area of Rovte plateau. On the left Bela bank two smaller karst springs Primcov and Bečkajev studenec (1.34) are situated, being fed by the water of near karst hinterland and at the same time connected by the hinterland of Kožuhov izvir (P. HABIČ 1976).

Mala Ljubljanica (1.3) is fed beside by Bela and Hribščica also by permanent spring Mali Močilnik (1.36) and by three springs of Veliki Močilnik (1.37), which are distributed in picturesque steephead, surrounded by 20—30 high precipiced walls. Some hundred meters below the confluence of Mala Ljubljanica and Hribščica, on the right bank the thermal spring Furlanove toplice (1.46) is situated.

The Velika Ljubljanica springs (1.4) are distributed in Retovje, which is similar to Močilnik, but much more dissected steephead with several springs.

On its left side, under the abrupt wall the springs Malo Okence (1.44) very similar to Veliko Okence (1.45) are situated. The later is one of principal Ljubljanica springs on the extreme south part of Retovje. The both Okence springs are active only at high waters.

Just opposite to Malo Okence, a smaller periodical spring, being active at high water together with Veliko Okence, is lying. Nortwards Retovje is little widened and from the right side the waters are bubbling on several places from the underground. The most picturesque and strong is the permanent spring Pod skalo (1.43), a little smaller, but specially interesting because of bubbling manner is the spring Pod orehom (1.42). The near lying Maroltov izvir (1.41) is walled and partly covered by house. Immediately below, the river bed of Velika Ljubljanica is widened on the passage from rocky to clayey ground. At right side the last spring of the series of Velika Ljubljanica springs is situated.

Low rocky reef separates Retovje from less expressive steephead where the Lubija springs are situated; there are periodic Smukov (1.24) and Gradarjev (1.23) izvir, permanent Jurčkov (1.21) and Ceglarjev izvir (1.22). Among Lubija and Bistra springs (1.1) some smaller, insignificant springs are situated. Bistra (1.1) is fed by three principal springs, the first is Grajski izvir (1.13), enclosing the former Carthusian monastery from the north side; on the opposite side from several fissures the water is flowing from Zupanov izvir (1.12); still further eastwards a similar series of fissured channels is situated, feeding Galetov izvir (1.11). Still futher eastwards two smaller springs are lying, the first is Pasji (1.15), the second Ribčev (1.14) studenec, which has periodical characteristics of intermittent spring.

The sinking streams, the nearest to the springs, are disposed west from Vrhnika in the region of Logatec and Rovte plateaus, covering about 100 km^2 of karst and non karst surface. The sinking stream Petkovščica (2.11) covers about 10 km^2, Rovtarica (2.21) together with Ovčica (2.22) 8 km^2 of mostly impermeable surface, but a part of the waters from the both river basins is disappearing into karstified dolomite underground. Similar can be stated also for neighbour, more westwards lying sinking streams, which are sinking immediately after the contact with more permeable limestones. Hotenka (2.31) and Žejski potok (2.32) include each 4 km^2 of dolomitic water basin, while Pikeljščica (2.51) only 2,5 km^2. South from these sinking streams Logaščica (2.41) discharges from about 20 km^2 of Triassic dolomite and sinks into Jačka ponors, before it reaches the Cretaceous limestones in the eastern border of Logaško polje.

The most important sinking stream in the hinterland of Vrhnika springs is Unica, flowing on Planinsko polje. Inflow are southern and western sides, outflow eastern and northern sides of Planinsko polje, extending on 16 km^2. It is known, that the waters from Postojna basin are flowing to Planinsko polje, as well as the waters from Cerkniško polje through Rakov Škocjan and the waters directly from the karst Javorniki Mt. (F. JENKO 1959, I. GAMS 1966, 1970). The principal Unica springs are situated in the southern polje's part in Cretaceous limestones; at high waters a real river is flowing out from 6 km long Planinska jama (3.9), where the confluence of waters from Cerknica, Javorniki Mt. and Pivka is located. The Malenščica brook (3.7) takes its springs in near lying steephead. High waters are not very expressive, while at low waters the strongest springs are Malni. East from Malni, already on the contact of limestone and dolomite, is lying Škratovka (3.6) spring. Periodic effluents are situated also in NW polje's part, below the Grčarevec village, where the high waters from a part of Hrušica plateau, and perhaps also from Hotenka, are flowing.

The principal Unica swallow-holes are disposed at northern polje's border near Podstene (3.1), where mostly medium and high waters are sinking. At low waters the whole Unica is disappearing in swallow-holes at eastern polje's border, where downwards river bed Mrčonovi ključi (3.44), Milavcovi ključi (3.42), Žrnki and Ribce (3.43), swallow-holes at Dolenje Loke (3.41), near Laška žaga (3.21) and others are disposed. The water is sinking directly from Unica bed through the polje's bottom across more than 150 swallow-holes and impassable fissure. Only at Dolenje Loke and in Škofji lom, up to 160 m long ponor caves are known.

At high waters to Planinsko polje much more water is flowing than the swallow-holes are capable to lead off, therefore polje is flooded several times in a year. At floods, lasting 1—2 months, the water increases up to 10 m and up to 40 millions of m^3 of water inundate the polje.

In Postojna flysh basin the superficial Nanoščica stream (4.1) flows into Pivka River. At high and medium water level Pivka gets a part of karst waters from western marginal zones of Javorniki, while the low waters from this region are flowing directly to Malenščica springs (P. HABIČ 1968). In karst depression Rakov Škocjan the waters from Cerkniško polje and partly from Javorniki are flowing in 2,5 km long superficial Rak (5.1) stream; the waters are taking their springs in Kotliči (5.2) and in near lying periodical springs, greater part of Cerknica waters is flowing from the cave Zelške jame (5.4). A part of Rak waters sinks already before the Great Natural Bridge, the principal ponor being situated in extensive, more than 1,2 km long cave Tkalca jama (5.0) which is not yet completely explored. The inflows at high waters are greater than swallow-holes capacities, therefore the Rak valley is periodically flooded.

Mostly flattened bottom of Cerkniško polje covers about 36 km^2, at floods it alters to spacious karst lake. Principal ponor caves and swallow-holes are disposed in Jamski zaliv at NW polje's border. The highest waters run off through the caves Mala and Velika Karlovica (6.01, 6.00), where more than 7 km of passable channels are known. Lower waters are sinking mostly in marginal swallow-holes, as are Narte (6.022), Kamnje (6.021) and Svinjske jame (6.02) and in numerous ground swallow-holes, which are disposed in central polje's bottom, in a good kilometer wide zone. It is widening from Rešeto (6.18), Vodonos (6.16), Retje (6.21) southwards at the foot of Javorniki over Bečki (6.15), Sitarica (6.13), Velika and Mala Ponikva (6.14) to swallow-holes and estavellas Geben (6.035), Kotel (6.038), and Češljenca (6.033) in Zadnji kraj and Lovišče (6.051) on the eastern side of Otok village. The most part of the year the ground swallow-holes are inundated, at dry period the last waters flowing to the polje are sinking there. Inflows are on eastern and southern and partly on western polje's side. Beside superficial Cerkniščica (6.45) with about 45 km^2 of hinterland, from Slivnica Mt. dolomitic slopes smaller streams as are Martinjščica (6.23) and Grahovščica (6.25) are flowing. On the eastern polje's part a little more abundant are karst springs of Žerovniščica (6.27) and Lipsenjščica, Šteberščica respectively (6.12), being fed by Bloščica (7.0) from Bloško polje and by waters from near karst hinterland, which partly flow through famous, 8 km long Križna jama. The cave is known because of numerous lakes, divided by rimstone formation. The principal karst waters take their springs in SE polje's corner in Obrh (6.07) and Cemun (6.071) and in other springs, which are flowing off to Stržen (6.08) directly from Javorniki and Snežnik, the important part of the water is contributed by higher lying Loško polje. The inflows frequently exceed the outflows, therefore Cerkniško polje is changed in average for 8 months per year in karst lake, which sometimes do not dry up during the whole year. At the highest water table (552 m), up to 80 millions of m^3 of water is accumulated.

Higher lying Loško polje is smaller (12 km^2), having, compared to Cerkniško and Planinsko poljes, pretty more narrow ponor area in NW corner, where the known ponor cave Golobina (8.0) is situated. At low waters the Obrh brook (8.01) sinks in before reaching Golobina; at high water it inudates the cave and a part of polje, the water quantity reaching 10 millions of m^3. The principal springs are lying on SE and E polje's side, there are permanent spring Veliki Obrh (8.24) and periodical spring Mali Obrh (8.15). Veliki Obrh is fed by the waters from higher lying Babno polje and from ouvala near Prezid, where there is sinking stream Trebuhovica (9.0) lying the highest in sinking streams system and being the most distant from Ljubljanica springs.

The altering of superficial and underground discharges in the hinterland of Ljubljanica springs is causing a series of hydrological enigmas, which are not yet entirely found out.

In the period of floods on Cerkniško and Planinsko poljes and in Rakov Škocjan it is impossible to measure neither inflow, neither outflow quantities. Because the floods are lasting for the longest period just on Cerkniško polje, their discharging quantities are the least known. The water tracing in Golobina (F. BIDOVEC 1968) has shown, that a part of waters from Loško polje can flow under the Cerkniško polje directly to Ljubljanica springs. The first useful data for understanding the karst hydrologic conditions in Ljubljanica river basin have been done by successive water tracings of sinking streams (A. ŠERKO 1946, I. GAMS 1965) in the years from 1910 till 1965.

Basing on these tracings the principal water connections between the ponors and belonging streams have been stated. But as each water tracing has been achieved in different hydrologic conditions, the results of these tracings have been pretty different too. The opened questions have been reexamined by new investigations and tracings, which have been realized in the years 1972—1975.

THE UNDERGROUND AND SUPERFICIAL WATER DISTRIBUTION

Before the beginning of investigations and combined water tracing experiment it was possible to compose an outline of underground and superficial waters in the Ljubljanica springs hiterland, as it is shown on the Fig. 5. There are drawn a parts known (8) and supposed watershed lines (9), superficial

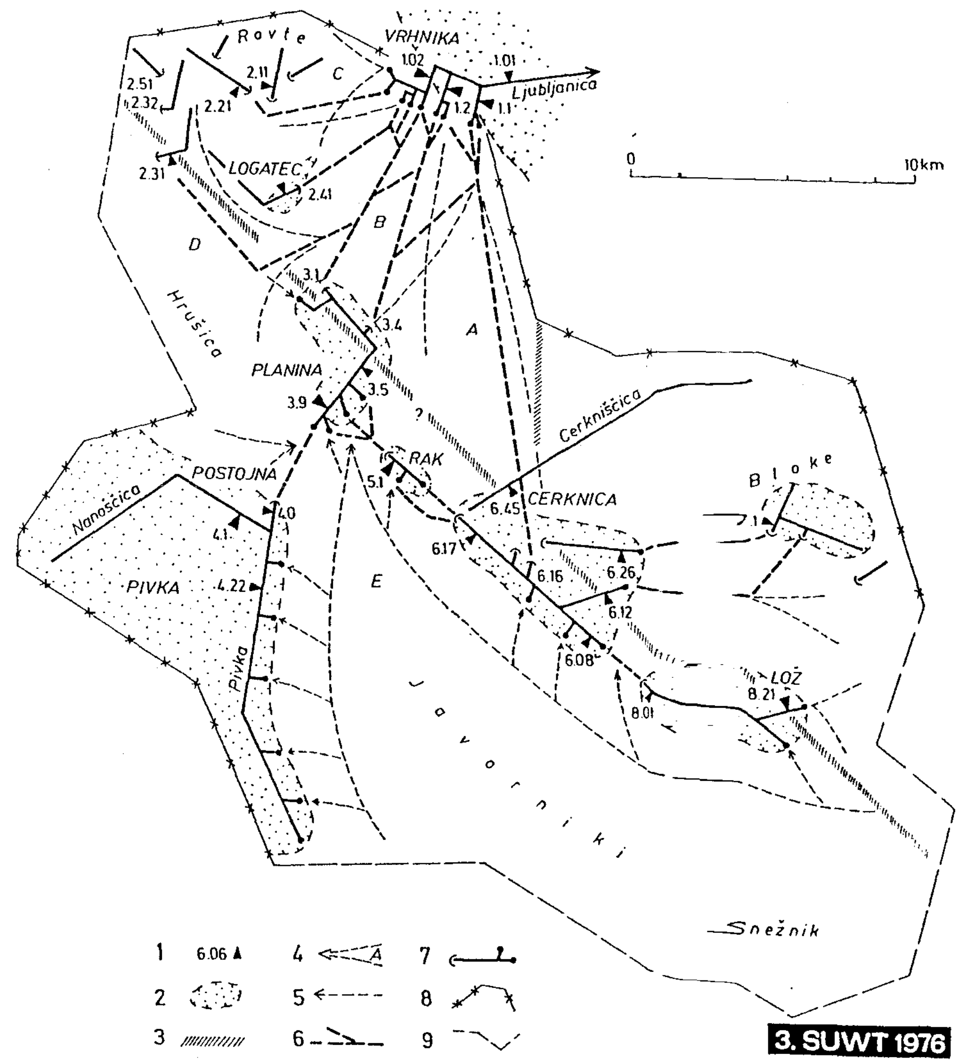


Fig. 5. *Schematic review of superficial and underground waters in Ljubljanica karst river basin.* 1 — important gauging stations, 2 — karst polje with sediment, 3 — central hydrogeologic relative barrier, 4 — intake area of permanent karst springs, 5 — periodic high water discharges of karst water, 6 — underground water connections, 7 — superficial stream with springs and ponors, 8 — superficial watershed, 9 — supposed karst watershed.

Sl. 5. *Shema površinskih in podzemeljskih voda v kraškem porečju Ljubljanice.* 1 — važnejše vodomerne postaje, 2 — kraško polje z naplavino, 3 — osrednja hidrogeološka pregrada, relativna bariera, 4 — zbirno območje stalnih kraških izvirov, 5 — občasni visokovodni prelivi kraške vode, 6 — podzemeljske vodne zveze, 7 — površinski tok z izviri in ponori, 8 — površinsko razvodje, 9 — kraško predpostavljeno razvodje.

flows — sinking streams (7), with corresponding underground connections (6); periodic high waters discharging from karst massifs (5), the areas of karst flows, feeding the permanent springs (4); central hydrogeologic barrier, dividing the water basin to upper and lower part (3); karst poljes (2); and the most important gauging stations (1), gathering the data for hydrological characteristic study of karst Ljubljanica.

In the region of Ljubljana Moor near Vrhnika (1.02) and near Komin (1.01) all the waters, flowing together from spacious, but only approximatively limited karst water basin, can be measured. Perhaps only a small part of water does not appear on the surface of Ljubljana Moor, feeding its groundwater. Otherwise the data about Ljubljanica (1.02), Lubija (1.2) and Bistra (1.1) discharges are important for the study of water balance of the entire water basin. Because of undefined extent of water basin it is difficult accurately define the total precipitations quantity and the real runoff coefficients, specially because there are considerable differences in distribution of precipitations and runoff; at short distances in karst Ljubljanica river basin, these values are very altered.

In sinking streams of karst poljes only a part of hydrogeologically heterogeneous water basin can be measured. Particular areas present uniform hydrographic regions, as for example water basins of Nanoščica (4.1) and Cerkniščica (6.45) in restricted sense. The heterogeneous regions, Pivka water basin (4.21) for example, being fed only by high waters from Javorniki, while the low waters are flowing off to Planinsko polje, are prevailing. The similar hydrographic circumstances are characteristic also for waters basins of Loško and Cerkniško poljes, for Rakov Škocjan and Planinsko polje.

Somewhat peculiar hydrographic type is presented by Bloke (7.0) and their vicinity, from where the superficial waters undergroundly flow to Cerkniško and Loško poljes and can be included into observation net (6.12, 6.21) together with other karst waters. In general the water basin is known, therefore there somewhat detailed study of water balance and superficial and karst runoff is possible.

Almost through the center of Ljubljanica water basin only partly permeable dolomitic barrier passes, forcing karst waters from southern water basin's half to discharge again into underground flow towards Ljubljanica springs. The majority of karst waters is discharging from higher to lower basins, only a small part is discharging across karstified barrier in the region between Planinsko and Cerkniško poljes and Hotedršica directly to Ljubljanica springs. These waters cannot be accurately measured, therefore the quantity of waters of upper Ljubljanica river basin, discharging across Planinsko polje, is not known (Unica, Hasberg 3.5) Regarding the data during the tracing the there average annual discharges are for 30—40 % smaller from annual discharges from total Ljubljanica karst water basin. The differences are greater in dry period (50 %), smaller at high waters (20 %). The intermediate affluents from karst between Cerkniško and Planinsko poljes and Ljubljansko Barje (marked on figure A, B, C) are influencing this differences, as well as the waters, undergroundly discharging through mentioned relative barrier from higher karst water basin (D, E, F).

The Logatec-Rovte region with nine smaller sinking streams on the surface and with permanent underground runoff from unknown karst hinterland of Hrušica (D) is somewhat similar to Bloke in hydrologic view. But the runoff from this region cannot be measured, because in underground these waters are intermixed with waters from other parts of karst Ljubljanica river basin. By water level recorders on sinking streams (2.1 to 2.5) probably not a half of runoff from this region is included in average.

The statement of direct runoff from Cerkniško polje towards the Ljubljanica springs presents special problematics, which can be solved by calculation of total inflow to Cerkniško polje and at the same time by measurement of runoff in the direction towards Rakov Škocjan and Planinsko polje and directly to Ljubljanica springs.

Also the question of waters runoff from Loško polje remains unsolved. When the Obrh springs on Cerkniško polje are completely dry, about 1 m^3/s of water is still sinking before Golobina on Loško polje. This water can flow under Javorniki near Cerkniško polje into Unica springs on Planinsko polje or well under Cerkniško polje into Bistra, Lubija and Ljubljanica springs.

By cited is obvious, that a lot of hydrologic enigmas are existing in the hinterland of Ljubljanica springs in spite of 100 years tradition of hydrologic investigations. The previous knowledge is based on different reliable data, regarding the tracings and other hydrologic measurements. Therefore a special attention has been paid to these questions in the frame of previous investigations.

Translated by Maja KRANJC

2.1.2 GEOLOGY AND HYDROGEOLOGY

S. BUSER, F. DROBNE, R. GOSPODARIČ

The prevailing part of Ljubljanica karst river basin is presented by geological map Ajdovščina and Postojna (Haidenschaft und Adelsberg) in scale 1 : 75.000, being composed together with commentary by F. KOSSMAT (1905). The mapping and geological surveys after 1945 have been done by geologists of Geološki zavod from Ljubljana, essentially completing the older data (S. BUSER 1965, S. BUSER 1973, M. BREZNIK 1962, K. GRAD 1962, M. PLENIČAR 1954, M. PLENIČAR 1970). As well the tectonic structure is much better studied, due to geologists from Idrija mine merits (J. MLAKAR 1969, L. PLACER & J. ČAR 1975).

For requirements of hydrogeological investigations the area among Vrhnika, Logatec and Planina has to be resurveyed, because the existing data had not been detailed enough. The special attention has been dedicated to hydrogeologic characteristics of the rocks, which had not been previously studied in detail.

The description of lithostratigraphic, tectonit and hydrogeologic conditions is based on till now published studies and on the field work, which had been done for the purposes of investigation program for 3rd International Symposium of Underground Water Tracing.

LITHOSTRATIGRAPHIC DESCRIPTION

The treated region of Ljubljanica river basin belongs to Outer and Inner Dinarid Mountains. For Outer Dinarids the shallow-sea facies of Jurassic and Cretaceous beds is characteristic (limestone, dolomite), while for the Inner Dinarids the deep-sea facies of the same age (flysh rock and others). The both geotectonic units contact south-east from Idrija fault zone, where in there lying tectonic windows shallow-marine Lower Cretaceous strata are still found.

On the investigations and water tracing experiment area Permo-Carboniferous, Permian, Triassic, Jurassic, Cretaceous, Paleocene, Eocene and Quaternary beds are lying denuded. The greatest extent is covered by Triassic beds, smaller by Jurassic and Cretaceous, while the smallest extent is covered by Permo-Carboniferous, Permian and Eocene beds. Quaternary sediments are limited to karst poljes and Ljubljansko Barje (Ljubljana Moor).

PERMO-CARBONIFEROUS AND PERMIAN BEDS

are found in narrow, long, and several times interrupted belt between Idrija and Vrhnika. Below they are represented by black clayey shale and quartz sandstone, conglomerate respectively, and above by »Gröden« clastites, bedded dolomite and limestone. The total stratigraphic thickness of these beds reaches up to 100 m, although on the treated region only a part of this thickness has been developed, because the beds are lying in tectonic nappes.

TRIASSIC BEDS

are lithologically variegated and stratigraphically well determined. The best they are studied east from Vrhnika up to Idrija, less in the eastern river basin side.

Everywhere about 600 m thick Scythian beds are lying, containing the most of dolomite and less of shale, sandstone, oölitic limestone and marl limestone. Anisian stage is developed in massive granular crushable dolomite 300 m thick. Ladinian stage is developed in thick-bedded dolomitic conglomerate of 400 m of thickness with tuffs and tuffites west from Rovte and in bedded limestone with cherts 100 m thick in the area of sinking streams Rovtarica and Petkovščica. Carnian stage contains Cordevol platy limestones with cherts thick up to 400 m and massive dolomite thick up to 300 m, found near the Podroteja springs on the western and near Borovnica, on the eastern part of the investigated region.

The upper part of Carnian stage (Jul and Tuval) is developed mostly in clastic rocks and in dolomite north from Hotedršica and Godovič and near G. Logatec, everywhere in klippes, nappes respectively. The clastites stratigraphic thicknees is assessed as up to 300 m, the dolomite thickness near Borovnica up to 250 m.

Norian and Rhaetian stages are developed in thin bedded granular dolomite and thick granular massive dolomite. Dolomite near faults is crushed to milonite breccias, crushed zones being wide more than hundred meters and can be considered as partial barrier. This dolomite thickness reaches up to 1000—1300 m.

JURASSIC BEDS

are developed in thickness about 1.600 m in karst facies, that is to say as limestones and dolomites. There is 6-times more limestone than dolomite. These rocks are composing the karst region between Ljubljansko Barje and Cerkniško polje and northern, eastern and southern border of the same polje. Some of Jurassic dolomites and limestones are overlain by the Upper Triassic dolomite near Planinsko polje, more of it are found on Hrušica plateau, where the underground watershed between Ljubljanica and Vipava rivers is situated.

Lower Liassic beds are presented by thick granular bituminous dolomite thick up to 100 m, which is well karstified. Middle Liassic contains some of bituminous bedded dolomite and more of bedded limestone mostly in the area of Ljubljanica springs, at northern border of Planinsko polje and near Cerknica.

Upper Liassic and Dogger can not be stratigraphically and lithologically distinguished. There is thin granular and oölitic limestone with inliers of coarse granular bituminous limestone in beds up to 800 m thick. In these beds the majority of Ljubljanica karst springs is situated.

Lower Malmian strata are represented by massive oölitic and reef limestone up to 350 m thick. In Upper Malmian coarse granular dolomite prevails, limestone beds are less frequent, total thickness amounts to 200 m. These beds are found alongside Logaška plateau in narrow belt between Lower Malmian limestone in footwall and Lower Cretaceous limestone in hanging wall. This rocks belt is crushed in discrete blocks, which are displaced in horizontal and vertical direction. Thus in Upper Malmian dolomite the abundance and characteristics of tectonic movement are easier to be assessed, being in adjoining, mostly uniformly composed rocks, which are also crushed, almost impossible. Between Lower and Upper Malmian intercalations of red and brown bauxite lenses are distinctive.

CRETACEOUS BEDS

are lying between Planinsko and Logaško poljes, where they are concordantly overlain by Jurassic beds, and in Idrija—Žiri region, where they present the compositional part of nappes (mostly of Čekovnik nappe).

In Lower Cretaceous, about 1200 m of thickness, limestone and dolomite, similar to Upper Malmian are lain at first, being followed by bedded, partly micritic limestone, which contains between Laze and Dolenji Logatec coarse inliers of dark grey bituminous bedded limestone and northeastern from Dolenji Logatec some beds of clayey marl. In these sediments the principal ponor zones and underground caves are situated in northern and northeastern border of Planinsko polje.

Upper Cretaceous beds (Cenomanian and Turonian) are represented by organogenic bedded and reef limestone and by platy limestone with cherts in the region between Planinsko and Logaško poljes.

Senonian beds are developed in form of bedded micritic limestone and massive rudist limestone up to 400 m thick and as marl in form of red and greenish marl in thickness up to 100 m. The finding places of these rock are in vicinity of Kališe.

Up to 50 m thick series of red and green marl and limestone breccias near Kališe is partly of Paleocene age. Erosional remains of flysh rocks (sandstone and marl) near Kališe are of Eocene age.

QUATERNARY SEDIMENTS

On karst surface clays, sands, gravels and fossil soil are known, being in some cases assessed to be of Quaternary age. Paleobotanic investigation proved Old Pleistocene vegetation in grey clay of karst depressions above Vrhnika and Logatec (see page 15). On contrary on karst poljes only Upper Pleistocene sediments are known. On Cerkniško polje in thickness from 5 to 15 m clay, sand and gravel sediments with organic remains of Würm and Holocene age occur. Similar sediments of 5 m thick have been found on Unško, Planinsko and Logaško poljes.

On Ljubljansko Barje the Würm sediments reach somewere up to 100 m of thickness, much more than all the other here lying sediments in foot wall and in hanging wall. The Moor's sediments are composed in detail by grey clay, silt and sand, calcareous clay, peat and black humus.

Quaternary sediments have been preserved also in underground caves together with autochthonous sediments as are sinters and rubbles.

TECTONIC SETTING

The karst Ljubljanica river basin lies on passage of alpine to dinaric structures (F. KOSSMAT 1912, I. RAKOVEC, 1956). About the character and extent of this passage very different ideas exist (R. GOSPODARIČ 1969). In the western river basin's part I. MLAKAR (1969) has proved the nappe structure, whereas S. BUSER (1965) has assessed the block structure for the eastern part. Different view to tectonic structure are obvious from geologic map Postojna (1967) including greater part of Ljubljanica river basin; on its base the hydrogeologic map (Annex 2) has been based. The field explorations regarding the described investigations have been directed more to researching the rocks hydrogeological characteristics, therefore the tectonic interpretation remains unachieved.

STRUCTURAL UNITS (Fig. 6)

Southwestern part of Ljubljanica river basin has nappe structure (I. MLAKAR 1969). The first nappe (Koševnik nappe) from Cretaceous beds is lying on autochthonous base. It has the greatest extent among Godovič, Hotedršica and Idrija, continuing towards Logatec, where it is covered by subsequent nappes. This nappe seems to be very important for underground waters discharge towards Ljubljanica and Idrijca.

The second nappe (Čekovnik nappe) is composed by Upper Triassic dolomite and partly by Carnian clastites. On the surface it can be followed in greater extent between Hotedršica and Godovič and south from line Hotedršica—Zala. To the same nappe also Upper Triassic dolomite of Zaplana between Vrhnika and Petkovec belongs. The third nappe (Idrija nappe) is found in wider area among Rovte, Logatec and Hotedršica and in more narrow belt up to Idrija. In inverted position several rocks from Permo-Carboniferous up to Upper Triassic are found. On the eastern nappe's part, where there are sinking streams Rovtarica, Pikeljščica and Žejski potok, impervious Permo-

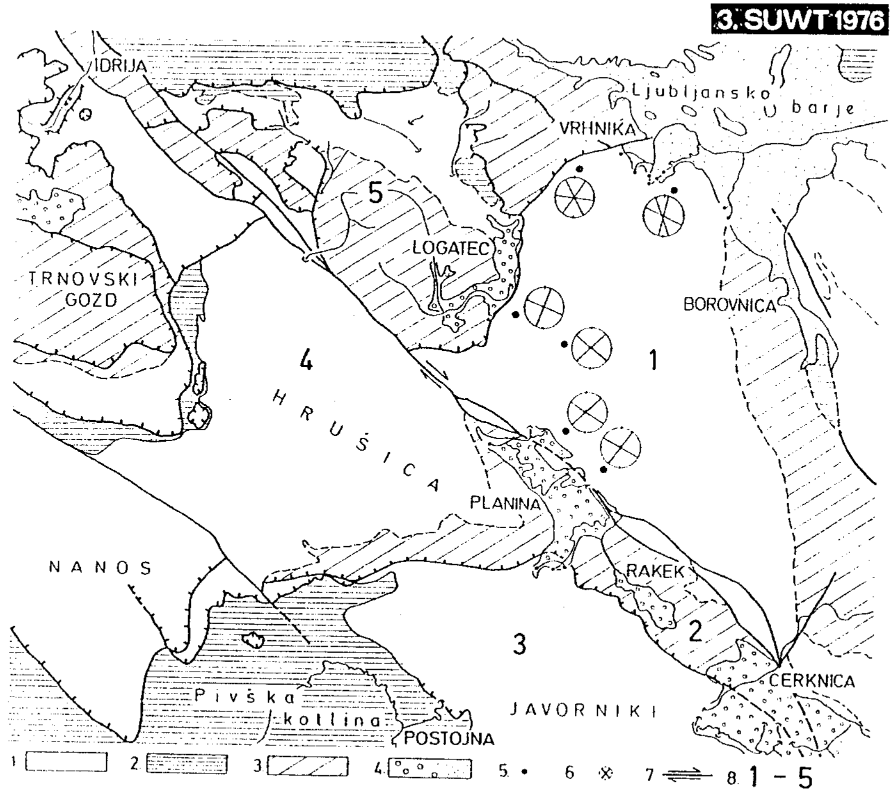


Fig. 6. *Hydrogeologic units in the central part of Ljubljanica karst river basin.* 1 — limestone, 2 — impermeable rocks (schists, e. c.), 3 — dolomite, 4 — sediments on the karst poljes and moor, 5 — location of rupture survey, 6 — rupture diagrams, simplified, 7 — Idrija wrench fault (⇆) and other faults, 8 — hydrogeologic units: (1) — Vrhnika-Cerknica block, (2) — Rakek-Cerknica imbricate structure, (3) — Javorniki-Snežnik block, (4) — Hrušica-block, (5) — Idrija-Žiri nappes area (all after S. BUSER 1965).

Sl. 6. *Hidrogeološke enote v osrednjem delu kraškega porečja Ljubljanice.* 1 — apnenec, 2 — nepropustne kamnine (skrilavci in drugo), 3 — dolomit, 4 — naplavine na kraških poljih in barju, 5 — lokacija merjenih ruptur, 6 — diagrami ruptur, poenostavljeni, 7 — Idrijski zmik (⇆) in drugi prelomi, 8 — hidrogeološke enote: (1) — Vrhniško-cerkniška gruda, (2) — Rakeško-cerkniška gruda, (3) — Javorniško-snežniška gruda, (4) — Hrušica, (5) — Idrijsko-žirovsko ozemlje pokrovov (vse po S. BUSERJU 1965).

Carboniferous, Permian and Lower Triassic rocks predomine; because of small nappe thickness they don't reach a great depth and don't influence to the underground discharge, which expires mostly in lower two nappes.

The central part of the region among Ljubljansko Barje, Logaško, Planinsko and Cerkniško polje belongs to autochthonous, which is broken to separate block, as for example Moor's basin with knobs, Vrhnika—Cerknica block, imbricated structure of Rakek—Cerknica, Hrušica and Javorniki—Snežnik blocks (S. BUSER 1965).

The Moor's basin is surrounded by NW—SE and NE—SW striked faults. In the basin's area several fault trenches and horsts exist, being the most important the fault trench north from the Ljubljanica springs area. It seems, that by this fault trench origin also former underground channels have been submerged and afterwards resedimented by Pleistocene sediments.

Vrhnika—Cerknica block is situated in the region of Logaška plateau among Vrhnika on north, and Planinsko and Cerkniško poljes on south. On eastern side near Borovnica fault, the eastern part of this block has raised the most, thus impermeable Carnian beds are found on the surface. Jurassic and Cretaceous limestone and dolomite beds are inclined towards west, without being folded. Questionable is Borovnica anticline structure, where the strata are inclined towards east because of faults. In addition the block is cut by several, differently directed faults.

Imbricated thrust of Rakek—Cerknica is composed by narrow belt of Upper Triassic and Jurassic dolomite between Rakek and Cerknica. On the south-western part the imbricated structure is overthrusted near Predjama fault to Cretaceous beds of Javorniki—Snežnik block, the structure itself being transformed to wide tectonic zone because of near lying Idrija fault. Thus it is representing the underground barrier for a part of waters flowing from Cerkniško jezero.

To the investigated region northern and eastern Hrušica part reach, formerly belonging to Vrhnika—Cerknica block, being interrupted by faults, specially by Idrija fault zone.

The northern part of Javorniki—Snežnik block is composed by Lower Cretaceous limestone, in southeastern part of Cerkniško polje also by Malmian limestone.

FAULTS

The investigated region is cut by several faults, which have been assessed by field work or well by photogeology. The most characteristic are the faults of NW—SE strike. The most important is Idrija fault, which is composing the fault zones by several parallel faults, specially among Kalce, Unec, Rakek and Cerknica. Near Idrija I. MLAKAR (1969) has assessed that the parts of nappes near Idrija fault are subhorizontally relatively displaced in the direction NW — SE, which can be considered as the important tectonic wrench-fault greatly contributing to geological and specially to hydrogeological structure of Ljubljanica river basin.

The dinaric faults zone has been followed also in crushed Upper Triassic dolomite and Jurassic Cretaceous limestones among Rovte, Logatec and further towards southeast to Logaška plateau. In Vrhnika vicinity also several NW —SE striked faults have been found in tectonically very crushed Jurassic limestone. The faults in the direction east-west have been found between Rovte and Idrija. The next fault of NE — SW strike is situated in the valley between Vrhnika and Logatec.

Mostly by aerial survey assessed faults in the direction north-south are situated in the region of Logaška plateau between Cerknica and Vrhnika, near Dolenji Logatec and in vicinity of Hotedršica.

Based on the field observations it can be concluded, that fault sets do not essentially influence to underground flows from Logaška plateau. The essential influence to these flows can be found in fissured limestone and dolomite. The ponors on northern border of Planinsko polje are bound to such, fissured limestone. The joints direction is mostly NE — SW. Similar conditions have been observed at karst Ljubljanica springs, where the water appears through water caves which had been developed more at joints than at faults.

TECTONIC PHASES

After recent informations (L. PLACER & J. ČAR 1975) the geologic structure of Idrija vicinity has been developed by Middle Triassic, early Tertiary and late Tertiary tectonic phases. Each particular phase is not temporally defined, because sure temporal indicators are missed. No doubt, that these phases have developed also in geologic structure of the whole Ljubljanica river basin.

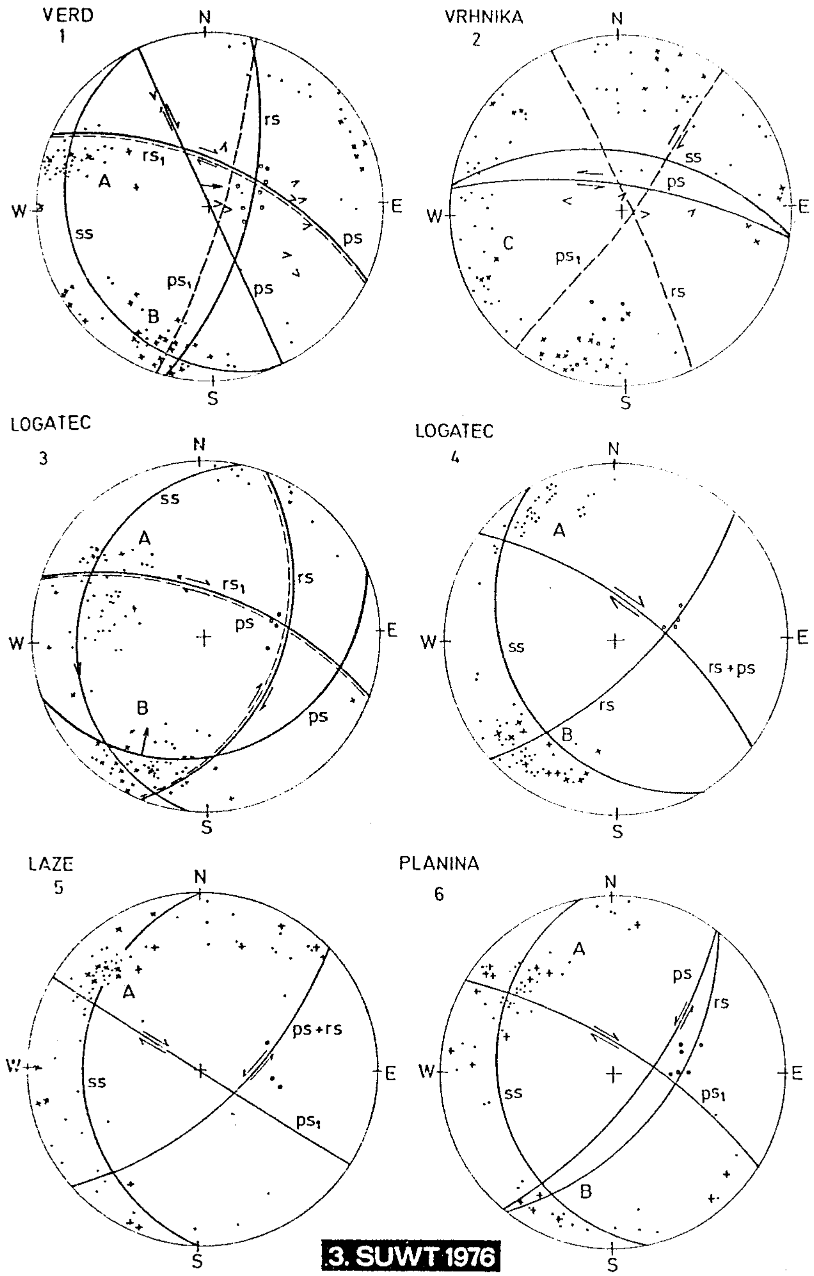
Middle Triassic phases are well seen in variegated lithology of the coresponding sediments. For early Tertiary phases (Pyrenean and others) the nappes origin between Logatec and Idrija and overthrusts between Planina and Cerknica are characteristic. At late Tertiary phases mostly horizontal movement of structural units have been asserted.

To cited phases also tectonic phases have to be added, which have influenced in Quaternary to formation of tectonic subsidence of Ljubljana Moor and of higher lying Karst. Some faults in Ljubljanica river basin are seismologically active still today.

THE MICROTECTONIC DATA

Several road and railway cutings in karst hinterland of Ljubljanica sprigs are offering in general good exposures about the crushed rocks. Unfortunate

Fig 7. *Rupture diagramms (1—6) with location survey point, the projection on lower half of Schmidt net is used.* O — bed plane pole, ● — joint plane pole, X — wrench- and other fault pole, > — direction of ± vertikal slip on the fault planes, ss — strike of bed planes, rs — strike of first joints set (A), rs₁ — strike of second, third joints set (B, C), ps — strike of wrench faults (dextral), ps₁ — strike of wrench faults (sinistral).



3. SUWT 1976

Fig. 7 — Sl. 7

only some cuts in Liassic and Dogger limestone near Vrhnika and in Lower Cretaceous limestone west from Logatec and alongside Planinsko polje have suited for microtectonic investigations. The data, gathered there, are shown in diagrams (Fig. 7) and explained in text.

The method of treated investigations has been based mostly on study of structural joints and faults. By this genetic method successful differentiation of joints and faults of different ages is possible, while the statistic treatment remains in secundary plan (P. BANKWITZ 1966, R. GOSPODARIČ 1973). By using this method for realized investigations we wanted to complete tectonic and hydrogeologic data from karst region among Vrhnika, Planina, Logatec and Cerknica.

In singular exposures the following joints and faults of different age have beed stated. In bedded Liassic limestone above Verd near Vrhnika, there are:

— older joint trending NNE—SSW (principal group),
— younger joints trending WNW—ESE,
— faults parallel to joints; dextral WNW—ESE striked wrench faults are prominent,
— vertically displaced blocks at older steep wrench faults.

In Dogger thick bedded oölitic limestone south from Vrhnika there are:
— folded beds in direction E—W,
— sinistral wrench faults, parallel to the bedding planes,
— normal faults in NNE—SSW strike with throw to the east.

In Lower Cretaceous limestone east from Logatec there are:
— older joints trending NNE—SSW,
— younger joints trending WNW—ESE,
— dextral wrench faults at joints trending NW—SE.

In Lower Cretaceous limestone at highway near Laze and at railway station Planina there are:
— joints trending NE—SW,
— prominent sinistral wrench faults trending NE—SW and less prominent dextral wrench faults trending NW—SE.

The singular diagrams are showing the principal strikes of beds, joints and faults planes, as they have been shown by some exposures of mesozoic limestone in investigated area. Two common diagrams (Fig. 8) are showing that the dextral wrenchfaults in NW — SE are the most prominent among faults, while among joints these in NE — SW. The wrench-faults have been asserted and developed from equally directed joints. Near Vrhnika at Moor's border NNW — SSE strike of fault is prevailing, showing the traces of the youngest vertical displacement. South from Vrhnika some joints are directed in this way, while the traces of vertical displacement at them are insignificant. Towards Planinsko polje two sets of joints (NW—SE, NE—SW) are developed in Lower Cretaceous limestone; at the polje's border there are only the joints in NE — SW, which are also changed into sinistral wrench-faults. Dextral wrench-faults in NW — SE are rare.

Besides data about orientation and sort of ruptures it is important for hydrological purposes to quote that although the joints are frequent it was nowhere stated that they cut the rocks in long sections. Everywhere they remain in beds and cut without interruption only two or three beds. Everywhere the short and steep joints are combined with gentle bed planes. Thus the water can percolate from the surface by degrees, more near connected gentle bed planes than near unconnected joints.

Regarding the crushed limestone near the surface the similar one can be expected deeper under the surface, as tectonic processes have changed the entire structural unit of Logatec plateau.

Similar hydrogeologic statements as for joints can be done also for faults. Tortuous and interrupted fault planes are more frequent than long continous faults. As mostly wrench-fault are in question, differently thick tectonic breccias zones are frequet. Such zone reaches the deepness where the underground water courses are flowing in the caves. More frequent wrench-faults in the direction NW — SE probably influence the orientation of ponor waters underground flow towards NW.

In the rocks above the Ljubljanica springs younger tectonic processes have vertically displaced the limestone blocks. The rocks have taken greater extent in horizontal position, while the intermediate steep faults have become hydrologically more active, pervious respectively. Probably the warm and 16.000 years old water in the spring Furlanove toplice (1.46) near Vrhnika (see the Chapt. 2.2.6) as well as the merging of water flows in karst (approximatively 1 km south from Moor's border) before their springs, are connected with this tectonic process, which is probably active still today, regarding the frequent earth-quakes in this region. In karst south from Moor this youngest

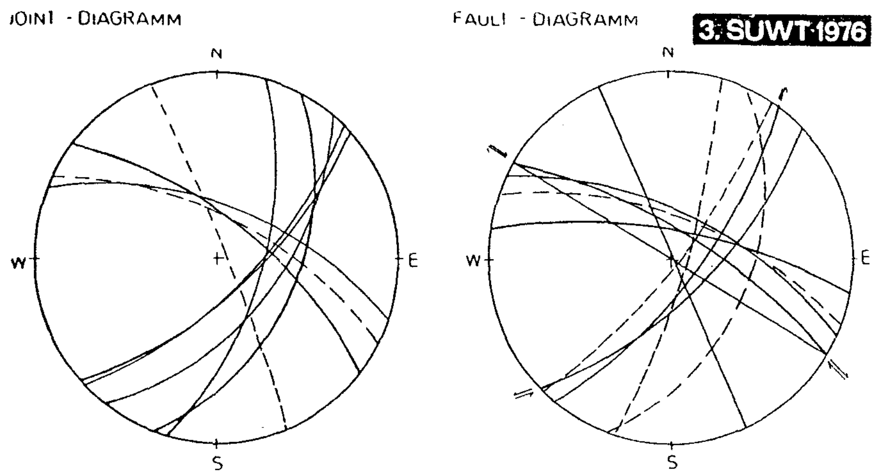


Fig. 8. Composed diagramms of joints sets and faults sets; note the uniform NW—SE and NE—SW directions at the Vrhnika—Cerknica block and the expressed direction NNW—SSE south of Vrhnika.

displacement has not been felt in such extent that its consequences could be seen in the ruptures of there denuded exposures. But the phenomenon of prominent NE — SW joints and wrench-fault at Planinsko polje has to be accentuated, being younger ponor caves at NE polje's border directed by them. These cavities join greater older channels, which direction is adjusted to northly directed beds.

HYDROGEOLOGIC CONDITIONS

The rocks, the rock complexes respectively, of Ljubljanica karst region can be divided after their permeability and porosity into four groups.

VERY PERMEABLE ROCKS

are represented by thin bedded, bedded and non bedded limestones and lime conglomerates of Mesozoic age. Fissured and karst porosity and unequal karstification, containing the karst underground water with unconnected water level, is significant.

The aquifers with karst porosity include the central region's part between Vrhnika and Planina. The permeability of these aquifers is extremely great in singular karstified zones, while it can be extremely small in the regions, which are not involved by the tectonics and karst corrosion. The underground water flow through the karstified zones is turbulent, without keeping the usual laws for underground water movements. The great discharges oscillation is characteristic for these zones, showing small retention ability. They represent good collectors.

FAIRLY PERMEABLE ROCKS

are bedded and non bedded dolomites and alteration of dolomite and limestone layers of Mesozoic age. The prevailing part of the region between Borovnica and Cerknica and between Logatec and Idrija but also between Planina and Cerknica is built by fairly permeable rocks. The fissured porosity prevails. There are few karstified rocks. The underground water flows through joints and pores laminary. These beds are acting double part, representing bad barriers towards limestones, and being collectors on the other side.

SLIGHTLY PERMEABLE TO IMPERMEABLE ROCKS

are represented by clastic deposits with carbonate rocks inliers of Permo-Carboniferous, Triassic, Cretaceous and Paleogene age with fissured porosity and unconnected underground water table. Different shales, silts and marls altering with other rocks are representing the impermeable layers — barriers in Borovnica valley, where they direct the karst waters runoff towards NW and to the region of Idrija—Žiri nappes, representing only surface barriers there.

DEPOSITS WITH INTERGRANULAR AND CAPILLARY POROSITY

are due to brook and river sediments (clay, silt, rubble, gravel) and to Moor's sediments (clay, organic clay, sand, silt) of Quaternary age. The permeability quickly alters in vertical and horizontal direction. Impermeable

Quarternary sediments on the Moor, up to 100 m thick, are presenting the barrier for karst water. Therefore it takes its numerous springs near Vrhnika, feeding the surface Ljubljanica river.

After lithologic structure and function several hydrogeological units can be distinguished according to tectonic structure of the region.

Regionally the Vrhnika—Cerknica block has enough simple structure. Its eastern part with impermeable Carnian beds and Upper Triassic dolomite presents hydrologic barrier. In central and western part, where the limestone predominates, the principal underground courses are distributed. Dolomite belt, situated in the central part of this unit, does not present any barrier for water flow.

The Rakek—Cerknica imbricated thrust with milonitic dolomite in central part presents partial or relative hydrogeologic barrier, to which well known karst bifurcation of Cerkniško polje is connected.

Snežnik—Javorniki massif and Hrušica plateau only partly reach the treated region. These two units are composed mostly by limestones, only in the area of Planinska gora Mt. they are built by dolomites, which are presenting hydrogeologic barrier.

Northwestern part of the treated region is presented by the nappe structure of Idrija—Žiri region. The dolomite of Idrija nappe and imbricated thrust of Zaplana are hanging barriers, because they are lying on permeable limestones, which render possible the water discharge under the dolomite nappe. In nappes of Idrija—Žiri region the blocks of permeable and impermeable rocks are altering. The latter are presenting only apparent, hanging barriers, respectively, which can be avoided in horizontal or in vertical direction by the water courses.

The impermeable barrier is presented also by Upper Triassic dolomite south from Podlipska valley. The dolomitic barrier near Podlipska valley and the barrier situated from Cerkniško polje towards Borovnica valley, are limiting the region of the most permeable, well karstified rocks near Vrhnika and force the karst waters to rise to the surface.

Translated by Maja KRANJC

GEOLOGIC SETTING OF THE PLANINSKO POLJE PONOR AREA

Summary

JOŽE ČAR

Planina polje and its wider surrounding is built by Upper Triassic dolomite, all Jurassic stratigraphic units und Lower and Upper Cretaceous lithological links.

The transition of Triassic to Jurassic is connected. Liassic developed mostly in dolomite. The inliers of organogenic and porous limestone with lithiotides (Fig. 2) couia be observed. Dogger and Lower Malm developed in white, granulated dolomite. Concordantly to Jurassic rocks bituminous Lower Cretaceous limestone with inliers of dark, granulated dolomite follow. Discordantly we can observe avove Lower Cretaceous lithological links basal rudist breccias, followed by differently light and almost white rudist Upper Cretaceous limestones. Paleocene and Eocene flysch sediments (Fig. 1, 2 and 3) can be found near Kališe.

In wider sense the majority of mapped region of the Planina polje ponor area belongs to *Hrušica nappe.* The other part belongs to *Snežnik thrust sheet* (L. Placer, 1981). The entire explored region is situated within the Idrija wrench-fault zone (Fig. 1).

Regarding the rock tectonic fracturing we can distinguish three zone species: *Fractured zones* are practically impermeable, characterized by tectonic clay, tectonic breccia and milonite "flour" and "grit". Partly and well permeable are *collapsed zones,* while *fissured zones* present an excellent permeable region thus in limestones as in dolomites. Several parallel fault zones on a region with well developed fractured zones contribute to diminishing of total region permeability (Fig. 1, 3 and 5).

Beside stated epirogenetic movements in the limit between Lower and Upper Cretaceous and in Upper Cretaceous on the treated region we know two types of tertiary tectonic deformations — older thrusting and younger subvertical movement (Fig. 1 and 3).

On flysch near Kališe we can observe the erosion remains of Upper Cretaceous limestone, belonging to *Koševnik interjacent slice* (L. Placer, 1981). Specially complicated structure was stated on Grahovše and near Ivanje selo, where *Ivanje selo and Unec over thrust units* were observed. The first is built by Upper Triassic dolomite and Liassic lithological links while the second by Upper Triassic stromatholite dolomite (Fig. 1).

The wide fault zone of Idrija wrench-fault is presented, beside dinarically directed Idrija wrench-fault, where the biggest relative displacement was observed, also by differently strong acompanying faults; it means *Grčarevec, Hotenjka, Lanski vrh, Babin dol, Mačkovec, Milavec and Grahovše faults* (Fig. 1).

While mapping, the *Podstene* and *Ravnik* fissured zones were eliminated (Fig. 1, 4 and 6).

An important part of Planina polje developed in Upper Triassic dolomite. Babin dol, region between Milavčevi ključi and Laze, a part of polje between Planina and Hasberg are built by Lower Cretaceous limestones. In te area of Unški log, Ključi and Loke different Jurassic lithological links can be observed.

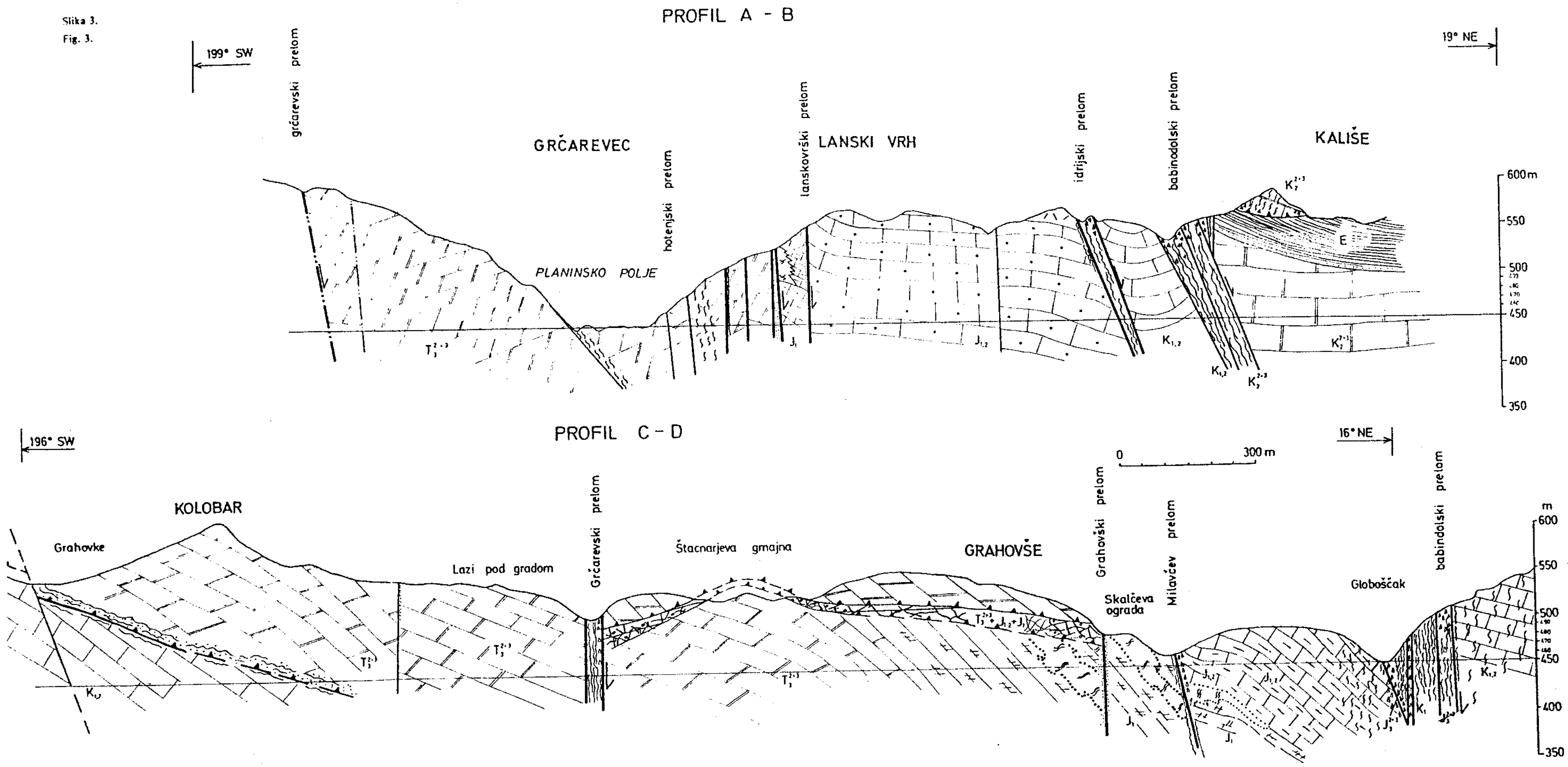
The data of mapping showed that ponors and swallow-holes on the border of Planina polje are genetically connected with fault zones and bed planes. In the case of Planina polje the both elements are interconnected, but fault zones strongly prevail. Because of strongly crushed rocks the majority of ponors is not accessible. Open ponors and bigger cave spaces can be expected mostly within less crushed rocks and between two fault zones. Cave system of Najdena jama clearly proves genetic connection between thin layered Lower Cretaceous limestones with non-resistant schist inliers and transition to granulated dolomite which even augments the permeability along bed planes. The other important cave system on the border of Planina polje — Logarček, is partly developed in tectonically less crushed block between two fissured zones and partly within these zones. Thin layered limestone rocks greatly influenced the Logarček genesis.

In limestones different doline shapes occur dependent upon tectonic setting. In thin layered limestones the dolines were found not having any direct connection with macroscopically stated tectonic elements. On mapped region the dolines on dolomite terrains are almost exclusively, directly or indirectly connected with fault zones.

Bigger collapsed dolines could be expected in fissured zones or in less damaged rocks. The collapsed dolines density is proportional to cavernosity of the area and dependent on tectonic setting.

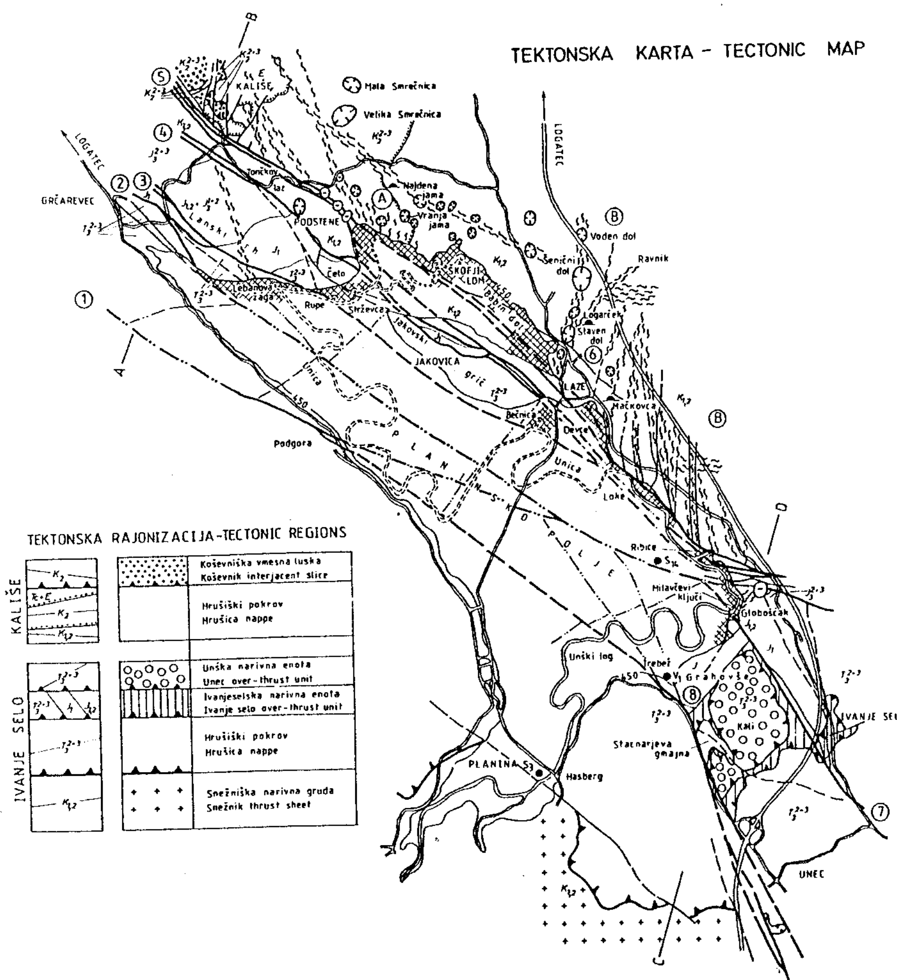
For the Planina polje ponor area two main predispositional elements for the development of the underground discharge directions are important: fissured systems and dip and strike of strata. Considering hydrologic bases both elements show main direction of the underground water flow. On the surface we can indirectly follow the general flow directions considering doline series in fissured zones and distribution of collapsed dolines.

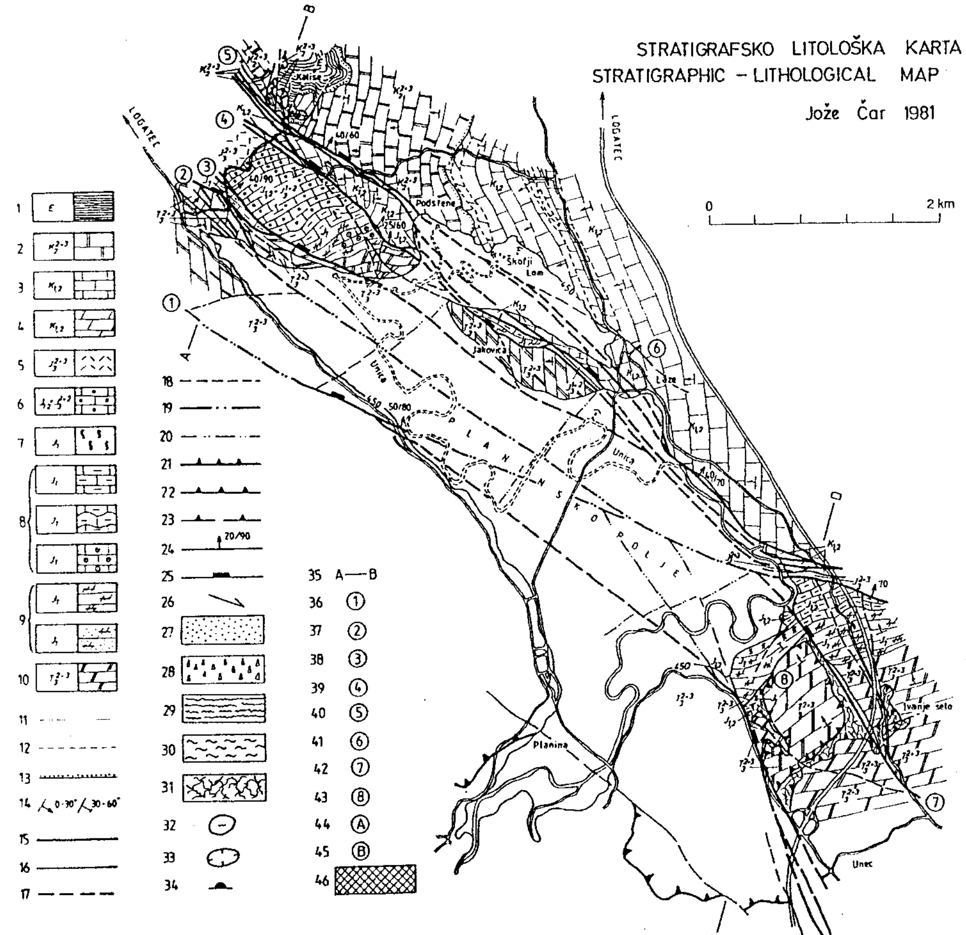
Slika 3.
Fig. 3.



EXPLANATIONS OF LEGEND ON FIGURES 1., 2. AND 3.

1. fliš — flysch
2. rudistni apnenec — rudist limestone
3. temnosivi mikritni apnenec, svetlosivi in beli organogeni apnenec — dark grey micritic limestone, light grey and white organogenic limestone
4. zrnati bituminozni dolomit — granulated bituminous dolomite
5. zrnati beli dolomit in beli apnenec — granulated white dolomite and white limestone
6. mikritni, oolitni in organogeni apnenec — micritic, oolithic and organogenic limestone
7. porozni dolomitizirani apnenec — porous dolomitized limestone
8. temnosivi mikritni, gomoljasti in oolitni apnenec — dark grey micritic, cobbled and oolithic limestone
9. bituminozni zrnati in peščeni dolomit — bituminous granulated and sandy dolomite
10. sivi, zrnati in stromatolitni dolomit — grey, granulated and stromatholitic dolomite
11. normalna stratigrafska ali litološka meja — normal stratigraphic or lithological margin
12. postopni litološki prehod — graded lithological transition
13. erozijska diskordanca — erosional discordance
14. smeri in vpadi plasti — strike and dip of strata
15. močan prelom — strong fault
16. šibek prelom — faint fault
17. močan prekrit prelom — strong covered fault
18. šibek prekrit prelom — faint covered fault
19. domnevni potek močnega preloma — supposed direction of strong fault
20. domnevni potek šibkega preloma — supposed direction of faint fault
21. meja pokrova — nappe boundary
22. meja vmesne luske ali neopredeljene narivne enote — boundary of interjacent slice of undefined thrust unit
23. prekrita meja vmesne luske ali neopredeljene narivne enote — covered boundary of interjacent slice or undefined thrust unit
24. smer in vpad prelomne ploskve — dip and strike of joint
25. relativno spuščen blok — relatively lowered block
26. smer vertikalne komponente premika — direction of vertical displacement component





Slika 1. Glej legendo na strani 105 (31)
Fig. 1. See Legend on Page 105 (31)

27. milonitna moka in zdrob — milonite "flour" and "grit"
28. tektonska breča — tectonic breccia
29. porušena cona — crushed zone
30. razpoklinska cona — fissured zone
31. tektonsko pretrto območje, kjer se menjavajo delno porušene ali milonitizirane različno stare kamenine — tectonically fractured area, where partly crushed or milonitic, differently old rocks alternate
32. vrtača v porušeni coni — doline in crushed zone
33. udornica — collapsed doline
34. vhod v jamo ali brezno — entrance to the cave or pothole
35. geološki profil — geologic profile
36. grčarevski prelom — Grčarevec fault
37. hotenjski prelom — Hotenjka fault
38. lanskovrški prelom — Lanski vrh fault
39. idrijski prelom — Idrija wrench fault
40. babindolski prelom — Babin dol fault
41. mačkovski prelom — Mačkovec fault
42. milavčev prelom — Milavec fault
43. grahovški prelom — Grahovec fault
44. podstensko razpoklinsko območje — Podstene fissured region
45. ravniško razpoklinsko območje — Ravnik fissured region
46. požiralno območje — ponor area

THE USE OF BIOLOGICAL INDICATORS FOR MONITORING AIR POLLUTION WITH MERCURY IN THE BROADER REGION OF IDRIJA

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Studies are being conducted in the broader region of Idrija, the location of rich mercury cinnabar ore deposits and the second largest mercury (Hg) mine in the world. In more than 500 years of uninterrupted operation, 13% of all the mercury produced in the world (approx. 150,000 t) was extracted and processed in the Idrija mine up to 1995. The mine still contains approximately the same share of world reserves, which will probably never be utilized. Because of the naturally and anthropogenically highly increased concentrations of mercury, geological and geographical particularities (even native elemental mercury) and the incredibly rich flora and fauna, this region is a true natural laboratory for numerous studies related to the transport and biotransformations of Hg in organisms and the environment. Since 1990, systematic sampling in the broader region of Idrija and analyses of mercury concentrations in organisms and environmental samples from the contaminated region and at control locations have been conducted within the scope of a complex, long-term environmental study aimed at evaluating the effects of geologically and anthropogenically increased Hg concentrations on the region. Measurements of concentration levels of total mercury and organic mercury compounds (Me-Hg-X and Me-Hg) were conducted on the samples. As selenium is known to play an antagonistic role in reducing the toxicity of mercury compounds, the selenium content was also measured in approx. 20 samples. Samples of some tissues and organs of roe deer (Capreolus capreolus L.) and mixed samples of their plant food, comprised of more than 40 plant species, as well as samples of soil were collected in the broader region of the Idrija mine and smeltery. The experimental part of the study deals primarily with problems related to monitoring Hg concentrations for longer periods of time and locating the spots where elemental Hg and ionic forms are transformed into the most toxic organic Hg compounds. As is evident from initial findings, there is a high probability that a substantial part of the transformations of Hg from ionic forms to MeHg on the level of terrestrial ecosystems may occur in the organisms of some herbivorous animals (Gnamuš et al. 1991, 1995, 1996). The objective of the study was to find the most suitable organisms in order to give an insight into the element's biogeochemical cycle, into biotransformation processes, the accumulation and transfer of mercury compounds into higher trophic levels of food chains, which, in the event of the danger of more serious contamination, would serve as an early warning of the threat to the Idrija population.

Samples of roe deer and their plant food as well as of soil were taken systematically (in the same regions), so that their Hg concentrations are directly comparable. On the basis of preliminary results and the distance from the main sources of contamination, the samples were classified into six regions (Figure 1: PS-1 to PS-6), each with an area of approx. 1.5 km², which covered the broader region of the Idrija basin. In order to confirm the role of the emission of Hg vapours from the smeltery in the contamination of the Idrija region with Hg, plant and soil samples intended for Hg analysis were also collected in the sampling region in the direct vicinity of the smeltery smokestack of the Idrija Mine (Figure 1: PS-Sm). Control regions of comparable size and suitable control indicator organisms were selected (Figure 2). The indicator organisms were selected so as to represent the links of various terrestrial food chains, which gives an insight into the biogeochemical Hg cycles and enables biotransformation processes of the element and helps to determine the intensity of accumulation and transfer of mercury compounds into higher trophic levels of the food chain. Also included in the complex ecological study of plant and animal bioindicators and soil samples from the broader Idrija region were regions where highly increased concentrations of Hg were determined in environmental samples and some

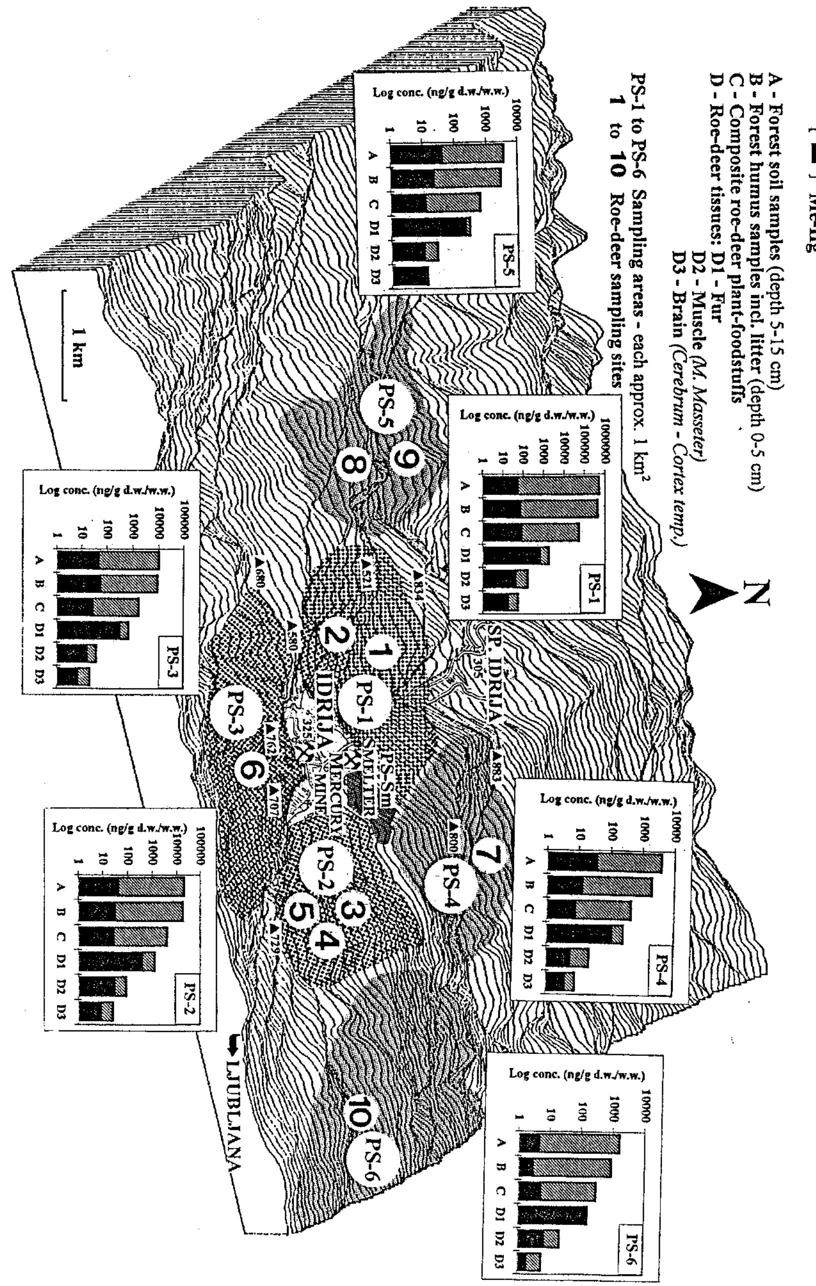


Figure 1. Sampling areas

organisms during the first extensive investigations conducted in the Idrija region in the early 70's by the Department of Nuclear Chemistry of the Jožef Stefan Institute (Byrne and Kosta, 1970, Byrne et al., 1971, Kosta et al., 1972, Stegnar et al., 1973 a,b, Kosta et al., 1974 a, b, c, 1975).

The present ecological investigations will also include a comparison of the above mentioned geologically and anthropogenically burdened mining region of Idrija with the area surrounding the former Podljubelj mercury mine, where the extraction of cinnabar ore was abandoned approx. one hundred years ago.

For the purpose of quantitatively determining Hg concentrations and speciation of the element, sensitive specific analytical techniques were used, including cold vapour atomic absorption spectrometry / atomic fluorescence spectrophotometry (CV-AAS / AFS) (Horvat et al., 1986, May et al., 1987, Liang and Bloom, 1993, Liang et al., 1994 a, b) and neutron activation analysis (NAA) (Byrne and Kosta, 1974). The accuracy of analytical results was varified using NRCC and IAEA standard reference materials. Special attention was devoted to the proper collection, preparation and storage of samples.

The results of studies conducted over several years are presented in Figure 1. The concentration levels of total mercury (T-Hg) and methylmercury compounds (Me-Hg) in samples from the Idrija region show some interesting mutual correlations and are highly dependent on the distance from the main sources of Hg emission. The total mercury and methylmercury concentrations in land and water ecosystems differ considerably. The same applies for the inorganic/organic Hg ratio and the boundaries of most polluted areas. Although water and terrestrial ecosystems together from a biocoenotic whole, they should be treated separately because of the above-mentioned findings and the different characteristics of the two types of ecosystems. The factors affecting both ecosystems and influencing the extent and intensity of contamination with Hg in one or the other medium are not directly comparable. As regards land ecosystems in the broader region of Idrija, it may be concluded that the extent and level of their contamination depends primarily on meteorological-atmospheric factors such as weather conditions, air pressure, humidity and temperature, on the direction, frequency and intensity of prevailing winds, as well as the exposure of individual areas to the said factors, i.e., the locations of individual sampling areas. Great differences were found in total Hg concentrations in land plant indicators and soil samples. In the broader mine smeltery area, the total Hg concentrations in plant samples were up to 200 times higher than those measured in sampling areas in the surroundings of Idrija and up to 500 times higher than those found at control locations. Even greater differences were found between total Hg concentrations in soil samples from the same locations. The Hg concentrations in the soil from the broader mine smeltery area were up to 500 times higher than those found in soil from the surroundings of Idrija and up to 1000 times higher than at the control locations, although there were no significant variations in sampling depth. Even higher concentrations were measured in the samples collected in the direct vicinity of the smeltery smokestack of the Idrija mine, where the total Hg concentrations in plant and soil samples were even up to 10,000 times higher than at the control locations.

Slightly smaller differences were found in animal indicators from the surroundings of contamination sources. The total Hg concentrations found were up to 100 times higher than in samples from the control locations. It should be noted, however, that none of the selected indicator animals had its habitat or territory in the direct vicinity of the mine-smeltery complex, where the highest concentrations in plant indicators and soil samples were found.

Due to the meteorological and geographical characteristics of the Idrija region, the contamination of its ecosystems with Hg is highly localized. Since large land predatory animals have much larger territories than their herbivorous prey, it has been observed that Hg concentrations in the tissues of predators mostly do not confirm the biomagnification effects characteristic of animals representing higher links in food chains. This fact strongly reduces their applicability as suitable bioindicators of intensive local contamination.

It is interesting to note that the concentrations of organic methylmercury compounds in all land samples diminish much more slowly with respect to their distance from the main sources of mercury emission than total Hg concentrations. In other words, the fraction of highly toxic Me-Hg-X compounds as a proportion of total Hg concentrations increases with distance. Similar characteristics were found in samples of water fauna collected downstream along the Idrija River (Kosta et al., 1974 a). The determination of excessively contami

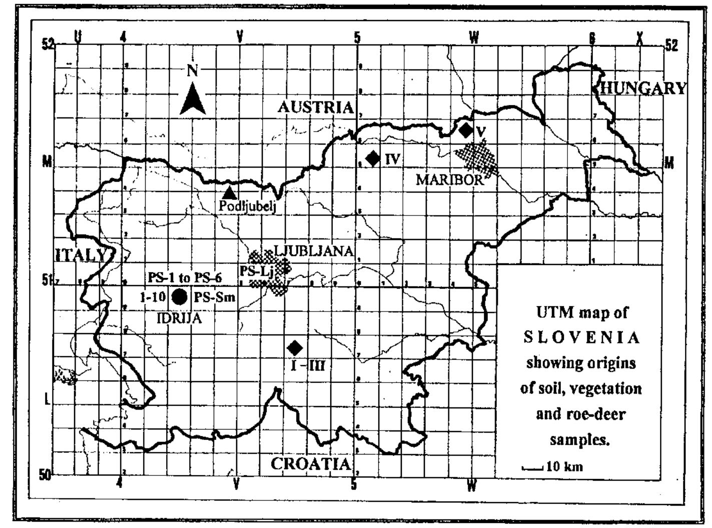


Figure 2. Map of Slovenia

nated areas in the water ecosystem of the River Idrijca, similar to those of land ecosystems, is a difficult task due to the hydrological characteristics of water currents. The influences of the contamination of the River Idrijca with Hg are even noticeable in the Gulf of Trieste in the Adriatic Sea. The level of Hg contamination can only be evaluated by comparing Hg concentrations in the river environment and the tributaries of the River Idrijca upstream from Idrija with those found downstream from the source of contamination. In past years the smelting plant operated only periodically and thus the emission of Hg into water is considerably smaller than in the past. Increased concentrations were observed mostly in bioindicators and sediments located far downstream, where hydrological factors caused the deposition of sediments, triggering biotransformation processes in aqueous biogeochemical cycles.

The results obtained show that, in contrast to the water ecosystem of the River Idrijica, where the center of contamination has moved some 10 km downstream, the contamination of land ecosystems surrounding Idrija is by far the most significant environmental problem in the Idrija basin itself. Terrestrila ecosystems are more sensitive than running waters to the enormous natural emission of volatile mercury from rocks in the broader surroundings of Idrija, which are a long-lasting process and continuously include additional quantities of Hg in the natural biogeochemical cycles of the element.

A comparison of the results of studies conducted in a recent five-year period with some data obtained in the 1970's show that Hg concentrations in living organisms still represent 3/4 of those found in the same or similar samples collected in the same region 20-25 years ago, when the mine operated with full capacity and up to 10 kg of mercury was emitted through the smeltery smokestack daily. The Hg concentrations measured in recent years in samples from Idrija and its surroundings were still 100 times to several 1000 times higher (depending on the sampling location and type of sample) than the concentrations of this metal in the same type of samples from the control locations. Analyses of samples collected in the period from 1990—1995 indicate that Hg concentrations do not change significantly from year to year. Only small variations were observed in the average annual Hg concentrations in plant soil samples from individual regions, probably due to varying weather conditions in the weeks before individual samplings. Therefore, the studies performed to date do not confirm the trend of reduction of Hg in plant and animal samples and samples from the Idrija region in recent years.

The reasons for the long-term persistence of increased Hg concentrations in the environment of the Idrija region are numerous, but the most crucial are probably the following:

1. The continuous natural emission of Hg — due to its high volatility and the presence of mercury—rich bedrock in the Idrija region, mercury is continuously being emitted from rocks in the form of elemental Hg vapour, which results in continuous natural contamination with Hg.

2. The scattered depots of gangue — the heritage of 500 years of human exploitation and processing of mercury ore— are an additional source of environmental pollution caused by inefficient ore-processing procedures used in the past.

3. The relief — because the basin is closed in on all sides and has numerous point sources of contamination (such as the mine facilities with ventilation shafts, the smeltery with its periodical Hg emissions, scattered depots of gangue with relatively high Hg content, certain areas with mercury — rich bedrock (Pront), and other continuous emissions resulting from the use of fossil fuel in households and for traffic purposes, elemental Hg vapour and other forms of Hg are often adsorbed on the surface of particulates in the air, which, under atmospheric influences, usually settle on surfaces close to sources of contamination before stronger winds manage to spread them over a broader area.

4. Biogeochemical transformation processes and accumulations along food chains — during the course of biogeochemical cycles mercury is transformed from its inorganic forms into much more toxic organic Hg compounds, predominantly into methylmercury compounds, which are very stable and accumulate in organisms and concentrate along food chains.

In view of the persistent influences of increased concentrations of mercury and its compounds on the environment, analyses of the concentrations of this heavy metal in the tissues of certain properly selected indicator animals may serve as a warning of the serious threat to the majority of other organisms, including humans. Comparisons of Hg and Se content in the tissues of some terrestrial animal indicators from highly contaminated areas and samples of control subjects with the results of post-mortem analyses of inhabitants of Idrija (Kosta et al. 1975, Zelenko, 1986) have confirmed that long exposure to Hg leads to the eventual exclusion of these two elements from normal biotransformation processes in most tissues of animals and humans.

The approach used in monitoring and evaluating the effects of Hg compounds on living organisms enables the quantitative determination of total Hg (and Se) content, the determination of the main chemical forms of Hg and their distribution in various tissues as indicators of extremely complicated processes which depend on:
— the chemical forms of the element itself and its oxidation state,
— the physical-chemical properties of compounds formed by a specific chemical form of Hg, and
— the transformation processes of individual forms of Hg taking place in organisms.

Each chemical form of Hg thus has a different metabolism and consequently a different toxic activity in the cells of organisms. Most often the ionic form of Hg, particulary Hg^{2+} represents the basis for the formation of various inorganic and Hg compounds, while the metabolism of compounds which it forms is to a great extent conditioned by the groups or radicals bound to the basic structure.

By selecting suitable animal groups for monitoring the accumulation of Hg compounds in living organisms and simultaneously monitoring concentrations in plant species and comparing them with the values obtained in environmental samples, it is possible to make an approximate estimate of the general level of exposure of a specific environment and to monitor the resulting load over a longer period of time, which is known as biomonitoring. Studies of the consequences of prolonged activity of increased Hg concentrations on organisms — exposure to elemental Hg^0 vapours, the influences of oxidized, inorganic ionic forms, the salts of mono — and di — valent mercury cations, and the activity of biologically and nonbiologically transformed inorganic and organic Hg compounds — have triggered countless new questions and are opening some interesting issues which as yet have remained uninvestigated in many aspects.

The results of systematic analyses of samples from Idrija and its surroundings performed with the objective of determining the effect of Hg on organisms and the environment several years after the abandonment of extensive mercury exploitation have shown that the concentrations of total mercury and in particular hazardous metylmercury compounds in biological samples are not as low as one would expect in view of the drastic reduction in mercury production in the Idrija mine in the past decade. Thus, the gradual shutdown of the mine and smeltery alone will not provide a short-term solution to the problem of mercury contamination of organisms and the environment in Idrija. The gap between reduced Hg emissions from the mining-processing complex and increased concentrations of Hg in the environment and living organisms could even last several decades, mostly as the consequence of bioaccumulation and biotransformation processes occurring in the biogeochemical cycles of surrounding ecosystems. More detailed knowledge of the actual state of the environment will therefore require numerous studies involving the continuous monitoring of related processes over longer periods, if we are to arrive at any significant conclusions.

The results and findings collected to date indicate that most of the selected biological indicators can be useful in monitoring the level of pollution with mercury both in Idrija and elsewhere in Europe — e.g. in the surroundings of the world's largest mercury mine in Almaden, Spain. Because of its broad concept, systematic and well-planned periodical sampling involving major land and water food chains can provide comprehensive information on the actual state of the environment.

The use of bioindicator organisms is of great importance because Hg concentrations in the tissues of plant and animal species provide data on biologically accessible forms of Hg, while the ambient monitoring of Hg concentrations in environmental samples such as air, soil and sediments reflects external exposure. Only a combination of both types of monitoring will provide a relatively accurate picture of the actual extent and intensity of contamination in a specific region. The proposed complex approach to pollution with Hg in the Idrija region allows for the monitoring of Hg concentration levels and the influences of various compounds of the element throughout the entire environmental biotope, as well as in individual plant and animal species, including humans. Such monitoring gives insight into the interdependence of numerous factors in a natural environment, yet it also opens many new questions which call for additional study.

The collected data may prove helpful in rehabilitation of the polluted environment in the Idrija region in the period up to the final shutdown of the Idrija Mercury Mine in 2006. As the Idrija mine was, until recently, one of three such plants still operating in the world, it offers a unique opportunity to investigate the effects of 500 years of intensive mining activities on the environment and to determine the qualitative and quantitative changes in the contamination of environmental ecosystems in the period of substantially reduced production in the late 80's and in the 90's, during the gradual shutdown of the mine in the period up to 2006, as well as after final shutdown of the mine and smeltery.

The environmental rehabilitation of the mine-smeltery area will first of all require the determination of current concentrations of the element and its compounds in environmental samples and organisms from the direct vicinity of the mining-processing complex and their comparison with naturally increased concentrations of Hg in the same types of samples from the broader Idrija region. Hg concentrations in the environment and biological species of the cinnabar region can never attain the low concentration levels characteristic of background areas.

As is the case in other research studies, the fact remains that the confirmation of findings and hypotheses drawn on the basis of this study will require extensive additional study. The long-term monitoring of air pollution by mercury through determining the concentration levels of the pollutant in environmental samples and the biological indicators representing links in food chains provides us with important information on the accumulation, transformation and interactions of the element and its compounds in organisms and their natural environment. Such an approach to the identification, study and solution of local pollution problems could, because of the complex nature of the results obtained, be used efficiently in the long — term monitoring of problems related to most other hazardous pollutants present in our environment.

2.6.3. Geological structure and hydrogeological position of the Hubelj spring (J. JANEŽ)

First hydrological data about the Hubelj spring were published by PUTICK (1928). Much later the studies about this spring were presented by HABIČ (1970, 1985, 1987). PLACER & ČAR (1974) explained the regional hydrogeological position of the Hubelj spring.

2.6.3.1. Extent and method of mapping

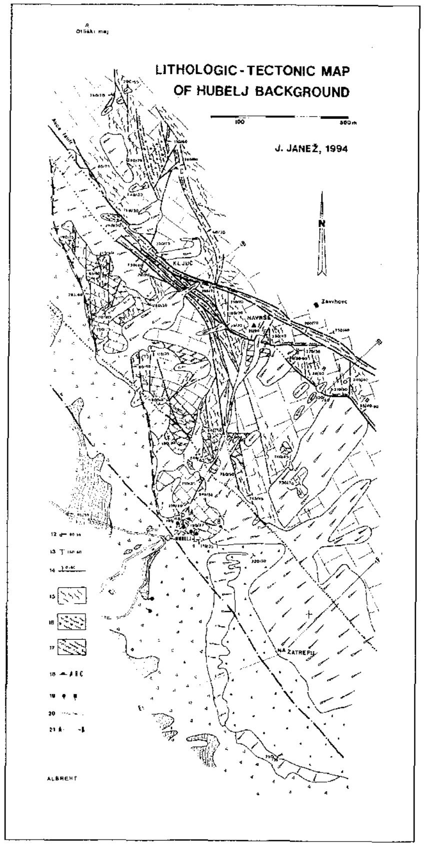


Fig. 2.24 Lithologic-tectonic map of Hubelj background: 1 - slope rubble, collapse block, screes; 2 - coarse-grained to block-like limestone slope breccia, younger, Quaternary; 3 - slope breccia, older, Quaternary; 4 - marlstone, siltstone and sandstone; flysch, Eocene; 5 - light brown limestone, usually grained, rarely thick, oolitic limestone, non-bedded, bedded to thick-bedded, Jurassic - Upper Lias and Dogger; 6 - pure grained dolomite, dolomitized oolitic limestone, bedded to thick-bedded or non-bedded - Jurassic - Upper Lias and Dogger; 7 - strong fault, visible and covered; 8 - weak fault, visible and covered; 9 - supposed fault; 10 - nappe border; 11 - lithological limit; 12 - dip and strike of inverse beds; 13 - dip and strike of normal beds; 14 - dip and strike of fault plane; 15 - fissure zone; 16 - broken zone; 17 - crushed zone; 18 - karst caves: A - Veliki Hubelj, B - Hubljeva Kuhinja, C - Otliška Jama; 19 - spring; 20 - surface water; 21 - cross-section.

Slightly more than 2 km² of the immediately background of the Hubelj spring was examined by a detailed geological mapping in 1994. The steep slope of the Trnovo plateau, including the edge of the plateau at the north-eastern side and the first outcrops of the Eocene flysch (impermeable edge of the karst aquifer) in the South and south-west were mapped (Fig. 2.24 and 2.25). The average incline of the terrain with numerous overhangs is over 45°. The altitude difference between the lowest (190 m) and the highest point (855 m) is 655 m.

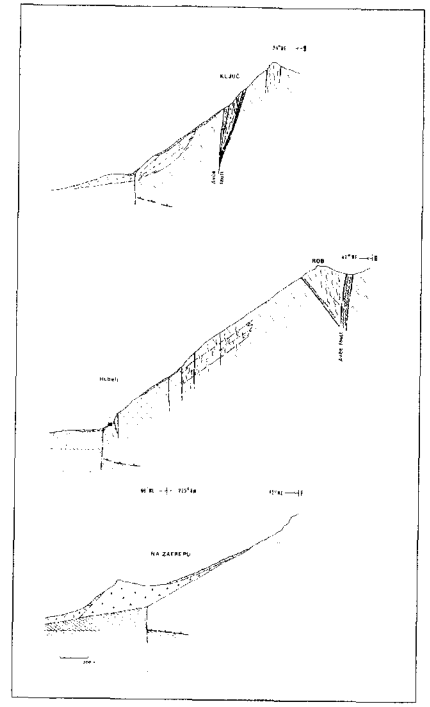


Fig. 2.25 Geological cross-sections near Hubelj.

The method of mapping of all outcrops is used. The scale of the map is 1:5000. The terrain is uncovered and the weathering zone is thin, so the identification of the bedrock is not difficult. Conditions on the flysch beds are rather different. Diluvium and weathering sediment cover the solid rocks and the outcrops are very rare. Besides, a thick layer of slope sediments - the Quaternary slope breccia, collapse blocks, slope rubbles and recent still active screes - covers a large part of Mesozoic and Tertiary bedrock and complicates the geological interpretation.

The objects of geological mapping were mainly the lithology of rocks, the character of the contact between different rock types and the tectonic conditions. The method of mapping and interpretation of the crushed zones character, introduced by PLACER (1982), was used. Further ČAR (1982) developed this method for geological mapping of karst. Crushed, broken and fissured zones can be distinguished on the base of the tectonic damage of the rock. ČAR & GOSPODARIČ (1988), JANEŽ & ČAR (1990) and ČAR & JANEŽ (1992) tested the method successfully for the explanation of geological, structural and hydrogeological position of karst springs on the edge of the Trnovo plateau and in Julian Alps. ŠEBELA & ČAR (1991) use this method to explain the evolution of some typical karst objects. It can also be applied for definition of hydrogeological background and protecting areas of karst springs (JANEŽ 1986).

Stratigraphic definition of the mapped lithologic units in respect to their age and position is based on the relevant literature (BUSER 1968, 1973).

2.6.3.2. Geological structure near the Hubelj spring

The mapped area consists of Jurassic, Eocene and Quaternary rocks. The slope of the Trnovo plateau between Otliški Maj, Navrše, Sinji Vrh and Hubelj spring is mainly built by light brown limestone. The limestone is usually grained, rarely thick. On several places it changes continuously into oolitic limestone. The limestone on Otliški Maj, Navrše and Rob is mostly non-bedded with rarely notable beds. Lower, in the spring area of Hubelj, the limestone beds are 40 cm to 2 m thick, some of them even 10 m.

The limestone is in several places dolomitized or recrystallized into a pure grained dolomite. Often, oolitic limestone changes into the oolitic dolomite. The transition from limestone to dolomite is progressive. Same as the limestone, the dolomite is bedded to thick-bedded or non-bedded.

Following the basic geological map, sheet Gorica (BUSER 1968; 1973), the carbonate rocks above the Hubelj spring are defined as Upper Jurassic (Oxfordian and Lower Kimmeridgian, $J_3^{1,2}$), but the beds are more likely of the Upper Lias and Dogger age ($J_{1,2}$ - brown and grey oolitic limestone, thick limestone, grained dolomite), due to their obvious lithological features.

The Eocene (Ypresian and Lower Lutetian ($E_{1,2}$)) flysch in the Vipava valley consists of changeable beds of marlstone, siltstone and sandstone. The beds are 5 cm to 30 cm thick. Flysch on the mapped area has no inliers of limestone breccia and calcarenites.

Slope breccia, collapse blocks, slope rubbles and recent still active screes present the Quaternary sediments. There are two types of breccia. The older breccia builds the overhang ridge and the flattened area south-eastern from the Hubelj spring. It is partly bedded, agglutinated and has greater share of rounded clasts. The younger breccia is more chaotic, coarse-grained and block like. The unconsolidated slope sediments, collapse blocks and slope rubbles are also of different age. The youngest are recent active screes, that can be found at the foot of the rocky overhangs of today still active tectonic zones.

The most expressive tectonic deformations are the result of the young fault tectonic activity. The main tectonic line is according to the interpretation found of BUSER (1968) the obvious continuation or one of the legs of the regional Avče-Dol fault. South-west under the Otliški Maj on the altitude of 500 m the visible fault plane (45/90) confines the limestone massive. The screes and slope rubbles accumulate on the south-western side of this plane. First outcrops of flysch can be found at the distance of 120 m. On location Ključ, southern from the Otlica cave, the fault zone is 50 to 70 m wide. At this point it divides into two legs that encircle the lens like peak of Navrše (857 m). The south-western fault plane builds the wall of Rob and the north-eastern leg represents 10 to 30 m wide broken zone. The valley southern from farm Zavrhovc was formed along this zone.

The course of the second fault line in the Dinaric direction is above the Hubelj spring at the altitude about 405 m. It is narrower, less marked and mostly covered with slope rubbles. It is displayed with a characteristic morphological step and with disposition of the connecting faults and crushed zones, those are interrupted at this line.

On the geological map (Fig. 2.24, and Fig. 2.25: geological cross sections) a supposed fault is drawn south-eastern from the springs of Hubelj. It is indicated by an outcrop of the tectonic breccia behind the abandoned army barracks near the Hubelj spring and by the geological and morphological conditions of the wider area.

Between these described tectonic lines there are the connecting crushed zones in the direction northwest-southeast. Their intensity varies from open wide fissured zones to crushed and broken zones. The broken zones are narrow and we present then on the geological map only with a line of a fault plane.

The beds of Jurassic limestone dip in general towards south-west. The dip angle changes between 30° and 60°. An evidently different dip direction can be established only at the western edge of the limestone, western and north-western above the Hubelj spring. In a narrow, up to 100 m wide belt at the contact between flysch and limestone, the dip direction turns towards south (strike 170° - 190°) and the dip angle reaches 75°. At the Hubelj spring the dip angle is a little lower (22° - 40°) and the beds dip towards south.

The character of the contact between the Mesozoic carbonate rocks of the Trnovo plateau and the flysch beds of the Vipava valley north-western from the mapped terrain is not problematic even though the contact is covered. This is undoubtedly a subvertical fault. But more unclear is the character of the contact between the carbonate rocks in the background of the Hubelj spring and the flysch beds south-western from the Avče-Dol fault on the section from Gosta Meja to the Hubelj spring, and also eastern from the Hubelj spring. On Gosta Meja location flysch undoubtedly lies under the thin layer of slope breccia at the altitude of 475 m, whereas near the Hubelj spring thus 235 m lower at the altitude of 240 m. The morphology of the terrain indicates, that towards east the upwarding of flysch is more gently. PLACER & ČAR (1974) described the structure as a depression, a synclinal bow of the Trnovo nappe thrust plane with the axis in the northeast-southwest direction. The change of a dip direction of the Jurassic beds from south-west to south and simultaneous rise of the dip angle at the contact with the flysch is also a proof for such explanation. The thrust character of the contact at the section between Gosta Meja and Hubelj spring is transformed with younger northwest-southeast and north-south oriented fault deformations.

2.6.3.3. Hydrogeological position of the Hubelj spring

It can be seen from the structural characteristics, that the Hubelj spring lies in the bottom of the expressive, narrow and deep structural depression in the thrust plane of the Trnovo nappe. Springs are situated in about 70 m wide belt at the altitudes from 240 to 265 m. Water generally comes from the bedplanes, widened by corrosion. The highest springs are in the eastern part and the altitudes of springs constantly decrease towards west. Above the permanent springs there are two caves. The "Veliki Hubelj" cave has the entrance at the altitude 280 m. Eastern from the spring there is the "Hubljeva Kuhinja" cave, which is not explored enough yet. The "Veliki Hubelj" cave is a horizontal cave - a temporary spring at high water - with permanent water inside also during draughts. The hydraulic gradient of the underground water behind the spring is very high (HABIČ 1985). The reason for such position of the water level is according to HABIČ (1970) the low permeability of the Jurassic limestone. PLACER & ČAR (1974) gave an additional interpretation on the basis of the flysch basement shape near the Hubelj spring. For the correct explanation also the influence of the neotectonic movements must be considered. The arrangement of the karst rooms and the position of the underground water indicate the neotectonic lifting of the block. The karst corrosion is slower than lifting and it is not able to fuse the underground flow. The opposite process was examined at the Lijak spring, which lies in the structural lowered block with the karst channel in the depth of 90 m (ČAR & GOSPODARIČ 1988). Naturally, there are no karst features formed above the spring Lijak because of the neotectonic lowering. In this case the term "immersed karst" has also the neotectonic meaning. Finally, the determination of the depth to the impermeable flysch basement of the karst aquifer would be very important for the final explanation of the hydrogeological structure of the Hubelj spring.

Čenčur Curk B.: Terenski eksperimentalni poligoni kot osnova pri študiju prenosa snovi v nezasičeni kraško-razpoklinski kamnini
Acta hydrotechnica 15/20 (1997), 111 str., Ljubljana

SUMMARY

INTRODUCTION

Over 40 % of the Slovenian territory is composed of carbonate rock, therefore aquifers in it are very important. The theory of solute transport in rock with intergranular porosity has been studied sufficiently, while fractured and karstified rock, especially the unsaturated zone, is quite poorly researched.

Field and laboratory experiments provide the basis for the study of solute transport. This paper focuses on field work. Experimental field sites can be used to discreticise and determine the parameters of karstified areas. Several such sites have been created in the world, but only to deposit radioactive waste into poorly permeable fractured igneous rock [Abelin et al., 1991a; 1991b; Cacas et al., 1990a; 1990b; 1990c; Guimera et al., 1997a; 1997b; Viitanen, 1994]. A few experiments have also been performed in permeable Slovenian karstic rock, but the objective of this research was only to establish the connection between pollutants from the surface and the underground space [Kogovšek, 1994; 1997]. The objective of this Master's thesis was to prepare methodological foundations for the selection and building of experimental field sites with respect to their purpose.

In studying natural processes it is very important to know the studied area well. For this reason, some basic terms, such as porosity, flow through porous media and solute transport in porous media are defined first.

THEORETICAL FOUNDATIONS OF FLOW AND SOLUTE TRANSPORT IN POROUS MEDIA

- **Porosity**

Porosity is a property of sediments or rock, which contain a certain share of empty spaces (Eq. 2.1) that are named pores or voids and are filled with a water solution and/or air. With respect to the morphology of voids, porosity can be divided into intergranular, fractured and channel types (Fig. 2.2, a, c, d). Channel porosity is formed by the dissolving of fractures, therefore the two types are frequently coexistent in the form of channel-fractured porosity (Fig. 2.2 e). In rocks with fractured porosity, the matrix can also be porous, which is named double porosity (Fig. 2.2.f).

Effective porosity, i.e. the flow of water (and consequently solute transport), is relevant for the permeability of rock (Eq. 2.2). Effective pores are only the interconnected ones those which are sufficiently large to allow gravitational flow of water.

In studying processes which take place in rocks, representative elementary volume (REV) should be mentioned as well. It is selected such that the physical and chemical properties of the rock are identical throughout it (Fig. 2.8 - REV1). By increasing the scale, an increasingly greater share of heterogeneous rock is included and a greater REV can be determined (Fig. 2.8 - REV2). The determination of REV is therefore related to the scale at which rock is studied. Questions appear of whether REV as defined here exists for karstified rock and whether it can be defined in a sensible manner, since the study of karstic rock would need to include the entire drainage structure of the karstic system.

- **Fluid flow in porous media**

Darcy's equation applies to laminar 1D flow of incompressible fluid in a homogeneous medium (Eq. 2.5, Fig. 2.9). In 3D space, this equation is a tensor equation and the permeability coefficient K is a tensor (Eq. 2.9). At high flow rates (turbulent flow in karstic rock), the tensor of turbulent (Reynolds stress) needs to be taken into account as well, and in the unsaturated zone the degree of rock saturation or the variation of the hydraulic permeability coefficient with water content in the soil.

In fractured rocks, water mainly flows via connected fractures and therefore depends on their geometry and properties (connections between fractures, density, aperture and surface roughness - Fig. 2.15). In the event of a high density of fractures and a large scale of studied area, a continuum (homogeneous space) can be assumed; otherwise, a discrete principle needs to be applied, in which flow through individual fractures and fracture network is described. In order to be able to do this, however, the spatial geometry of fractures needs to be known. In the unsaturated zone, large voids (fractures) are dry, while the surface of small pores remains covered with a water film (the matrix is partially saturated). Flow through fractures is therefore impeded due to the presence of air, except through smaller apertures which represent flow conduits (Fig. 2.18).

In general, two types of flows are present in karstic areas: channel flow with high flow rates, low residence times and a small degree of water mixing, and diffuse flow in the matrix, which acts as a storage, with slow water flow and long residence times (Fig. 2.22).

- **Solute transport in porous media**

The main solute transport processes are advection, dispersion and diffusion. Advection is solute transport due to the flow of water containing solutes. Dispersion is a process of mixing of fluids in a porous medium due to their different flow rates, as a result of friction, different pore sizes and different flow paths (Fig. 2.26), which results in the disturbance of an otherwise sharp pollutant front (Fig. 2.24). Diffusion is solute flow from an area with its higher concentration towards the area with a lower one (molecular level). The processes of diffusion and dispersion are difficult to distinguish and are therefore often studied together, as hydrodynamics dispersion.

The essential equation of solute transport is the advection-diffusion equation (Eq. 2.42), which takes into account advection, hydrodynamic dispersion and biochemical processes: dissolving/precipitation, sorption, ion exchange, oxidation/reduction and kinetic reactions. In the unsaturated zone, moisture content Θ must be taken into account as well.

All of the above considerations also apply to fractured rock. The causes of hydrodynamic dispersion include diffusion into the matrix and different flow rates due to fracture surface roughness and friction, different fracture lengths and fracture densities, and mixing at fracture intersections (Figs 2.28 and 2.30).

In karstic rock, sorption and filtration capacities are very low due to rapid transport, therefore residence times are short and decomposition is less effective. On the other hand, conditions favouring oxidation frequently occur, which can lower the concentration of certain pollutants. Due to their alkalinity, karstic areas are less sensitive to acid rain (Fig. 2.31).

- **Modelling of flow and solute transport**

The selection of the study scale is of great importance for the modelling of processes which take place in karstified rock (Fig. 2.34). Discrete models of individual fractures and parallel fractures (Fig. 2.33) are more suitable for detailed studies at small scales. For medium size study areas, fracture network models are used and for regional studies continuum models and multicontinuum models (double porosity), in which the REV can be defined.

STUDY OF FLOW AND SOLUTE TRANSPORT

The heterogeneity of karstified rocks introduces a problem of scale. The REV practically cannot be defined in karstic rocks, since one would need to study a very wide area or even the entire system with both karstic conduits and fractures. With such a large REV, only general relationships between processes which take place in rock can be given.

Due to the heterogeneity, parameters like hydraulic permeability and hydrodynamic dispersion depend on the scale. At the laboratory level it is thus possible to comprise only pores and microfractures, macrofractures at the level of drillholes, and the network of karstic conduits at the regional level (Fig. 3.1).

Hydrogeological parameters can be determined in a laboratory or in the field. Methods used are direct (structural and geomorphologic research, surface and cave mapping, coredrilling) or indirect (geophysics, geochemistry, tracer tests). Table 3.1 gives a review of methods used in the study of karstic aquifers.

Every interruption, i.e. discontinuity, in the rock is important for water flow and solute transport. Discontinuities include: fractures, faults, stratifications, stylolites, schistosities and foliations. Detailed studies of karstified rock must therefore include the determination of fracture parameters: orientation (Fig. 3.2), density (spacing) (Fig. 3.3), length, roughness (Fig. 3.4), wall strength, aperture and filling (Fig. 3.5 b, c), seepage, number of sets and block size (Fig. 3.6).

Structural elements can be determined in various ways: by standard fracture mapping, by photogravimetry or according to Louis (1972) and Eraso (Veselič & Čenčur Curk, 1996). Eraso's method predicts the most frequent directions of water flow and is based on microtectonic analysis. In Louis' method, the description of fractures is made first with regard to parameters (Tab. 3.2). Hydraulically effective fractures are obtained using two weights (presence of water and fracture aperture).

EXPERIMENTAL FIELD SITES

In recent years, numerous detailed research studies have been carried out with the objective of studying the safety of depositing radioactive waste into rock and in order to be able to determine "safe" rocks. Table 4.1 presents a few sites at which research mainly focused on the understanding of the hydromechanics of rocks, solute transport and heat transfer in fractured igneous rocks. In addition to igneous rocks, salt mines are also of interest for the deposition of radioactive waste.

Experimental field sites are a very important tool for detailed studies of flow and solute transport in karstified rocks. Possible locations for such sites include mine tunnels, artificial tunnels, karstic caves and quarries. For natural caves, their specific features need to be taken into account, since they were created along the most permeable conduits and are therefore predetermined, while in artificial tunnels the stress-strain state of rock in the vicinity of the tunnel changes as a result of digging.

The design of experimental field sites is presented in Table 4.2. When an experimental field site is selected, an accurate survey of the surface and underground structures is first performed. The basic characteristics of rock at the site must be determined first. This is followed by petrographic and structural analyses of the rock in order to determine fracture parameters. A group of experiments are performed next: agrohydrological measurements and tracer test. As an upgrading (or independently), geophysical and geochemical methods can be performed - isotope methods (water balance measurements).

EXAMPLES OF EXPERIMENTAL FIELD SITES

Three experimental field sites were selected within the framework of the study of solute transport in fractured and karstified rock. One site was located at the Pb-Zn Mine in Mežica (Fig. 5.1), since it was desired to conduct its comparison with other experimental field sites for the study of fractured igneous rocks elsewhere in the world. The main sources of pollution in Slovenia are located on the Earth's surface, therefore two additional experimental field sites were selected in order to study the relationship between the surface and the underground layers. The following factors were used for site selection: the type of rock, thickness of the surface layer, presence of outcrop on the surface, artificial tunnels and access. On this basis, tunnels at Unška Koliševka (Fig. 5.2) and Sinji Vrh (Fig. 5.3) were selected.

Of the above-mentioned three experimental field sites at which the first three phases of site design were completed (Table 4.2), only one was used for further research and measurements. We were above all interested in processes taking place in the unsaturated zone immediately below the surface, since (as was mentioned above) the main sources of pollution in Slovenia are located on the surface and the solute transport through the unsaturated zone of karstified rock is quite unresearched. The Mežica mine was therefore eliminated as an option, even though it would be very interesting to perform experiments at this site, in more permeable carbonate rocks, in order to enable their comparison with studies carried out in fractured igneous rocks. The remaining two sites were located at Unška Koliševka and at Sinji Vrh. At the Sinji Vrh site the surface is covered both by meadows and by sparse karstic forests, while at Unška Koliševka the entire surface is covered in forest. In addition, tunnels at Unška Koliševka are very branched and frequently visited; it would therefore be difficult to close them to prevent visitors from destroying the water collection structures. For all of the stated reasons, the Sinji Vrh site was selected.

Due to the outcrop on the surface above the tunnel, a segment around the intersection of tunnels was selected as the experimental site (Fig. 5.4). The height difference between the outcrop and tunnel ceiling ranged from 10 to 13 m. The surface above the tunnel intersection is covered by a meadow and a forest towards the south-west.

Statistical structural analyses according to Eraso and according to Louis were performed first. Eraso's method predicts the most frequent directions of water flow and is based on microtectonic analysis. In using Louis' method, the description of fractures is made first with regard to fracture parameters. Hydraulically effective fractures are obtained using two weights, the presence of water and fracture aperture.

The area was mapped in detail at a 1: 20 scale. The majority of discontinuities in the tunnel were subvertical, with a dolomitised fault zone at the intersection (Fig. 5.5), while the angle of inclination of the layers was less steep. The locations of drillholes (Figs. 5.4 and 5.8) for injecting the tracer in tracer tests were determined on the basis of produced profiles (Figs. 5.6 and 5.7). Drillholes were made on the surface through the humus layer and for further 10-20 cm into the rock. A plastic tube was inserted in order to prevent their collapse and chemical reactions between the injection tracer and the soil. A special structure with a total length of 49 m (Fig. 5.9) was made in order to collect water seeping from tunnel ceilings.

A preliminary experiment was carried out first in order to acquire information on the main properties of flow through the rock. To simplify detection, NaCl was used as a tracer. Water seeping from the tunnel ceiling was collected in the tunnel and the basic parameters were measured. Chemical analyses were performed at the laboratory of the Institute of Mining, Geology and the Environment. Soon after injecting, the tracer appeared in two places - in the fourth and fifth segments. The tracer test showed a single main flow conduit. Naturally, this result was not sufficient in order to determine flows through the fractured system in general.

The objective of research was to establish flow characteristics in the entire rock mass, therefore additional drillholes were made and another preliminary experiment was conducted. Again, NaCl was used as a tracer. Now it was detected in a greater number of structure segments (in addition to segments 4 and 5, tracer was also found in segments 6, 8, 9, 10, 11, 13, 15 and 25).

Both preliminary experiments were carried out under different hydrological conditions: the first one in the saturated zone and the second one in the unsaturated zone. The results of both preliminary experiments confirmed that in the unsaturated zone water first fills the voids and then flow may occur. Flow behaviour was thus determined and the appropriateness of drillhole locations was confirmed, so the main experiment of longer duration could be conducted with the use of several different tracers.

CONCLUSIONS

Solute transport is determined by flow conditions and flow by rock properties, above all porosity, more accurately its spatial distribution and the characteristics of voids. The flow of water through fractured and karstified rock therefore differs to a large extent from its flow through other types of rock. In studying solute transport, rock porosity and the properties of flow through the rock must first be studied well; only then can solute transport, (i.e. pollution problems -- from the applicative viewpoint) be solved. Flow and solute transport through fractured rocks mainly take place via connected fractures of larger or smaller apertures. However, the influence of diffusion into the rock matrix and solute sorption onto matrix grains and microfractures must not be neglected. Flow and solute transport through karstic rock is performed via flow conduits, which were formed by the dissolving of the fracture network. In nature, the two types of porosity are usually coexistent -- in karstified rocks. In such rocks the variability of flow and solute transport through karstic conduits, fractures and rock matrix must be taken into account. For this reason a term triple (or in the case of karstified rocks without karstic conduits, double) porosity is used.

Karstified rock has a complicated geometrical structure with complex hydraulic, mechanical, thermal and chemical processes which are closely interrelated. Attempts are made to illustrate natural processes by mathematical models (simplification), which can yield much data and study different situations related to a certain problem. Prior to mathematical modelling, good knowledge of the physical nature of processes to be simulated is required (conceptual models) and representative input data must be available; that can be obtained on experimental field sites. Two concepts for the study or modelling of karstified rocks exist. The continuum approach assumes that at a certain scale the rock included in the study is homogeneous and can be presented as a continuum with the REV, while its parameters are average values of the REV. Due to the heterogeneity of karstified rock, such rock is difficult to describe using the REV, since it would be very large. For this reason, karstic conduits and main fractures are studied explicitly (discontinuum approach). But this means that more accurate data is required and the fracture geometry and parameters need to be known both for the surface and for underground areas (experimental field sites). In addition, such a model can be built only at a small scale.

The study scale is important for the selection of the model. The continuum approach is suitable for studies performed at large scales, in which rock is deemed to be homogenous and represents a single continuum or several continuums. One should be aware that this is only an approximation, but in practice the data on rock structure is often lacking, and this approach is the only alternative in the modelling and parameter determination. Discontinuum models (individual fracture, parallel fracture and fracture network models) are used in detailed studies of flow and solute transport in karstified rock. Available data must be taken into account in the selection of the model, but the reverse way is more optimal: a model type is selected first and the plan of studies is designed later.

Due to the heterogeneity of karstified rock, the parameters of flow and solute transport (porosity, permeability, dispersion rate, etc.) depend on the scale used. Hydrodynamic dispersion increases logarithmically with an increase in migration distance, which creates several doubts as to the use of the standard concept of dispersion (Fick's law) in karstified rock, which takes into account constant dispersion rate, independently of the flow path.

All over the world, a large number of studies in karstified rock were carried out at the regional scale, such that many karstic areas are well known as a whole. However, in such research it is possible to give only general relationships between processes taking place in rock, while it was our objective to study the processes of flow and solute transport at small scales. Detailed study of these processes was performed at an experimental field site, where (vertical) flow behaviour and solute transport through the unsaturated zone of the rock - aquifer - can be determined, as well as the influence of the pedological horizon on solute transport. Geodetic survey is first performed at the site (Table 4.2) and then petrographical analysis of the rock is carried out. This is followed by establishing of the detailed rock structure on the basis of which tracer experiments are planned. The geophysical and geochemical isotope methods can serve for a better understanding of processes or as independent methods. Each set of studies requires special instruments.

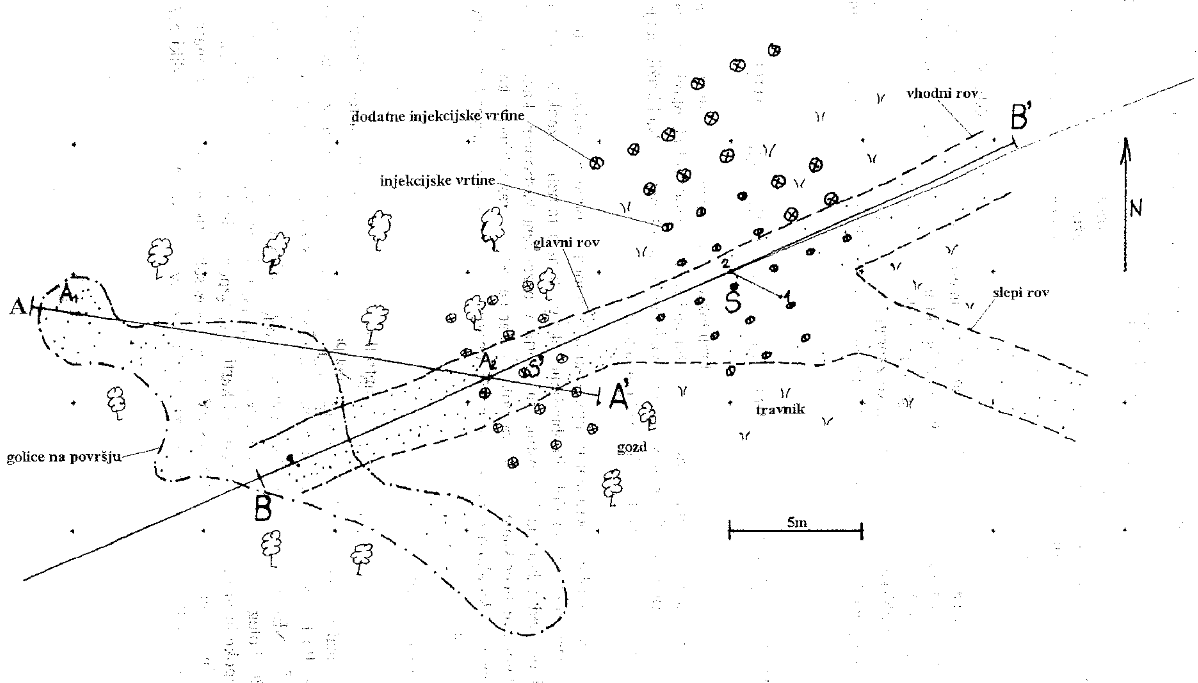
For a detailed study of processes and discontinuum modelling, small scale data is required, and it is obtained at experimental field sites. Fractures and conduits play the crucial role for flow and solute transport, therefore detailed structural analysis of rock at such sites is very important. In studying rock at experimental field sites, non-destructive methods must be used, or structure would be disturbed and incorrect results would be obtained. Experimental field sites are intended for theoretical studies of processes and the testing of methods suitable for their study. Better knowledge of flow and solute transport would enable the determination of protected water source areas or quicker interventions in the case of ecological disasters (e.g. spillage and penetration of hydrocarbons in the underground layers).

The first three phases of designing experimental field sites and preliminary tracer tests were performed at the Sinji Vrh site (Table 4.2). Tracer tests were supposed to be carried out at least three times: firstly, a preliminary test to obtain the initial information on water flow followed by two tests in different climatic conditions (during droughts and during rainy periods). Structural analyses were performed according to Eraso and Louis. The first method is customarily used more for detailed structural studies of rock, and the second one for regional determination of the most frequent directions of water drainage. The Sinji Vrh site was intended for the testing of the agreement between the two methods and establishing the suitability of Eraso's method for small scale studies. The two methods showed satisfactory agreement. In addition, standard mapping of fractures was performed and a map was produced at a 1: 20 scale. Two preliminary tracer tests with NaCl were also carried out at this site. The first one showed only one main flow conduit, i.e. a fault in front of the intersection of tunnels (segments 4 and 5; Fig. 5.5). However, this result was not satisfactory for flow determination in the fracture system in general. One should be aware that such direct routes exist in karstic areas and are very important for the transport of pollutants, since any interventions are almost impossible in such cases. The performed experiment is the first approximation of flow conditions at the site. In addition to this conduit, it was desired to determine flow characteristics in the entire fractured rock mass (longer residence times) at the site. For this reason, another preliminary experiment was carried out, which was more successful and showed a more disperse flow through the rock, and that is more characteristic of fractured rocks in general.

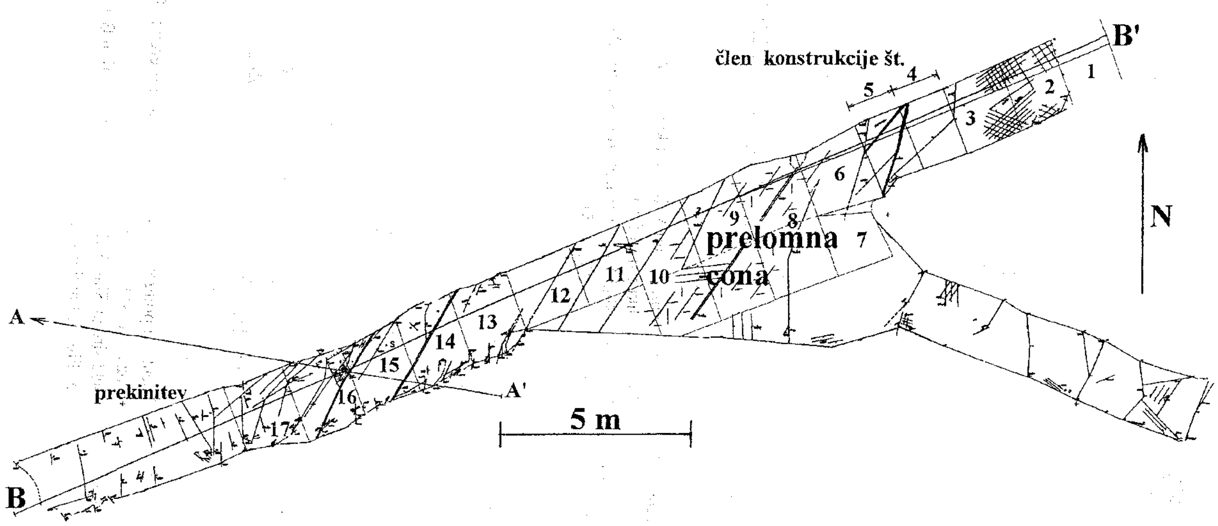
Many questions remain open for further work: the use of sites for applicative studies; the influence of pedological horizon on solute transport; selection of a geophysical method suitable for the study of underground structures and comparisons of different modelling concepts.

The final objective of the project was to establish which model best describes flow and solute transport and to compare the results obtained by discrete models and continuum models. However, many researchers believe that it has been proven in karstified rocks and above all in karstic rocks that the standard hydrogeological interpretation by experts is often more reliable than model calculations. According to Quinlan (1990), a well prepared, accurately performed and correctly interpreted tracer test is worth 1000 expert opinions or 10 numerical simulations of processes which take place in karstic rocks. I believe that the reason for their opinion lies in a pronounced heterogeneity and complexity of the karstified system, which makes a correct and accurate discretisation of space as the basis for discrete models almost impossible. On the other hand, simple continuum models provide only a general picture of the system, which can only be obtained through experiments. All this holds true when studying momentary states of processes, while for the prediction of processes modelling cannot be avoided.

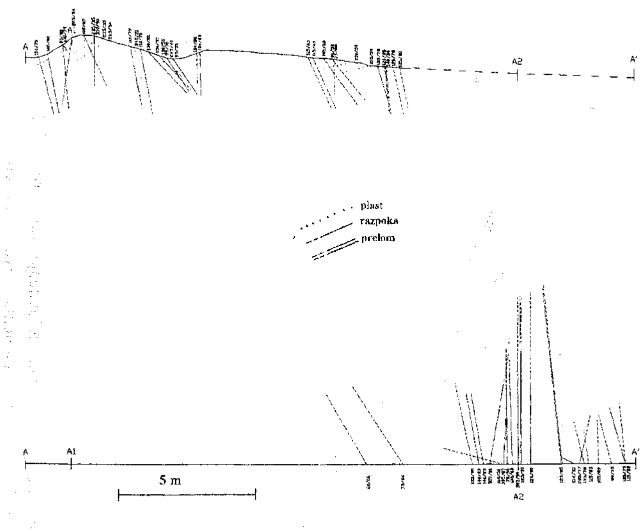
Perhaps, in the far future, a roboroach developed by Japanese scientists, which could function as a video camera in drillholes, will contribute to the discretisation of space. In this manner it would be possible to determine the position of spatial discontinuities and their properties (width, roughness and connections between fractures).



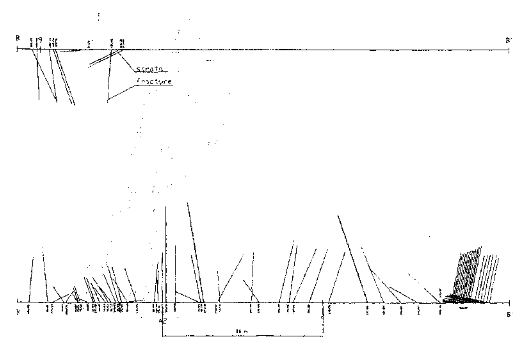
Slika 5.4 Terenski eksperimentalni poligon Sinji Vrh - situacija golic na površini in rovov pod površino.
Figure 5.4 Experimental field site at Sinji Vrh - outcrops and tunnels.



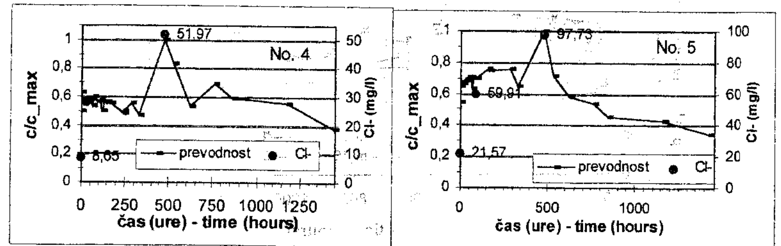
Slika 5.5 Terenski eksperimentalni poligon Sinji Vrh - prikaz razpok v rovu in potek konstrukcije za lovljenje vode, pronicajoče iz stropa.
Figure 5.5 Experimental field site at Sinji Vrh - ground plan of the fractures in the tunnel and segments of water collecting construction.



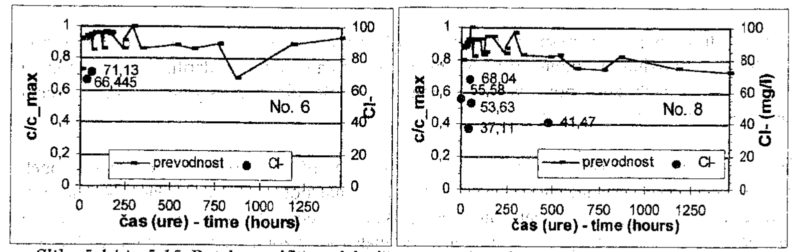
Slika 5.6 Terenski eksperimentalni poligon Sinji Vrh - vertikalni prerez A-A' (položaj glej sliki 5.4 in 5.5).
Figure 5.6 Experimental field site at Sinji Vrh - vertical cross section A-A' (see Fig. 5.4 and Fig. 5.5).



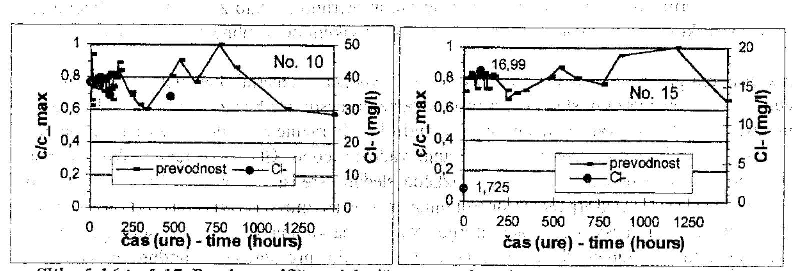
Slika 5.7 Terenski eksperimentalni poligon Sinji Vrh - vertikalni prerez B-B' (položaj glej sliki 5.4 in 5.5).
Figure 5.7 Experimental field site at Sinji Vrh - vertical cross section B-B' (see Fig. 5.4 and Fig. 5.5).



Slika 5.12 in 5.13 Potek specifične električne prevodnosti (normirane glede na največjo vrednost) in vsebnosti Cl^- ionov v vzorcih vode na odvzemnem mestu člena št. 4 in 5.
Figure 5.12 and 5.13 Specific el. conductivities and Cl^- ion contents in segment No. 4 and 5.



Slika 5.14 in 5.15 Potek specifične električne prevodnosti (normirane glede na največjo vrednost) in vsebnosti Cl^- ionov v vzorcih vode na odvzemnem mestu člena št. 6 in 8.
Figure 5.14 and 5.15 Specific el. conductivities and Cl^- ion contents in segment No. 6 and 8.



Slika 5.16 in 5.17 Potek specifične električne prevodnosti (normirane glede na največjo vrednost) in vsebnosti Cl^- ionov v vzorcih vode na odvzemnem mestu člena št. 10 in 15.
Figure 5.16 and 5.17 Specific el. conductivities and Cl^- ion contents in segment No. 10 and 15.

MIHEVC, A. & PETRIČ, M. (1997): Field Guide of Karst in Slovenia - 7th International
..racing. – Acta Carsologica Supplementum, 26 (1): 1-98, 52 Abb.; Ljubljana.

Škocjanske Jame Caves

Škocjanske Jame are the most important underground phenomenon of Kras, of Slovenia and also one of the finest caves in the world.

In the sense of geotectonical distribution the karst of Škocjanske Jame belongs to Outer Dinarids making part of Dinaric carbonate platform. The oldest rocks in the territory are Upper Cretaceous bedded limestones alternating with rudistid limestones. In these rocks the majority of underground features of Škocjanske Jame developed. The upper part of Škocjanske Jame geological column consists of different Paleocene foraminiferal limestones.

They are a system of ponor caves at the contact of impermeable (flysch) and carbonate rocks, made by the Reka sinking river. After reaching carbonate terrain the Reka river incises in a canyon, about 2 km long, and finally, under 100 m high, vertical limestone wall on top of which lies the village of Škocjan (which gave the name to the caves), disappears underground. A sort of dry valleys and a set of collapsed dolines around the actual swallow-hole indicate that during the evolution the sinking point of the river moved. After running under the village of Škocjan the Reka reappears in the bottom of two collapsed dolines, Mala Dolina and Velika Dolina. In the western slope of Velika Dolina (160 m high wall) the Reka finally disappears underground. During long geomorphologic history the Reka downcut extremely vast underground passages, including an underground gorge, 100 m deep. After 2 km approx. the main passage ends (for a man) by a siphon (dived through in 1991). Beyond the siphon the passage of huge dimensions continues towards Kačna Jama, about 1,5 km far. In front of siphon lies the chamber Martelova dvorana. Its biggest dimensions being 308 x 123 x 146 m and calculated volume of 2,1 million m^3 it ranges among the biggest underground chambers in the world.

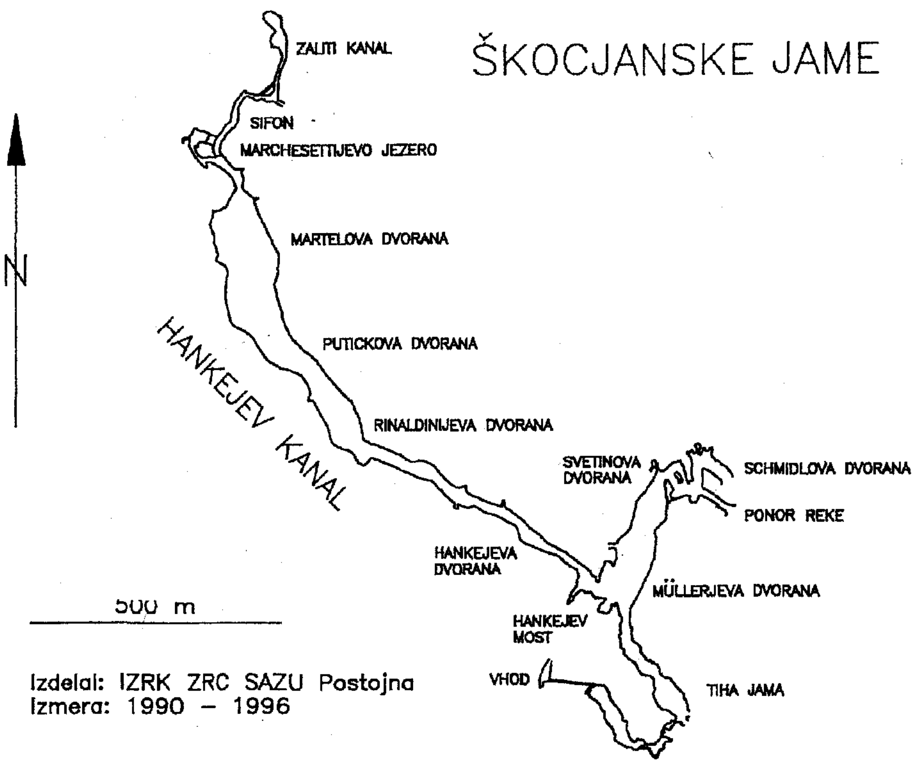


Fig. 1.9: Plan of Škocjanske Jame.

The Reka river water level substantially varies in the cave, reaching the level over 100 m above the siphon.

Škocjanske Jame is a very important cave from cultural and technical point of view. There are the rests from Mesolithic Period on. Specially important are Tominčeva Jama, as the largest cave burial site of all the Eastern Alps and nearby Jama na Prevali, Iron Age cult site with important remains of weapons. From the last century the remains of pathways in Alpine style are preserved, a sort of technical monument. A good example are the rests of fear-respected Mačja brv (Cat's Walk) spanning across the river at the height of 90 m.

Škocjanske Jame were mentioned in antiquity already. The first attempt of water tracing is documented from 1599. 1819 a part of the caves was displayed for tourist visit. In 1839 the underground water passage started to be explored, in 1890 the explorers reached the final siphon and the cavers dived it in 1991. 1986 the caves were inscribed in the List of World's heritage of UNESCO.

Škocjanske Jame and its vicinity are formed of Upper Cretaceous and Paleogene limestones. The collapse dolines Lisična and Sapendol, to the north-east of the cave, developed in Upper Cretaceous Turonian (K^2_2) limestone that stretches as other geological formations of this part of karst in Dinaric trend NW-SE. Light grey somewhere even white limestone is abundant in Rudist fauna. The villages Brežec and Betanja are located on Turonian limestone. The collapse dolines close to the swallow-hole of the Reka river, called Mala and Velika Dolina entirely developed in Senonian limestone (K_2^3). In this limestone the Rudist shells are more rare, yet this limestone is locally abundant with distinctive microfauna and flora. Arcaeologically interesting cave Tominčeva Jama (to the north of Velika Dolina), a part of Drčivnik collapse doline and the western part of Hankejev kanal (the passage in the cave) developed in Senonian limestone. The village Matavun is located on Senonian limestone also. A larger part of central passages of Škocjanske Jame lies in thinnly laminated dark grey to black very bituminous Maastrichtian limestone (K_2^4). Typical of it are beside other fossil remains Gyropleura sp. that are mostly transported to this secondary site. This is why the shells are very broken. Typical are also foraminiferas Rhapydionina liburnica. In this part of Upper Cretaceous there are frequent lenses and thin beds of coal which was exploited

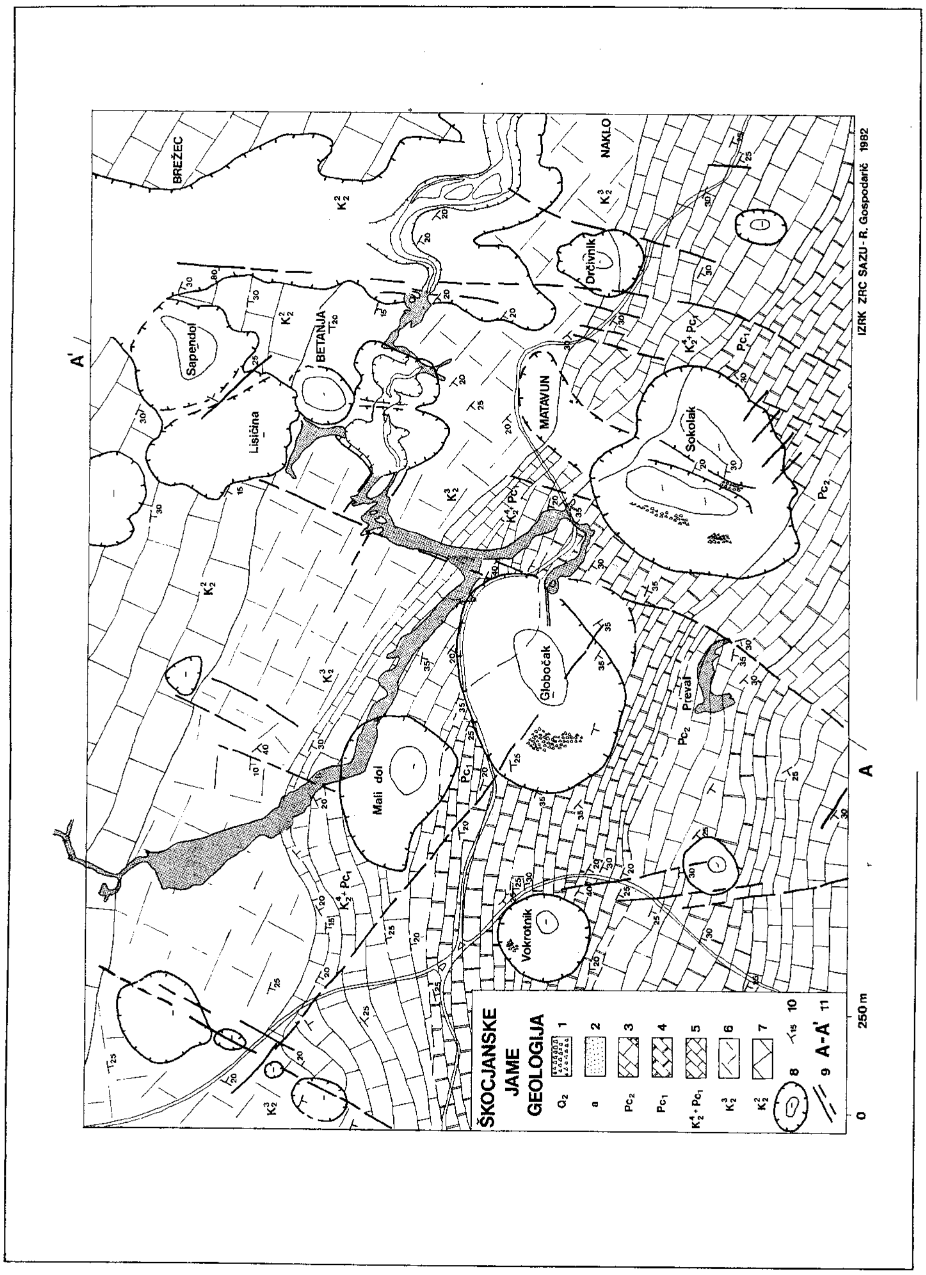


Fig. 1.10: Geology of Škocjanske Jame surroundings.

near Škocjanske Jame at the beginning of this century. The collapse dolines Mali Dol, Globočak, where lies the entrance into the show cave, and Sokolak are bounded by Maastrichtian limestone. All the three collapse dolines are also located in Lower Paleogene (Paleocene) Danian limestone. Danian limestone (Pc_1) is dark grey to black in colour and extremely homogeneous and compact. In some horizons are found, beside interesting and still slightly problematic fossil called Microcodium elegans, a numerous Haraceas flora (for example Porochara stacheana, Lagynophora liburnica), various snails (Stomatopsis sp, Cosinia sp.) and also corals. The highest in the geological column of Škocjanske Jame appears Upper Paleocene light to dark grey Thanetian limestone. By an unaided eye and particular by microscope it is very nice looking as it contains a rich association of various microfossils, Milliolidae are prevailing.

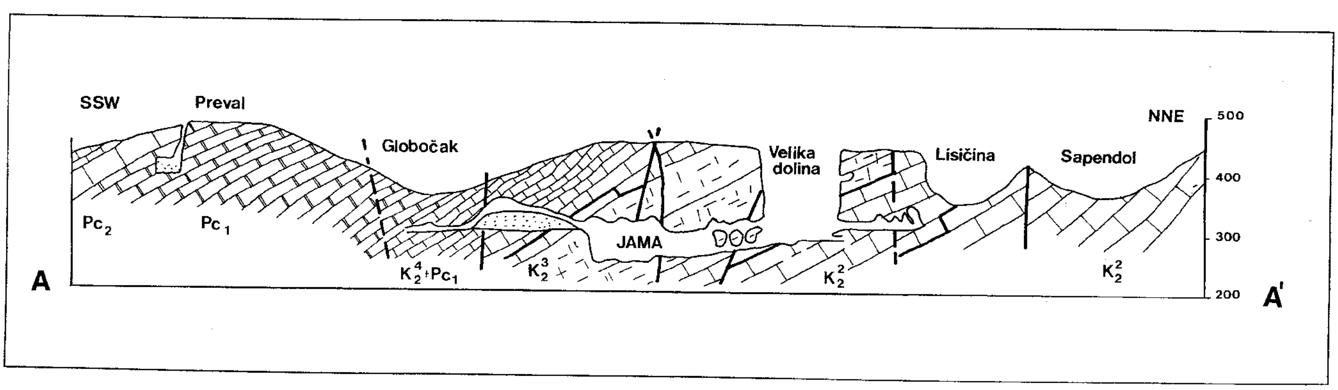


Fig. 1.11: Geological cross section of Škocjanske Jame surroundings.

SCHECKE, R. & SCHREIBER, B. (1996): Grundwasserschutz in Karstgebieten - Mülldeponierung und Trinkwassergewinnung am Beispiel von Logatec/Slowenien. – 165 S., 65 Abb., 22 Tab., 2 Anl., Anh; Clausthal (Unveröff. Dipl.-Arb. TU Clausthal).

1.3.3 Geologische Verhältnisse

1.3.3.1 Stratigraphie und Petrographie

Im Untersuchungsgebiet sind Sedimentgesteinsbildungen vom Karbon bis zum Quartär aufgeschlossen (SCHECKE 1996, SCHREIBER 1996), wobei mächtige, größtenteils verkarstete, mesozoische Karbonatabfolgen dominieren.

Ca. 3,5 km nordwestlich von Logatec bei der Ortschaft Zaplana sind klastische Gesteine des Karbons und des terrestrisch ausgebildeten Perms zu finden, wobei Wechsellagerungen von Sand- und Siltsteinen mit Einschaltungen von Tonsteinlagen das charakteristische Erscheinungsbild prägen (s. Kap. 7.2). Die älteste Einheit der Trias bilden im Arbeitsgebiet die Dolomite sowie Sand- bzw. Siltsteine des Skyths, die einen relativ kleinen Ausstrichsbereich ca. 2 km nördlich von Logatec haben. Den massigen, stark fossilführenden sowie verkarsteten Kalken des Ladins folgen im Hangenden massige, körnige Dolomite des Cordevols. Beide Einheiten sind vorwiegend im Norden von Logatec zu finden. Am nördlichen Ortsrand der Ortschaft treten vor allem die klastischen Bildungen, Kalke und Tuffite des Jul/Tuvals (s. Kap. 7.3) in Erscheinung. Die größte flächenmäßige Ausdehnung im Untersuchungsgebiet besitzen die Dolomitgesteine des norisch/rätischen Hauptdolomits, der i.d.R. gering, aber nördlich von Logatec z.T. stark verkarstet ist. Als jurassische Bildung ist im Süden von Logatec eine Wechsellagerung von Kalksteinen und Dolomiten des Malms zu nennen. Äußerst stark verkarstete Karbonate der Kreide sind im Osten und Süden von Logatec zu finden, wobei mächtige Kalksteinabfolgen dominieren, in die innerhalb der Unteren Kreide vereinzelt Dolomitlagen eingeschaltet sind. Die tertiären Bildungen sind durch Sandsteine und mergelige Kalksteine gekennzeichnet, wobei die kleinen tertiären Einschuppungen ca. 3 km südwestlich von Logatec flächenmäßig nur eine untergeordnete Rolle spielen. Bei den quartären Lockergesteinen im Umfeld von Logatec handelt es sich vorwiegend um relativ geringmächtige, fluviatile Ablagerungen im Bereich der Logaško Polje und vereinzelter, kleiner Bachläufe sowie um geringmächtige, quartäre Bodenbildungen.

1.3.3.2 Tektonik

Die tektonischen Verhältnisse des Arbeitsgebietes sind durch einen Deckenbau (s. Abb. 3) und eine Bruchtektonik der Dinarischen Gebirgsbildung gekennzeichnet (SCHECKE 1996, SCHREIBER 1996). Im Umfeld von Logatec streichen die Überschiebungsflächen von insgesamt vier Decken (Koševnik-, Hrušica-, Čekovnik- und Trnovo-Decke) aus, wobei die Störungsbahnen mit 20–40° nach Norden bis Nordwesten einfallen und oftmals als Grundwasserstauer wirken. Die Trnovo-Decke besitzt nach PLACER (1981) mit ca. 56 km die größte Überschiebungsweite gegenüber dem autochthonen Untergrund. Am weitesten nach Süden stößt im Untersuchungsgebiet die Koševnik-Decke vor. Neben den Karbonaten des Jura und der Oberen Kreide gehören dieser Deckeneinheit eozäne Bildungen an. Die Hrušica-, die aus den Kalken der Unteren Kreide im Untersuchungsgebiet aufgebaut ist, wird von der Koševnik-Decke überlagert (s. Abb. 3). Auf diese Deckeneinheit ist die Čekovnik-Decke überschoben, der ausschließlich die Karbonate des Hauptdolomits angehören. Das oberste Glied dieses Deckenstapels bildet im Raum Logatec die Trnovo-Decke, die gleichzeitig auch die größte flächenmäßige Ausdehnung im Arbeitsgebiet besitzt. Innerhalb der Trnovo-Decke sind Gesteine vom Karbon bis zum Nor/Rät zu finden.

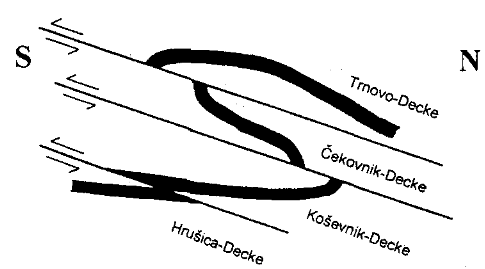


Abb. 3: Deckenbau aufgrund einer Abscherung von Faltenscheiteln im Raum Logatec (schematisch) aus SCHREIBER (1996).

Neben dem Deckenbau ist eine zumeist dinarisch (NW-SE) und querdinarisch (NE-SW) streichende Bruchtektonik für die tektonischen Verhältnisse im Raum Logatec charakteristisch (s. Kap. 5.3.4). Dazu zählt die 2,5 km westlich des Arbeitsgebietes verlaufende Idrija-Verwerfung, eine rechtslaterale Horizontalverschiebung, die nach MLAKAR (1964) einen Versatz von ca. 2,5–9 km besitzt. Für die Störung war die ca. 20 km nordwestlich von Logatec gelegene Bergbaustadt Idrija namensgebend, die durch ihre ladinischen Quecksilbervererzungen bekannt ist.

6 km östlich von Logatec ist der südwestliche Rand der Senke von Ljubljana zu finden, die sich seit dem Alttertiär um mehrere 100 m gegenüber dem Umland eingesenkt hat und in der heute noch rezente Bewegungen zu beobachten sind.

9 Zusammenfassung [2)]

Karstgebiete sind Landschaften, in denen sich aufgrund der starken Wasserlöslichkeit der anstehenden Gesteine (vorwiegend Karbonatgesteine) das Entwässerungsnetz in den Untergrund verlagert hat. Während sich die Böden der Hochflächen von Karstgebieten durch Trockenheit auszeichnen, sind in Tälern, in denen sich Vorfluter befinden, z.T. ergiebige Karstquellen zu finden.

Durch die Löslichkeit der Gesteine kommt es im Untergrund von Karstgebieten zu einer Erweiterung von Hohlräumen, aus der höhere Sicker- und Fließgeschwindigkeiten der Karstwässer resultieren. Zudem ist der Oberflächenkontakt zwischen den Karstwässern und dem Gestein aufgrund der großen Hohlräume im Vergeich zu Poren- und Kluftgrundwasserleitern sehr gering. Karstgrundwasserleiter weisen daher i.d.R. ein schlechtes Reinigungsvermögen gegenüber Schadstoffen auf. Aus diesen Gründen sind Grundwässer und aus diesen gewonnene Trinkwässer in Karstgebieten durch anthropogen verursachte Schadstoffeinträge, wie z.B. durch Müllablagerungen, besonders gefährdet.

Logatec, eine Gemeinde mit etwa 9700 Einwohnern, liegt in den slowenischen Dinariden, ca. 30 km südwestlich der slowenischen Hauptstadt Ljubljana. In der Umgebung von Logatec stehen z.T. intensiv verkarstete Kalksteine und Dolomite des Mesozoikums an. Die Abfälle der Haushalte und des in Logatec ansässigen Gewerbes gelangen zum größten Teil zu einer Mülldeponie nordöstlich des Ortskerns, die eine Einlagerungsgenehmigung bis in das Jahr 1997 hat. Die Mülldeponie wurde an einem Dolinenhang im Bereich relativ stark verkarsteter Dolomite der Unteren Trias (Skyth) angelegt. Zwischen dem anstehenden Gestein und dem Deponiekörper befindet sich eine sandig-siltige, tonhaltige Lockergesteinslage von wenigen Dezimetern bis zu wenigen Metern Mächtigkeit. Die Müllablagerungen haben ein Volumen von ca. 80.000 m^3 und bestehen u.a. zu ca. 45 % aus Hausmüll, ca. 20 % aus Sperrmüll, 15 % aus Bauschutt und ca. 10 % aus industriellen und gewerblichen Abfällen. Desweiteren werden Klärschlämme in die Doline und Abwässer eines papierherstellenden Betriebes in ein Absetzbecken eingeleitet.

Die Sickerwässer des Deponiekörpers und des Absetzbeckens sammeln sich zu einem großen Teil in der Sohle der Doline und versickern anschließend in den Untergrund. Die Menge des Deponiesickerwassers beläuft sich auf durchschnittlich ca. 251–314 l/h. Nach tektonischen Aspekten und Markierungs- (Tracer-)versuchen aus den Siebziger Jahren zu urteilen, gelangen die Sickerwässer zu den etwa 6 km nordöstlich der Deponie gelegenen Karstquellen Kožuhov und Primkov nahe der Stadt Vrhnika, deren Wässer in den Vorfluter Ljubljanica fließen. Bei einer von HABIČ (1976) ermittelten mittleren Quellschüttung der Quellen Kožuhov und Primkov von 310 l/s kommen die Deponiesickerwässer mit einem theoretischen Verdünnungsgrad von etwa 1:4000 in den Quellen zutage.

Die Beprobung der im Dolinenzentrum befindlichen Wässer sowie des vermeintlichen Deponieoberstromes (Schwinden der Bäche Rovtarica und Petkovščica) und des Deponieunterstromes (Quellen Kožuhov und Primkov) ergab, daß trotz der starken Belastung der Deponiewässer, insbesondere mit Schwermetallen, die Wässer des Deponieunterstromes gegenüber den Wässern des Deponieoberstromes keine erhöhten Konzentrationen der untersuchten Parameter aufwiesen. Grund hierfür ist vermutlich zum einen die geringe, aber vorhandene Filterwirkung der Lockergesteinslage unter dem Deponiekörper durch enthaltene Tone und organisches Material, zum anderen die große Entfernung zwischen der Deponie und den Quellen und die Verdünnung des Deponiesickerwassers im Karstgrundwasserleiter. Zudem besitzt die einmalige Beprobung keinen repräsentativen Charakter.

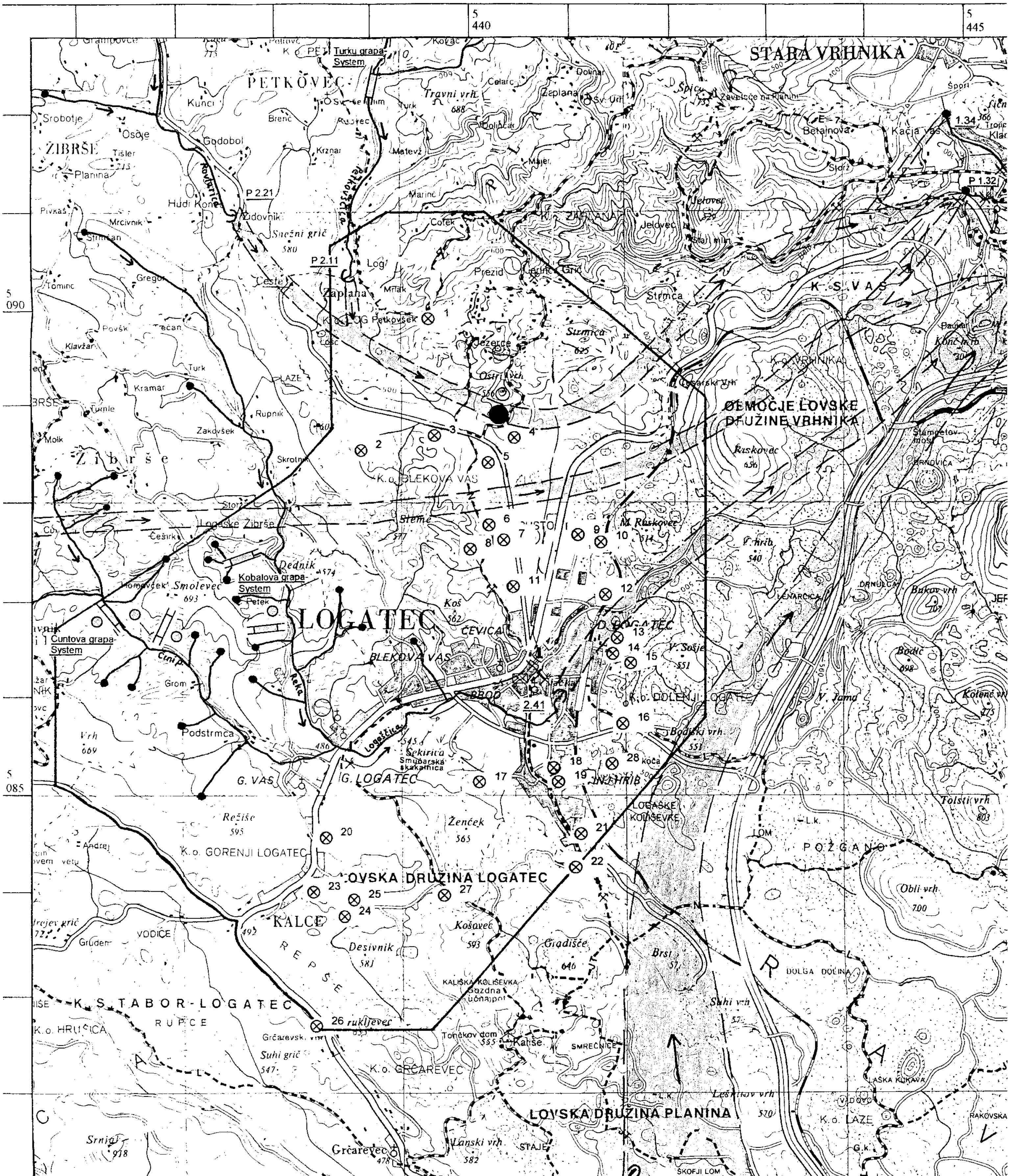
Der Versuch, mit Hilfe der bisher geringen Datenzahl eine Gefährdungsabschätzung der Mülldeponie Logatec auf Basis des Altlastenhandbuches Niedersachsen für das Schutzgut Grundwasser durchzuführen, hat zum Ergebnis, daß ein Handlungsbedarf besteht und weitere Untersuchungen notwendig sind. Diesbezüglich sind vor allem die Lokalisierung des Karstgrundwasserhauptflusses, eine genauere Bestimmung der Müllzusammensetzung, die Durchlässigkeiten und Filterwirkung des Deponieuntergrundes und die Beprobung der Sikkerwässer und der betroffenen Quellen über längere Zeiträume zu nennen.

Der Handlungsbedarf wird dadurch eingeschränkt, daß weder die Trinkwasserversorgung der Stadt Vrhnika, noch die Trinkwasserversorgung der Gemeinde Logatec durch die Deponie direkt gefährdet ist. Bei dem Schutzgut handelt es sich jedoch um Grundwasserressourcen, deren Bedeutung nicht unterschätzt werden sollte.

In unmittelbarer Umgebung von Logatec wurde trotz örtlich anstehender sandig-toniger Gesteine kein geeigneter Alternativstandort für eine Mülldeponierung vorgefunden.

Neben der Mülldeponie Logatec tragen weitere Faktoren wie die wilde Deponierung von Abfällen, der Bahn- und Autoverkehr, die landwirtschaftliche Nutzung etc. zur Verschmutzung des Karstgrundwassers in der Umgebung von Logatec bei. Allein das wild abgelagerte Müllvolumen beläuft sich auf 20.000 m^3 in einem Gebiet der Größe von 33 km^2. Aus diesem Grund ist die Forderung nach einem umfassenden Grund- bzw. Trinkwasserschutz im Fall Logatec, jedoch auch in anderen derart betroffenen Karstgebieten gerechtfertigt. Da ein Karstgrundwasserleiter gänzlich andere Eigenschaften hat als ein Poren- und Kluftgrundwasserleiter, ist die pauschale Anwendung der Untergliederung in die Trinkwasserschutzzonen I, II und III sowie deren Nutzungseinschränkungen in Karstgebieten nur eingeschränkt zweckmäßig. In die Kriterien zur Festlegung von Schutzzonen für Grund- bzw. Trinkwasser und von Nutzungseinschränkungen soll nach HÖTZL (1996) die jeweilige Verletzbarkeit (Vulnerabilität) des örtlichen Karstgrundwasserleiters eingehen. Auf diese Art und Weise kann auch eine sinnvolle Entscheidung über die Sanierungsbedürftigkeit von geregelten und wilden Deponien in Karstgebieten gewährleistet werden.

Voraussetzung für einen aktiven Grundwasserschutz ist zudem eine verstärkte Umweltbewußtseinsbildung der Bevölkerung. Nur auf diese Weise kann langfristig die Verminderung von Beeinträchtigungen des Grundwassers ermöglicht werden.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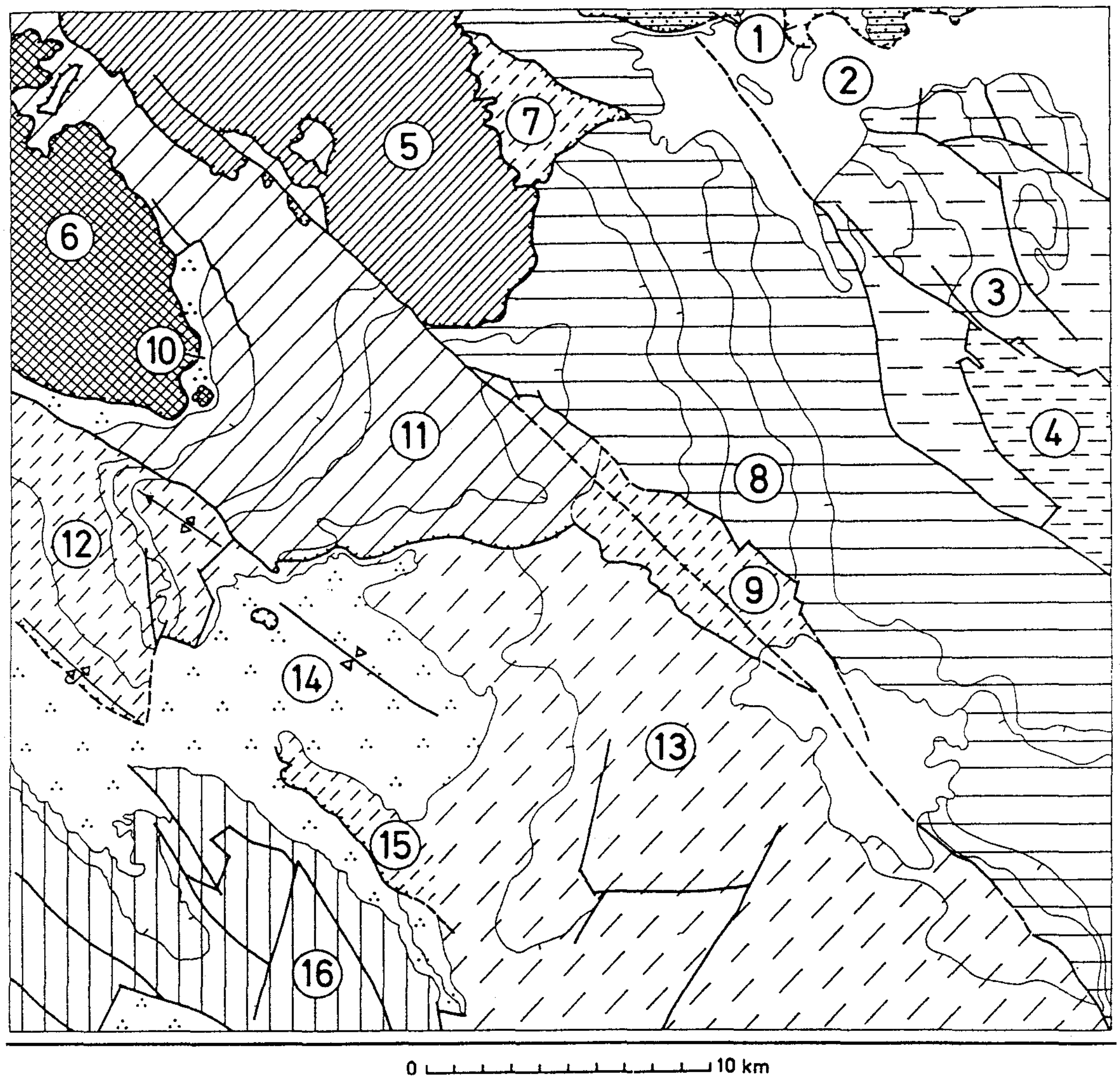
STARA VRHNIKA
PETKOVEC
ZIBRŠE
LOGATEC
Turku grapa-System
Kobalova grapa-System
Cuntova grapa-System
P 2.21
P 2.11
P 1.34
P 1.32
2.41
K.o. BLEKOVA VAS
K.o. VRHNIKA
OBMOČJE LOVSKE DRUŽINE VRHNIKA
K.o. DOLENJI LOGATEC
K.o. GORENJI LOGATEC
LOVSKA DRUŽINA LOGATEC
K.S. TABOR-LOGATEC
K.o. HRUŠICA
K.o. GRČAREVEC
LOVSKA DRUŽINA PLANINA
K.o. LAZE
K. S. VAS
POŽGANO
KALCE
REPŠE
RUPCE
LOGAŠKE KOLIŠEVKE
BLEKOVA VAS
CEVICA
G. LOGATEC
D. LOGATEC
G. VAS
Podstrmca
Smolevec
Dednik
Steme
Strmica
Ženček
Desivnik
Košavec
Gradišče
Brst
Travni vrh
Raskovec
Bukov vrh
Obli vrh
Tolsti vrh
26 rukljevec
Grčarevec
Tomkov dom
SMREČNICE
DOLGA DOLINA
LAŠKA KUKAVA
ŠKOFJI LOM
VODIČE
LOM

Tektonische Übersicht des Kartenblatts Postojna (Zvezni Geološki Zavod Beograd)



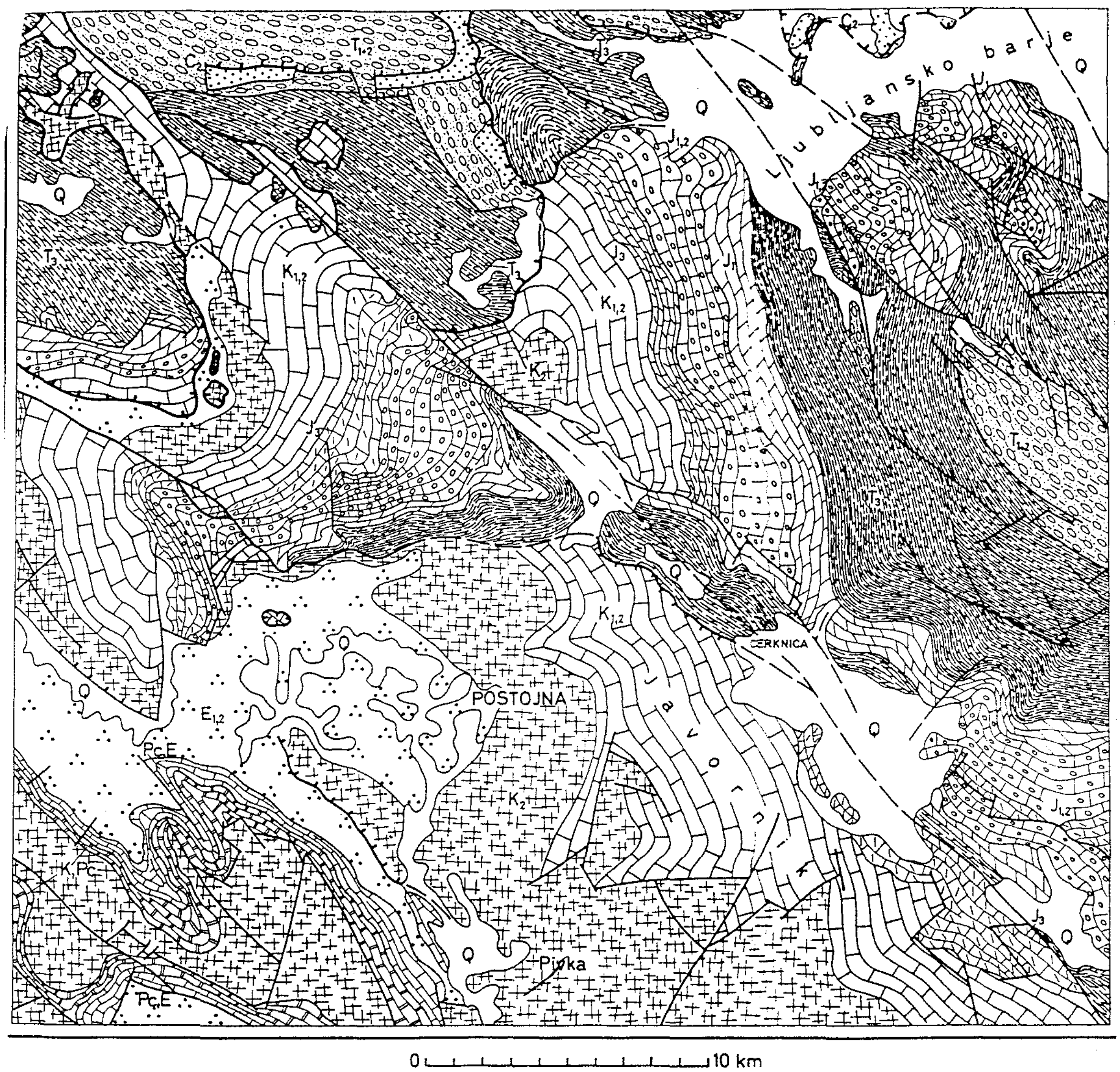
Sl. 3. Pregledna tektonska karta lista Postojna. Generalized tectonic map of the Postojna sheet. Обзоррная тектоническая карта листа Постойна.

1. Poljansko—Vrhniški nizi. — 2. Ljubljansko barje. — 3. Krimsko hribovje. — 4. Rakitniška gruda. — 5. Idrijsko-žirovsko ozemlje. — 6. Trnovski gozd. — 7. Zaplanska luska. — 8. Vrhniško-cerkniška gruda. — 9. Rakeško-cerkniška luska. — 10. Goričko-vipavski fliš. — 11. Hrušica. — 12. Nanos. — 13. Javorniško-snežniške grude. — 14. Fliš Postojnske in Pivške kadunje. — 15. Prestranški ravnik. — 16. Tržaško-komenska planota.

1. Poljana—Vrhnika highlands. — 2. Ljubljana depression. — 3. Krim hills. — 4. Rakitna block. — 5. Idrija—Žiri area. — 6. Trnovski gozd. — 7. Zaplana overthrust. — 8. Vrhnika-Cerkno block. — 9. Rakek—Cerkno overthrust. — 10. Gorica—Vipava Flysch. — 11. Hrušica. — 12. Nanos. — 13. Javornik-Snežnik blocks. — 14. Flysch of the Postojna and Pivka depressions. — 15. Prestranje area. — 16. Trst—Komen plateau.

1. Полянско-Врхникские холмы. — 2. Люблянская впадина. — 3. Кримские холмы. — 4. Блок Ракитни. — 5. Область Идриа-Жири. — 6. Трновский гозд. — 7. Запланская чешуя. — 8. Блок Врхника—Церкно. — 9. Чешуя Ракек—Церкно. — 10. Флиш Випавы и Горицы. — 11. Хрушица. — 12. Нанос. — 13. Блокы Яворник-Снежник. — 14. Флиш Постойнской и Пивской впадин. — 15. Область Престранье. — 16. Плоскогорье Трст—Комен.

Geologische Übersicht des Kartenblatts Postojna (Zvezni Geološki Zavod Beograd)



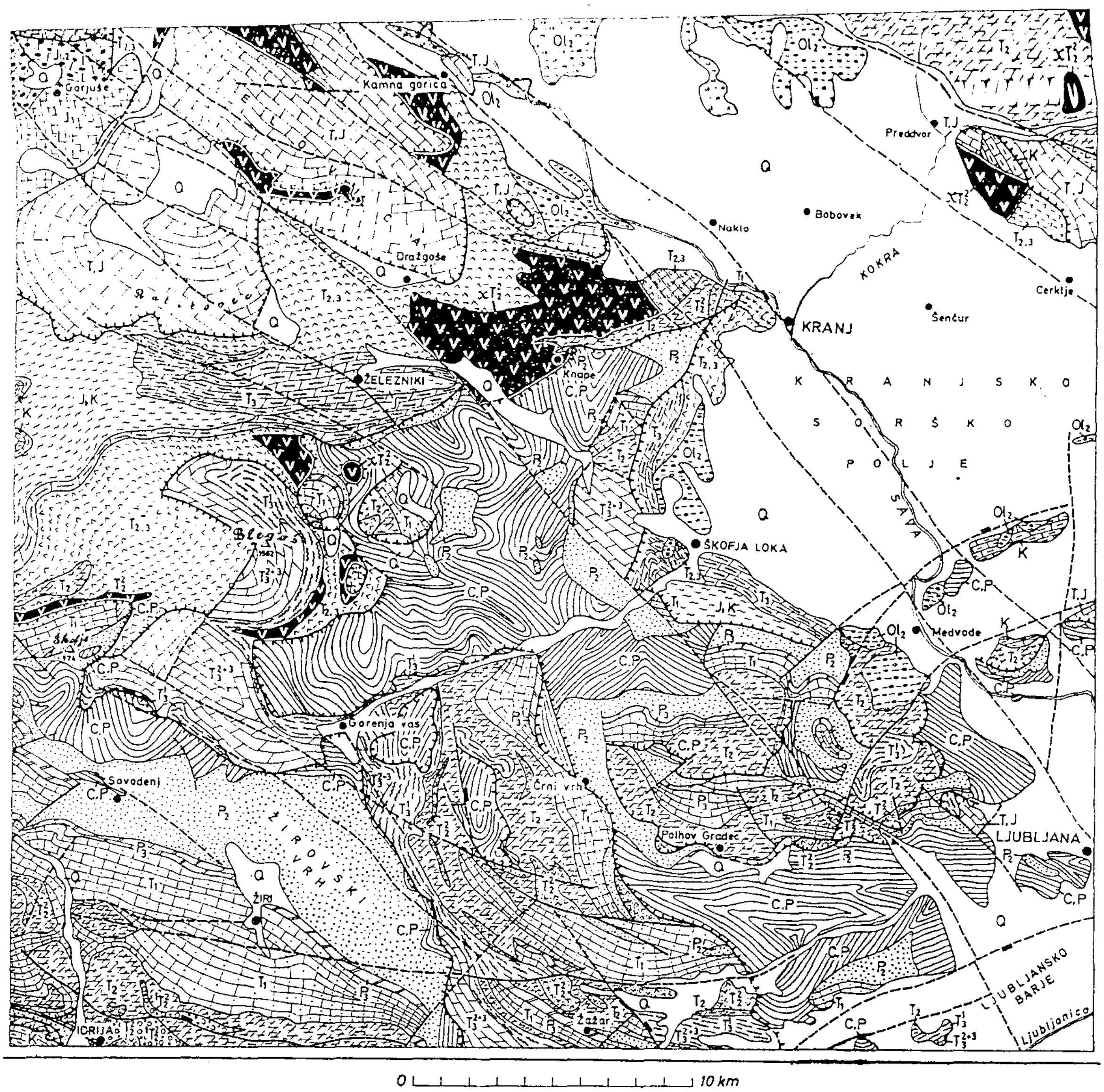
J_1 — Liada: dolomiti in apnenci. Liassic: dolomites and limestones. Лейас: доломиты и известняки.

T_3 — Zgornja triada: glavni dolomit, karbonatne in klastične kamenine. Upper Triassic: „Hauptdolomit", carbonaceous and clastic sediments. Верхний триас: „главный доломит", карбонатовые и кластические породы.

T_{1-2} — Spodnja in srednja triada: dolomiti, apnenci, glinasti skrilavci, peščenjaki, breče, tufi, tufiti in porfiriti. Lower and Middle Triassic: dolomites, limestones, shales, sandstones, breccia, tuffs, tuffites and porphyrites. Нижний и средний триас: доломиты, известняки, мергели, песчаники, брекчии, туфы, туффиты и порфириты.

C+P — Sr. karbon in sr. perm: peščenjaki in glinasti skrilavci. Middle Carboniferous and Middle Permian: sandstones and shales. Средний карбон и средняя пермь: песчаники и сланцы.

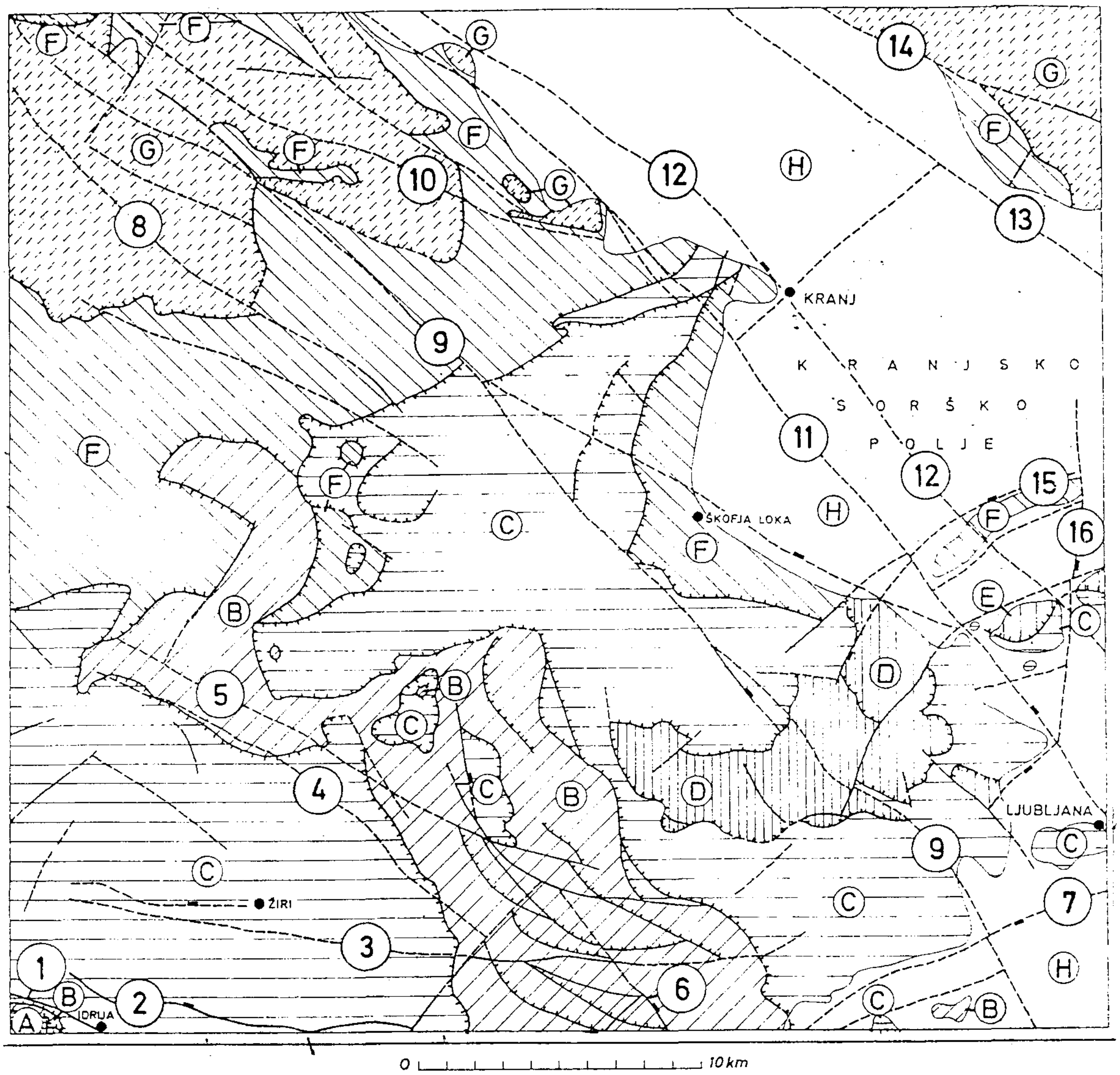
Geologische Übersicht des Kartenblatts Kranj (Zvezni Geološki Zavod Beograd)



Sl. 2. — Pregledna geološka karta lista Kranj. Generalized geological map of the Kranj sheet. Обзорная геологическая карта листа Крань.

Q	— Kvartar. Quaternary. Четвертичная система.
Ol_2	— Srednji oligocen: konglomerat, peščenjak, lapornata glina, tuf. Middle Oligocene: conglomerates, sandstones, marly clay, tuff. Средний олигоцен: конгломераты, песчаники, мергелистая глина, туф.
K	— Kreda: skladovit apnenec, lapornat apnenec, lapor, breča. Cretaceous: stratified limestone, marly limestone, marl. breccia. Мел: слоистый известняк, мергелистый известняк, брекчия.
J,K	— Jura, kreda: črn glinast skrilavac in lapor, apnenec z rožencem, mangan. Jurassic, Cretaceous: black clayey schists and marls, cherty limestones, manganese. Юра, мел: черные глинистые сланцы и мергели, известняк с яшмой, марганец.
$J_{1,2}$	— Liada, dogger?: ploščast apnenec z rožencem. Liassic, Dogger?: bedded cherty limestones. Лейас, доггер?: слоистые известняки с яшмой.
J_1	— Liada: neplastovit, deloma ooliten apnenec. Liassic: unstratified, partly oolitic limestones. Лейас: неслоистые, частично оолитовые известняки.

Tektonische Übersicht des Kartenblatts Kranj (Zvezni Geološki Zavod Beograd)



Sl. 3. — Pregledna tektonska karta Kranj. Generalized tectonic map of the Kranj sheet. Обзорная тектоническая карта лист Крань.

A. Koševniški pokrov. The nappe of koševnik. Покров Кошевника. B. Blegoško-vrhniški nizi. Blegoš Vrhnika highlands. Возвышенность Блегош—Верхника. C. Škofjeloško trnovski pokrov. The nappe of Škofja Loka and Trnovo. Покров Шкофя Лока и Трново. D. Polhograjsko območje. The area of Polhovgradec. Область Полховградеца. F. Selška cona. The zone of Selce. Зона Селце. G. Jeloviški pokrov. The nappe of Jelovica. Еловицкий покров. H. Ljubljanska kotlina in Ljubljansko barje. Ljubljana depression and Ljubljana Barje. Люблянская котловина и Люблянское Барье.

1. Idrijski prelom, Idrija fault. Идрийский разлом. 2. Lomsko-zavraški prelom. Lom- Zavratalec fault. Разлом Лом — Завратец. 3. Ledinski prelom. Ledine fault. Лединский разлом. 4. Trebijski prelom. Trebije fault. Требийский разлом. 5. Hotaveljski prelom. Hotavlje fault. Разлом Хотавле. 6. Borovniški prelom. Borovnica fault. Боровнишкий разлом. 7. Viški prelom. Vič fault. Вишкий разлом. 8. Ratitovški prelom. Ratitovec fault. Разлом Ратитовец. 9. Dražgoški prelom. Dražgoše fault. Разлом Дражгоше. 10. Jeloviški prelom. Jelovica fault. Разлом Еловица. 11. Blejski prelom. Bled fault. Бледский разлом. 12. Kranjski prelom. Kranj fault. Краньский разлом. 13. Cerkljanski prelom. Cerkno fault. Разлом Церкно. 14. Savski prelom. Sava fault. Савский разлом. 15. Smledniški prelom. Smlednik fault. Разлом Смледник. 16. Ljubljanski prelom. Ljubljana fault. Люблянский разлом.

U. Premru

Geologic structure of Central Slovenia

Summary

The region of Slovenia consists of the following tectonic units: Austroalpin, Southern Alps, Outer Dinarides, Periadriatic Lineament, Pannonian basin, and Plioquaternary fault basins.

The Austroalpin is part of the transitional oceanic plate (fig. 10). Its basement composed of simatic mafite rocks is overlain by Paleozoic metamorphic leptogeosynclinal rocks, passing into partly cratonized Upper Paleozoic rocks. Pelagic and neritic Mesozoic sediments represent already alpidic cratonization, and the start of forming an epigeosyncline. The postgeosynclinal cycle of the Alpine orogeny is characterized by subsequent magmatism, overthrusting, and large scale right lateral separation followed by small scale left lateral separation along transcurrent faults.

The Southern Alps as well as the Outer Dinarides are related to the epigeosynclinal part of the continental Adriatic plate. Their basement composed of the crystalline rocks is overlain by epigeosynclinal sediments of the Variscan and Alpine orogeny. The Southern Alps represent the epieugeosynclinal, the Outer Dinarides the epimiogeosynclinal part of the continental plate. The Southern Alps are an equivalent of the Inner Dinarides, but differ from them by their lithological and paleogeographic features. During the tardygeosynclinal cycle several parallel Flysch troughs were formed; during the postgeosynclinal cycle followed several phases of overthrusting and large scale right lateral separations along transcurrent faults.

Today, the Periadriatic Lineament is a completely consumed oceanic plate; its development is characterized by strong magmatic intrusions and tectonic deformations. During the tardygeosynclinal cycle of the Alpine orogeny, it was the central zone of transcurrent faults, at the end of the cycle, however, the root zone of overthrusts. In the north of the Lineament thrusting was directed northwards, in the south of the Lineament southwards.

The Pannonian basin originated in the tardygeosynclinal cycle of the Alpine orogeny. Its basement are the tectonical units of Austroalpin, Southern Alps. Outer Dinarides and Periadriatic Lineament. It represents the marginal periadriatic basin with inner molasse. During the postgeosynclinal cycle it underwent strong tectonic processes: faulting, folding and overthrusting.

The Plioquaternary fault basins originated in the last phasis of tectonic deformation of the Alpine orogen due to gradual subsiding along faults.

The Central part of Slovenia belongs partly to the Southern Alps and partly to the Outer Dinarides. By means of the facies analysis the author divides it to structure-facies units (figs. 1 and 2). The Southern Alps are here divided into the Savinja, Upper Carniola, and Slovene zones; the Outer Dinarides into the Idrija and Friuli zones. The individual zones are subdivided into subzones. The Ljubljana zone serves to indicate the boundary between the Southern Alps and the Outer Dinarides. During the Triassic and Jurassic ages there a stable carbonate platform was bordered by a more mobile epieugeosyncline in the north and an epimiogeosyncline in the south. The stability of the boundary zone was reflected still in Middle and Upper Cretaceous, when the Flysch troughs originated.

Through the palinspastic distribution of the zones and subzones the activity of the Podvolovljek left lateral transform fault is indicated (fig. 1), that is partly identical with the Ljubljana—Vienna fault. Today it is seen at the surface only at Podvolovljek, but otherwhere it is covered by younger overthrusts and displaced along right-lateral transcurrent faults related to the Periadriatic Lineament (fig. 2). In its origin and activity it is similar to the Zagreb fault. In the west of the Podvolovljek fault the Slovene zone is most distinctive, being substituted by the Upper Carniola zone east of the fault. In the Slovene zone the epieugeosynclinal sedimentation took place from the Upper Anisian stage till end of the Langobardian substage, when it passed in Upper Triassic epimiogeosynclinal sedimentation, and for a short time over the Lower Jurassic epieugeosyncline into the Jurassic and Lower Cretaceous epimiogeosyncline, finally to the Upper Cretaceous Flysch epimiogeosyncline. An alternation of epieugeosynclinal, epimiogeosynclinal and neritic carbonate sedimentation is characteristic of the Upper Carniola zone. In the epieugeosyncline intermediate carbonate platforms occurred. In Lower Cretaceous the first Flysch epimigeosynclines developed. Two parallel Flysch troughs extended in the west of the fault, and three in the east of the fault where they joined together into o whole Flysch epimigeosyncline in Upper Cretaceous (figs. 3, 4, 5, 6 and 7).

In Central Slovenia three epigeosynclinal belts are recognized. In the Alpine region the Slovenia epigeosynclinal belt spreads in the west of the Podvolovljek fault and the Carinthia epigeosynclinal belt in the east of the fault. The Outer Dinarides appear to be less influenced by the activity of the Podvolovljek fault; they have the nature of an indivisible epigeosynclinal belt.

The distribution of the structure-facies units indicates clearly a diverging of the epigeosynclinal area of the Southern Alps from the Outer Dinarides. This divergence can be seen most clearly in the Ladinian and Carnic stage, in Lower Jurassic and Cretaceous. The reason for the branching off appears to be left--lateral separation of the transform Podvolovljek fault, and the related spreading of the epigeosynclinal space in the east of the fault. Due to this extension new subzones generated in the Upper Carniola and Idrija zones. They reach up to the Podvolovljek fault, or thin out immediately in its vicinity from east westwards.

In the Ladinian stage and in Lower Jurassic the epigeosynclinal space of the Southern Alps shows the strongest phase of its extension, probably connected with the extension of the Pennine oceanic plate. The extension is remarkable on both sides of the Podvolovljek fault. In the Slovene zone as well as in the

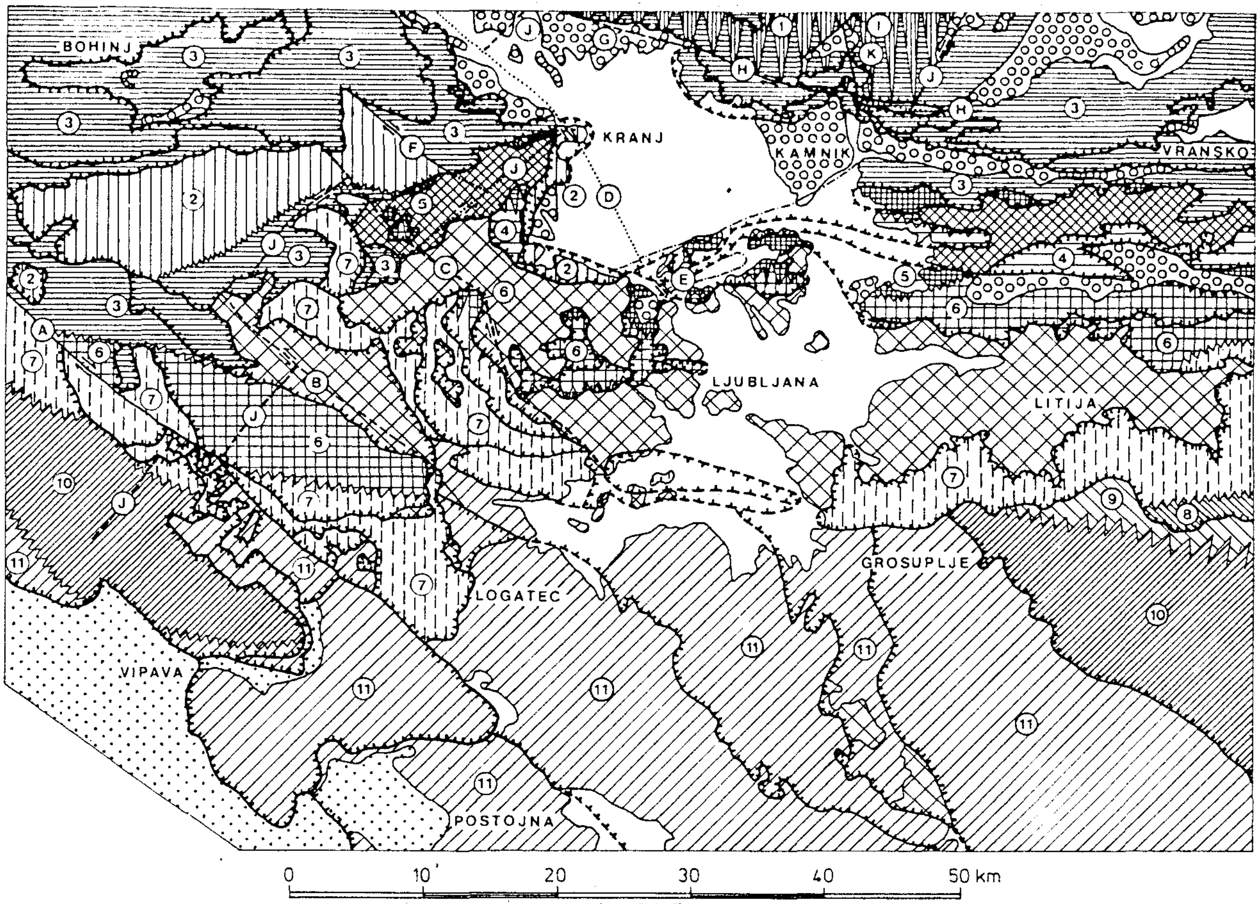


Fig. 2. Structure-facies map of Central Slovenia

Alpidski geosinklinalni ciklus
Alpine geosynclinal cycle

Južne Alpe
Southern Alps

- (1) Savinjska cona / Savinja zone
- (2) Slovenska cona / Slovene zone
- (3) Selška podcona / Selca subzone
- (4) Limbarska podcona / Limbar subzone
- (5) Zagorska podcona / Zagorje subzone

(3)–(5): Gorenjska cona / Upper Carniola zone

Mejna cona med J Alpami in Zun Dinaridi
Border zone between the S. Alps and Outer Dinarides

- (6) Ljubljanska cona / Ljubljana zone

Zunanji Dinaridi
Outer Dinarides

- (7) Kanomeljska podcona / Kanomlja subzone
- (8) Zasavska podcona / Zasavje subzone

(7)–(8): Idrijska cona / Idrija zone

- (9) Trebanjska podcona / Trebnje subzone
- (10) Dolenjska podcona / Lower Carniola subzone
- (11) Notranjska podcona / Inner Carniola subzone

(9)–(11): Furlanska cona / Friuli zone

Alpidski tardiogeosinklinalni ciklus
Alpine tardy-geosynclinal cycle

- Terciarni sedimenti J Alp / Tertiary sediments of the Southern Alps
- Terciarni sedimenti Zun. Dinaridov / Tertiary sediments of the Outer Dinarides

Alpidski postgeosinklinalni ciklus
Alpine post-geosynclinal cycle

- Pliokvartarne udorine / Plio-Quaternary subsidence basins

Predalpidski ciklus
Pre-Alpine cycle

- Mladopaleozojski sedimenti J. Alp (a) in Zun. Dinaridov (b) / Late-Paleozoic sediments of the S. Alps (a) and of the Outer Dinarides (b)

Ostali znaki
Other signs

- Meja terciarnih sedimentov na površju / Boundary of Tertiary deposits along a free surface
- Meja terciarnih sedimentov pod kvartarnimi naplavinami / Boundary of Tertiary deposits beneath the Quaternary deposits
- Nariv ali luska na površju / Superficial thrust- and imbricate-structure
- Nariv ali luska pod kvartarnimi naplavinami / Thrust- and imbricate-structure beneath the Quaternary deposits
- Prednarivni prelom na površju / Fault older than overthrust along a free surface
- Prelom v spodnjih narivih ali pokrit s kvartarnimi naplavinami / Fault buried by younger overthrust or by the Quaternary deposits
- Prelom, erodiran / Fault, eroded
- Fleksura / Flexure
- Meja med conami in podconami (pregib) / Boundary zone / subzone

Prednarivni prelomi - Faults older than overthrust

- (A) Idrijski prelom / Idrija fault
- (B) Sovodenjski prelom / Sovodenj fault
- (C) Ratitovški prelom / Ratitovec fault
- (D) Blejski prelom I / 1st Bled fault
- (E) Blejski prelom II / 2nd Bled fault
- (F) Škofjeloški prelom / Škofja Loka fault
- (G) Savski prelom I / 1st Sava fault
- (H) Savski prelom II / 2nd Sava fault
- (I) Savinjski prelom / Savinja fault
- (J) Podvoloveljski prelom / Podvolovljek fault
- (K) Kamniški prelom / Kamnik fault

axial part of the Selca subzone, that belongs to the Upper Carniola zone, regional low-grade metamorphic rocks and hydrothermally altered rocks of the keratophyre-spilite association occur. The narrow belt of the rocks indicates the first stage of the rift valley of a marginal sea. In the south, as well as in the north of the rift valley ridges of pelagic limestone were layered. The creation of the marginal sea is somewhat indicated also by the Lower Jurassic volcanism.

The structure-facies analysis anabled to determine the faults preceding the thrust faulting from the Laramide orogeny. The Southern Alpine region is characterized by the right-lateral transcurrent faults, in the Outer Dinarides, however, both the right- and left-lateral faults occurred. The author considers the Sava, Savinja and Kamnik faults to have preceded the thrust faulting. The Idrija, Ratitovec, Bled, Sovodenj and Škofja Loka faults, however, appear to have moved to the left as well as to the right. All of them have renewed in the neotectonic period. Just due to the activity of the transcurrent faults the Southern Alps have been displaced into the Carpathian Mountains.

In the development of Central Slovenia two youngest phases of overthrusting can be distinguished in the tardygeosynclinal cycle. In the Outer Dinarides the youngest overthrusting occurred during the Illyrian—Pyrenean orogeny between the Middle Eocene and Middle Oligocene, and in the Southern Alps in the Rhodanian orogeny at the end of the Miocene epoch. The Cerknica, Blegoš and Kamnik schuppen structures originated between Oligocene epoch and end of Tortonian stage. The overthrust tectonic units do not exactly coincide with the structure-facies units of the alpidic geosynclinal cycle. The structure-facies units of the Southern Alps are for some tens of kilometers thrust over the structural units of the Outer Dinarides; therefore the overthrust structure of the Southern Alps extends rather far into the structure-facies units of the Outer Dinarides. In the western part of Central Slovenia there are overthrusts related to both phases; therefore the structure is of Alpine-Dinaric nature.

The Southern Alps are the least stable part of Slovenia. After Triassic and Lower Jurassic extension they have been displaced towards SE and E along the system of the right-lateral transcurrent faults. Later they have been compressed due to folding. In neotectonic time inherited structures were superimposed. The neotectonic boundary between the Southern Alps and the Outer Dinarides does not follow the boundary of the overthrust structure, and even less the boundary of the structure-facies units. During the tardygeosynclinal and postgeosynclinal cycle the boundary was moved southwards, so, that the structure-facies units are overlapped by the overthrusts of the Southern Alps for some tens of kilometers.

Mineralogy of the Uranium Deposit of Žirovski Vrh, Slovenia/Yugoslavia
A Reflected Light, SEM, Electron Microprobe and PIXE Investigation

M. K. PAVIĆEVIĆ and A. El GORESY

Abstract

The uranium deposit of Žirovski Vrh is located in the southwestern part of Yugoslavia and is hosted by Permian-Gredenian sandstones. The deposit is interpreted as of epithermal origin and probably formed by transport of uranium in solution and deposition in the sandstone. Xylene structures of primitive plants of younger Paleozoic sediments were encountered.
Recently, microprobe investigations on uranium minerals were performed by Simova et al. (1983, 1984). Based on the UO_2/SiO_2 and (U + Ca)/Si ratios, these authors suggest the presence of five uranium minerals, four of them are thought to be new.
Our studies indicate that the uranium mineralization is not restricted to the uraniferous veins in the sandstones. A cosiderable amount of uranium minerals was discovered in carbonaceous matter and fossil wood. Major components are coffinite and pitchblende. Other REE-rich minerals, presumably carbonates, were also encountered. In contrast to former reports by Simova et al. (1983), our results indicate that coffinite displays a complex chemistry with high concentrations in REE (average 11.4 wt.% total rare earth). Concentrations of REE, Hf, and Pb vary considerably. The totals are close to 100% indicating the reported shortage in the totals to be due to incomplete analysis. Pitchblende in the carbonaceous material contains higher concentrations in REE than in the coexisting coffinite. Due to the high CaO-, and P_2O_5-contents, we interpret this result as suggesting the presence of REE-bearing phosphates and carbonates intimately intergrown with pitchblende.
The uranium mineralization is very probably of sedimentary origin or due to low temperature hydrothermal activity. Mobilization of UO_2, PbO, REE_2O_3 took place in a younger episode, thus redistributing these elements among various uranium minerals. The total PbO-content in pitchblende is too high to be attributed to in-situ decay. The measured Pb is probably a mixture of mobilized radiogenic lead, primordial lead, and pristine radiogenic lead. Hence, the total U/Pb ratios cannot be used to determine the age of the mineralization. Both Pb and U were involved in the mobilization and contamination of coffinite and pitchblende and the amount of ^{204}Pb and the $^{206}Pb/^{207}Pb$ ratio in individual minerals are unknown so far. The genetic evolution of the deposit and the temporal determination of the metamorphic episodes can only be obtained by mass spectrometric Pb/U systematics.

1. Introduction and geologic setting

The uranium deposit of Žirovski Vrh is located west of Ljubljana and belongs to the Škofija Loka-Idrija metallogenic region (fig. 1). The deposit attracted attention after the discovery of the radioactive anomaly and of secondary uranium minerals (Berce et al. 1960; Ivanović 1961; Ramovš 1965; Marković 1961). The uranium mineralization lies in the sedimentary red gradenian layers in a tick Permian succession (Radusinović 1967). According to Ramovš (1965) and Omaljev (1969), the sediments are Permian and Permocarboniferous in age. The sedimentation may have lasted for 20 million years (Omaljev 1969). The clastic sediments in which the uranium mineralization is emplaced are characterized by their red colour due to the presence of hematite. Clay minerals and lime are the major adhesive of the clastic grains.

The geology of the area is typical of the metallogenic province of Northern Italy and West Yugoslavia (Janković 1962, 1963; Janković et al. 1964, 1970, 1971). The intensive volcanic activity in the upper Carboniferous produced the quartz porphyry and is the main source of the clastic sediments (Mittempergher 1972). Žirovski Vrh lies in the youngest upper layers of the sedimentary succession (Omaljev 1969).

The major constituents of the sediments are quartz, fragments of igneous rocks with rare mica and feldspars. Plant residues and coal are ubiquitous.

According to Radusinović (1967), the primary zone of the deposit consists of a complex assemblage of uranium minerals and Pb, Fe, and Cu-sulfides. These assemblages include pitchblende, pyrite, galena, sphalerite, chalcopyrite, tetrahedrite, chalcocite, arsenopyrite, pyrrhotite, marcasite, bornite, and covellite. In addition, he reported the presence of autonite, torbernite, metatorbernite, and other secondary minerals.

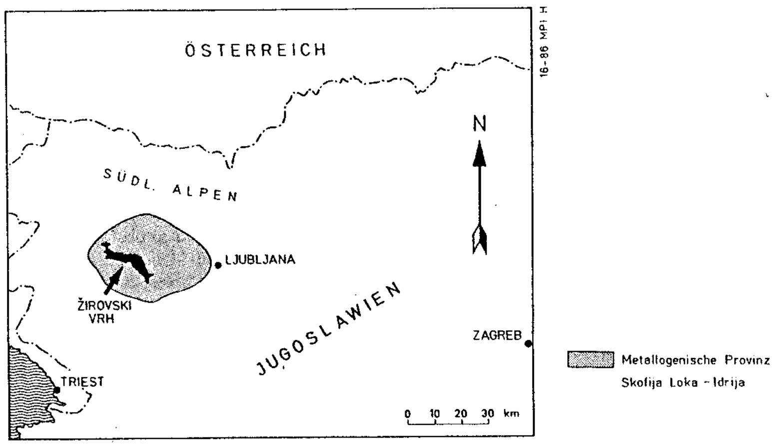


Fig. 1. A geographic map at the three countries corner Yugoslavia-Austria-Italy, depicting the location of the uranium deposit of Žirovski Vrh within the metallogenic province of Skofija-Loka-Idrija.

Kurat et al. (1977) and Simova et al. (1983) conducted mineralogical and microprobe studies on the uranium minerals of Žirovski Vrh. In addition to pitchblende, they reported the presence of "water-bearing coffinite" $USiO_4$ nH_2O and other unidentified U-silicates. The uranium minerals in Žirovski Vrh were also subject of a detailed TEM investigation (Hanzlik 1981). The presence of coffinite was confirmed and, in addition, ekanite, rutherfordite, and uranophane were also found. The latter three minerals suggest the formation of the deposit under oxidizing conditions from underground water.

2. Analytical methods

High quality polished sections were prepared to conduct a combination of studies including reflected light microscopy, scanning electron microscopy (SEM), electron probe microanalysis, and proton probe microanalysis (PIXE). One major intention for the selection of these various methods is to study the fine textures of the mineral assemblages at high resolution in comparison to regular high magnification reflected light microscopy and to secure the quality of the analysis by covering the trace element household by PIXE. This is specifically important to check the amount of H_2O or OH present in the uranium minerals. In many previously published microprobe analyses of uranium minerals, specifically coffinite, the amount of water or OH detected varies considerably. However, the real concentration is unknown since little attempt was made to quantitatively analyze numerous minor elements like the lanthanide group, Zr, Hf, Pb, V, Nb, etc. One major analytical problem is the accurate measurement of lanthanide element concentrations, especially at low concentration levels ($< 0{,}5$ wt.% REE_2O_3). This problem arises from two sources: 1. There are some 19 $L\beta$ and $L\gamma$ X-ray overlaps of elements of lower atomic number over the $L\alpha$'s of elements of higher atomic number. The deconvolution requires accurate experimental determination of the overlapping factors. 2. Since the $L\alpha$, $L\beta$ and $L\gamma$ of REE elements are numerous, it is difficult to measure the background with the required accuracy.

The SEM investigations were conducted using a Cambridge 180 S scanning electron microscope with an attached Si(Li) detector (147 eV resolution). The quantitative analyses of the mineral phases were carried out with a fully automated computer-controlled SEMQ electron microprobe using wavelength dispersive spectrometers. A special analytical procedure and a peak deconvolution programme were used to correct for X-ray overlaps of $L\beta$ and $L\gamma$ lines of lanthanide elements on the $L\alpha$ lines of lanthanides of higher atomic number; this procedure corrected for 19 overlaps in the lanthanide-group elements (El Goresy et al. 1984).

PIXE investigations were performed at the Heidelberg Proton Microprobe attached to the linear Tandem Van de Graaff accelerator of the Max-Planck-Institut für Kernphysik (Bosch et al. 1978). Analyses were carried out on the same grains analyzed previously by SEM and electron microprobe using an excitation energy of 3 MeV protons. The data were collected with a Si(Li) energy dispersive detector. The beam diameter was set at spot size of 1 mm^2, since it was planned to determine the bulk abundance of minor and trace elements in carbonaceous materials.

3. Petrography, assemblages, and mineral chemistry

The uranium mineralization is massively but not exclusively (as believed by Omaljev 1982) concentrated in the grey clastic sediments. Our investigation indicates two distinct types of assemblages in different host materials:

(1) Uranium mineralization in the interstices between the clastic quartz sand grains. All previous reports were confined to this type only (Radusinović 1967; Kurat et al. 1976; Omaljev 1982; Simova et al. 1983).

(2) The investigations of carbonaceous material and graphite-like objects (called anthracite by Omaljev 1982) from Žirovski Vrh revealed a considerable amount of uranium- and REE-rich minerals discovered therein for the first time. Both host materials occur in the same samples and the carbonaceous material or graphite-like objects occur as inclusions in the sandstones. Figure 2 is a low magnification photograph of both lithologies in a part of the sandstone, which is highly enriched in uranium minerals. In each sample studied, the carbonaceous material is of clastic nature indicating that it is not contemporaneous with the uranium mineralization of the first type (fig. 2).

3.1 Uranium mineralization in sandstone

In this paragenetic type, the uranium minerals occur as impregnations between the detrital ragged quartz grains (fig. 3, 4, 5). The impregnations contain two types of materials distinctly different in form and reflectance: (a) Compact higher reflecting material consisting majorily of pitchblende veins usually bordering the quartz grains (fig. 4 and 5), and (b) loosely compacted low reflecting spherules with coffinite as a major component filling the regions between the pitchblende veins (fig. 4 and 5). Secondary uranium minerals also occur within this region. Some of the impregnations may consist exclusively of either pitchblende or coffinite (fig. 6). Both minerals are fine-grained. (< 20 microns). This feature creates difficulties in the microscopic identifications of the individual phases. The problem, however, can be solved by applying BSE or SE imaging techniques under SEM. Using SEM will not only expand the imaging capabilities towards higher magnifications, but also allows fast and accurate identifications based on brightness and qualitative chemical analyses with an attached EDAX system. Both minerals are anhedral. In particular, coffinite rarely displays the typical tetragonal habit. To secure accurate analysis of both minerals, and due to their fine-grained nature, electron microprobe analyses were carried out only in compact areas.

Pitchblende: EDAX analysis indicated that the mineral is not pure UO_2. The spectrum indicated the presence of rare earth elements but no Th. Table 1 depicts the results of quantitative measurements of 32 elements. Of considerable interest are the high concentrations of Pb (6.34% PbO). This amount cannot consist exclusively of radiogenic ^{206}Pb and ^{207}Pb formed by in situ radioactive decay of ^{238}U and ^{235}U. Otherwise, the assumption that all Pb is radiogenic would lead to unreasonably high ages of several

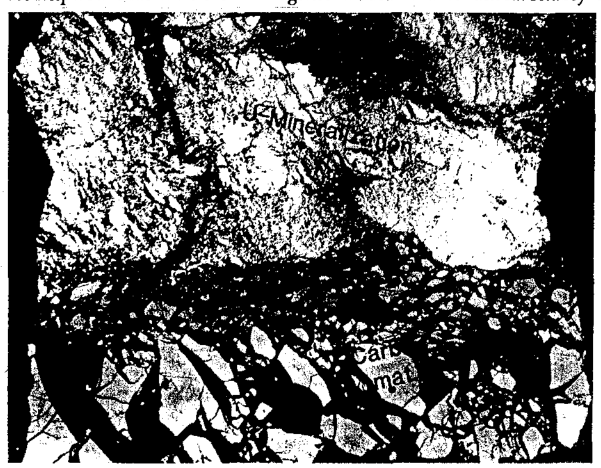


Fig. 2. A low magnification photograph of a polished section showing the uranium impregnations mineralization side to side with the clastic carbonaceous material. Width of photograph: 2.5 cm.

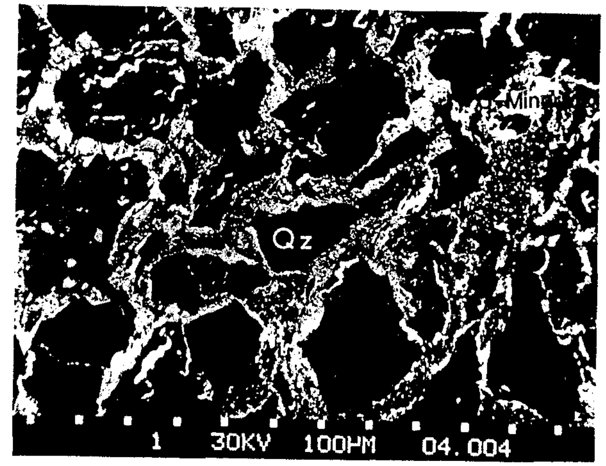


Fig. 3. SEM secondary electron imaging photograph of the impregnation paragenetic type. The uranium mineralization occurs in the interstices of the ragged quartz (Qz) grains.

Fig. 4. Details from Fig. 3. Bright compact masses are pitchblende. Darker spherulitic objects consist mainly of coffinite.

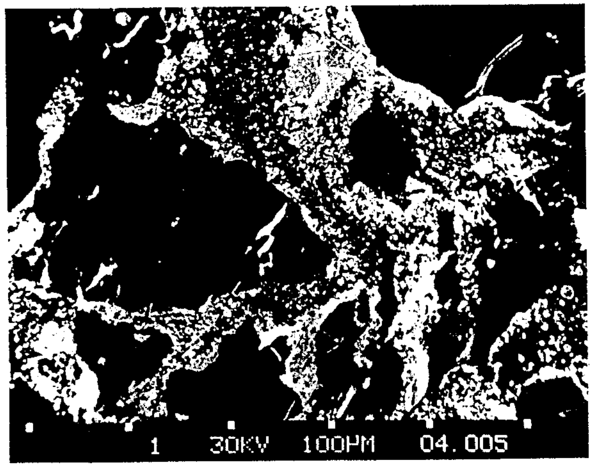


Fig. 5. Reflected light photomicrograph of massive pitchblende in an impregnation vein. Length of photograph 200 microns.

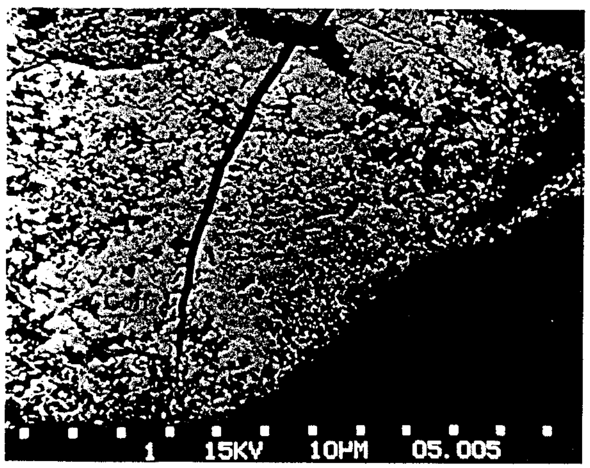


Fig. 6. SEM photograph of a part of vein impregnations consisting mainly of partly compacted coffinite.

billion years. We believe that such high local concentrations of lead are due to its highly mobile nature. Hence, this lead consists not only of pristine radiogenic and ^{204}Pb but also mobilized radiogenic lead. The results also indicate high concentrations in SiO_2, P_2O_5, K_2O, CaO, and V_2O_3. We interpret this as a result of electron beam overlap with minor phosphates and perhaps coffinite intimately intergrown with the pitchblende.

Table 1. Composition of Pitchblende Žirovski Vrh (wt.%).

	%		%	Traces
UO_2	89.34	La_2O_3	0.06	Na
SiO_2	2.14	Ce_2O_3	0.40	Co
MgO	n.d.	Pr_2O_3	n.d.	Ni
Al_2O_3	0.16	Nd_2O_3	0.23	Cu
P_2O_5	0.86	Sm_2O_3	0.09	As
S	0.27	Eu_2O_3	0.16	Se
K_2O	0.55	Gd_2O_3	0.01	Ag
Cao	0.80	Tb_2O_3	0.07	Cs
TiO	0.07	Dy_2O_3	0.34	Th
V_2O_3	0.90	Ho_2O_3	0.18	
Cr_2O_3	n.d.	Er_2O_3	n.d.	Totals = 104.1%
MnO	0.24	Tm_2O_3	0.14	
FeO	0.22	Yb_2O_3	n.d.	
Y_2O_3	0.31	Lu_2O_3	0.06	
ZrO_2	0.04	HfO_2	0.11	
BaO	0.02	PbO	6.34	

Table 2. Composition of Coffinite Žirovski Vrh (wt.%).

	%		%	Traces
UO_2	64.45	La_2O_3	0.30	Na
SiO_2	16.41	Ce_2O_3	1.08	Co
MgO	0.16	Pr_2O_3	0.30	Ni
Al_2O_3	1.31	Nd_2O_3	1.54	Cu
P_2O_5	1.13	Sm_2O_3	0.62	As
S	0.17	Eu_2O_3	0.51	Se
K_2O	0.57	Gd_2O_3	0.66	Ag
Cao	0.27	Tb_2O_3	0.78	Cs
TiO	0.38	Dy_2O_3	0.70	Th
V_2O_3	0.80	Ho_2O_3	1.05	
Cr_2O_3	0.20	Er_2O_3	0.89.	Totals = 102.5%
MnO	0.23	Tm_2O_3	0.82	
FeO	0.49	Yb_2O_3	1,00	
Y_2O_3	0.84	Lu_2O_3	1,16	
ZrO_2	0.20	HfO_2	1.85	
BaO	0.35	PbO	1.27	

The high totals may also be a result of such overlap, since subtracttion of these elements leads to acceptable results.

Coffinite: The composition of coffinite is displayed in Table 2. A striking feature are the high sums (> 102%) and high concentration in lanthanides (12.25 wt.% REE). The analyses also indicate high concentrations in Hf (1.85 wt.% HfO_2). Likewise pitchblende, other oxides like Al_2O_3, P_2O_5, K_2O, and V_2O_3 were detected. However, we believe also that in this case it is due to contamination from phosphates and silicates intimately intergrown with coffinite. A very important result, however, is that even after subtraction of these elements from the totals, the sum is still close to 100% (97.87%). Taking into account the analytical uncertainties, we belive that this result has a severe consequence to the interpretations of electron microprobe analyses of coffinite. In all previous analyses of coffinite published in the literature, any considerable shortage of the totals was explained as due to the presence of OH substituting for other cations in the coffinite structure. However, the major part of these analyses either did not include the REE or only some of these elements were analyzed. If in our case we would ignore the REE elements, Zr, and Hf, we would have a shortage of 14.1%, which would have been attributed to OH in the coffinite structure. Our results indicate that the amount of OH (if present) is much smaller than anticipated. Ignoring the REE, Zr, and Hf, would certainly lead to erroneous results and misleading interpretations.

A striking feature is the high preference of Hf, Zr, and REE to coffinite in comparison to pitchblende which is probably structure-controlled.

3.2 Carbonaceous material

In reflected light, no visible inclusions of uraniferous minerals were observed in the carbonaceous material or graphite-like objects. However, carbonaceous materials are potential hosts for uranium, REE, Zr, V, etc. Consequently, they were subject to a detailed SEM study. An X-ray spectrum of an area of 2 mm^2 collected at 30 keV excitation voltage indicated without doubt that the material is highly enriched in U and other elements (fig. 7). In addition to the high concentrations in U, considerable amounts of Al, Si, S, Ca, Cs, REE, As, Y, etc. were recorded. This illustrates the complexity of the assemblages enriched in these elements.

Under the SEM the carbonaceous material and graphite-like objects were found to be loaded with minute inclusions (< 10 microns, fig. 8). Surprisingly, these inclusions are dominantly oriented along one direction, specifically in the graphite-like objects (fig. 8). At higher magnification, it became evident that the inclusions are majorily of prismatic nature and hence it is expected that pitchblende is not the major component of these inclusions (figs. 9 and 10). Due to the high penetration depth of electrons in carbon, it was possible to image some of the inclusions below the polished surface of the graphite-like material to obtain information on the morphology of the inclusions in the third dimension (fig. 10).

Electron microprobe analyses of various inclusions indicate the quite complex nature of the assemblages in comparison to those found in the sandstone impregnations. In addition to pitchblende and coffinite, various phases with high concentrations in REE were found. Some of these phases were found to be selectively enriched in some lanthanide elements; e.g.: 15.1 wt.% Nd_2O_3, 1.96 wt.% SmO_2, 2.86 wt.% Gd, and 14.4

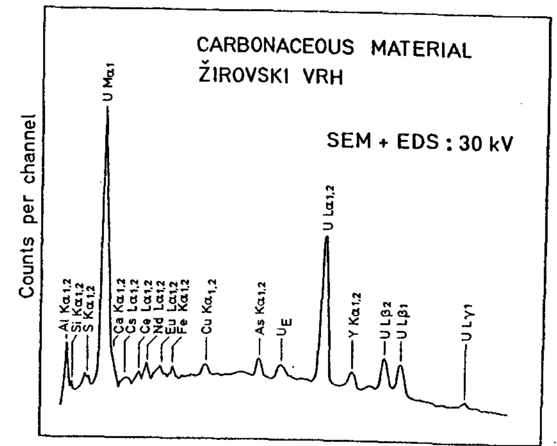


Fig. 7. EDAX spectrum of carbonaceous material depicting the K lines of Al, Si, S, Ca, Fe, Cu, and As, the L lines of REE, and M lines of Cs and U.

wt.% UO_2. The totals were always below 100% (between 40—80%). We believe that the major part of these REE-rich minerals consists of REE-rich carbonates.

Pitchblende: Table 3 depicts the composition of pitchblende in the carbonaceous material. Chemical composition of pitchblende in carbonaceous material is distinct from its counterpart in the impregnations: a) it contains lower concentrations in UO_2 and PbO; b) it is considerably enriched in lanthanide elements. This raises the question of the genetic link between the U-rich minerals in the carbonaceous material and their counterparts in the impregnations.

Coffinite: Coffinite in the carbonaceous material is also enriched in lanthanide elements, Zr and Hf. Likewise in the impregnations, coffinite here shows higher Hf than Zr concentrations. However, the total REE is lower than in coffinite in the impregnations. In contrast, the PbO-content is higher than in coffinite in the impregnations. Compared to the behaviour in the impregnations, this clearly indicates a different partitioning behaviour of these elements in the carbonaceous materials (table 4).

In order to get information on the abundance of minor and trace elements in the mineral assemblages of the carbonaceous material, PIXE (Proton-Induced X-ray Emission) analyses were carried out in several areas of a polished section. The collected spectrum is shown in fig. 11. In addition to the U-, M-, L-lines, X-ray lines of Al, Si, P, S, Ag, Ca, Ba, V, REE, Pb, Se, Y, and Zr were detected. In agreement with previous reports on Žirovski Vrh, no Th spectra were observed. This figure also demonstrates the superiority of PIXE over electron microprobe techniques for detection of heavy elements with low concentrations (see also fig. 7).

Table 3. Composition of Pitchblende in Carbonaceous Material Žirovski Vrh (wt.%).

	%		%	Traces
UO_2	68.39	La_2O_3	0.52	Na
SiO_2	4.52	Ce_2O_3	0.76	Co
MgO	0.24	Pr_2O_3	n.d.	Ni
Al_2O_3	0.47	Nd_2O_3	0.71	Cu
P_2O_5	1.31	Sm_2O_3	0.76	As
S	0.38	Eu_2O_3	0.61	Se
K_2O	0.59	Gd_2O_3	0.51	Ag
Cao	0.70	Tb_2O_3	0.90	Cs
TiO	0.36	Dy_2O_3	0.80	Th
V_2O_3	0.78	Ho_2O_3	0.89	
Cr_2O_3	0.18	Er_2O_3	0.81	Totals = 96.5%
MnO	0.29	Tm_2O_3	1.13	
FeO	0.45	Yb_2O_3	0.78	
Y_2O_3	0.51	Lu_2O_3	1.05	
ZrO_2	0.31	HfO_2	1.68	
BaO	0.32	PbO	4.83	

The origin of the carbonaceous material could be discerned by examination at high resolution with the SEM. Plant residues with well preserved cellular structure are quite abundant. The material now consists of pitchblende or pitchblende and coffinite (figs. 12 and 13).

Table 4. Composition of Coffinite in Carbonaceous Material Žirovski Vrh (wt.%).

	%		%	Traces
UO_2	62.23	La_2O_3	0.36	Na
SiO_2	12.95	Ce_2O_3	0.91	Co
MgO	0.25	Pr_2O_3	n.d.	Ni
Al_2O_3	6.19	Nd_2O_3	1.19	Cu
P_2O_5	2.99	Sm_2O_3	0.64	As
S	0.79	Eu_2O_3	0.08	Se
K_2O	0.65	Gd_2O_3	0.34	Ag
Cao	1.15	Tb_2O_3	0.68	Cs
TiO	0.46	Dy_2O_3	0.69	Th
V_2O_3	0.71	Ho_2O_3	0.73	
Cr_2O_3	0.11	Er_2O_3	0.23.	Totals = 101.7%
MnO	0.16	Tm_2O_3	0.55	
FeO	0.38	Yb_2O_3	0.48	
Y_2O_3	1.59	Lu_2O_3	0.77	
ZrO_2	0.19	HfO_2	0.94	
BaO	0.34	PbO	1.97	

4. Discussion

The uranium-rich mineralization in Žirovski Vrh is much more complex than anticipated in all previously published reports on this deposit. Uranium-rich minerals are present both as impregnations and inclusions in pristine carbonaceous materials. This raises the question of the genetic relationships between U and the rare earth elements. Compared to the ore in the impregnations, the carbonaceous materials and the graphite-like objects are enriched in REE. Also in the carbonaceous materials pitchblende shows higher concentrations of lanthanides than in the impregnations. If the emplacement of U, REE, Zr, and Hf were contemporaneous, then why do REE, Zr, and Hf show higher preference to pitchblende and coffinite in the carbonaceous materials? It is noteworthy that our investigations indicate the presence of REE-rich carbonates in carbonaceous materials. These minerals could have acted as traps for U introduced by solutions. Pitchblende and coffinite precipitated in the impregnations should then contain lower concentrations of these elements.

More difficult to explain is the relatively high concentrations of REE in coffinite compared to pitchblende in the impregnations, on the one hand, and the higher REE abundance of pitchblende compared to coffinite in the carbonaceous material, on the other. Crystal chemical effects cannot explain this contrasting behaviour. Nor could this feature be explained as a result of formation at different temperatures since both parageneses occur together. It is more plausible to attribute this feature to a high concentration of these elements in the carbonaceous materials prior to the U-ore emplacement. We suspect, however, that the high REE-content of pitchblende in the carbonaceous material is perhaps the result of the presence of submicroscopic clastic aggregates of REE-rich inclusions in pitchblende. The same may also hold for SiO_2, P_2O_5, K_2O, and CaO detected in both coffinite and pitchblende due to the presence of phosphates.

If all detectable minor elements in coffinite are measured with the electron microprobe, then the deviation of the totals from 100% is quite small. For this reason, we believe that the amount of H_2O or OH in the coffinite structure is very small. Previous reports on high OH-concentrations in coffinite are definitely in error due to lack of complete analysis.

5. Conclusions

Several conclusions can be drawn from the present investigations:

(1) The uranium mineralization in Žirovski Vrh is probably of sedimentary origin, perhaps cogenetic with the sandstone.

(2) Mobilization of UO_2 and PbO took place in a younger episode thus redistributing these elements among various uranium minerals.

(3) Carbonaceous materials enriched in REE-minerals acted as traps for U both during the primary mineralization and the late mobilization episodes.

(4) The total U/Pb ratios measured with the electron microprobe cannot be used to determine the age of the mineralizations since a) both elements are involved in the mobilization and b) the amount of ^{204}Pb and the $^{206}Pb/^{207}Pb$ is unknown so far.

Die Abbildungen 8, 9, 10, 11, 12 und 13 wurden ausgelassen.

ZIROVSKI VRH URANIUM MINE WATER MANAGEMENT

30.11.1999 Borsla, Bulgarien

Zmago Logar, Boris Likar, Ivan Gantar

SUMMARY

Zirovski vrh uranium mine and its facilities are situated on the north-eastern slopes of the Žirovski Vrh ridge (960 m) and on the southern slopes of Crna gora (611m) respectively. Mine elevation is from 430 m (bottom of the valley) to 580 m (P-1 adit). All effluents from the mine and mill objects flow into the Brebovscica river (with average yearly flow of 0.74 m^3/s):

- run off mine water,
- mine waste pile Jazbec outflow,
- mill tailings Boršt outflows,
- effluents from mine temporary mine waste piles P-1, P-9, P-36 of minor significance.

The first three are monitored in details as well as the recipient surface water flows (the Todrascica brook and the Brebovscica river). The impact of radioactive polluted outflows on named waters is proved, but far under the maximal permitted limit.

The future planes are to minimise the uranium concentrations in the run off mine water by target underground drilling to avoid clean water contamination and prevent contamination of the mine waste pile and tailings waters by percolation.

Area	Mio USD
Underground mine remediation	19.00
Mine waste pile remediation	6.50
Mill tailings remediation	2.24
Total investment costs	**27.74**

Above figures do not include operation costs of the Zirovski Vrh Mine, approximately 2.2 Mio USD per year nowadays. The last implementation schedule foresights the end of remediation works in year 2005. After that starts trial monitoring of 5 years to prove the quality of performed work.

1. INTRODUCTION

Zirovski Vrh Uranium Mine is situated 45 km west from Ljubljana the capitol of Slovenia. The ore body in Groeden sandstone was discovered in 1960, the ore production started in 1982, yellow cake production in 1984. The yellow cake production ceased in 1990. The production site remediation activities are going on since that time. Only 620,000 tons of ore with 0.7 kg of U per ton was processed and 450 tons of yellow cake was produced.

Zirovski vrh uranium mine and its facilities are situated on the north-eastern slopes of the Žirovski Vrh ridge (960 m). The underground mine elevation is from 430 m (bottom of the valley) to 580 m (P-1 adit). The mill was located in the valley of the river Brebovscica (415 m) and the mill tailings (530 –560 m) on the southern slopes of Crna gora mountain (611m). Figure 1 shows location of all important mine objects.

The clime is subalpine with snow (1 m) and low temperatures in winter (minimum – 28 ^{0}C, average – 0.5 ^{0}C) and hot weather in summer (maximum 37 ^{0}C, average 17 ^{0}C). The precipitation's are in the range between 1390 mm/m^2 in dry years and 2450 mm/m^2 in wet years, respectively. Average total annual precipitation is 1800 mm/m^2. Ratio between rainfall and snowfall is 85 % of rain and 15 % of snow in a year. Evaporation rate is ca. 500 mm/a.

The effluents from the mine and mill objects flow into the Brebovscica river (with average yearly flow of 2650 m^3/h (740 l/s). The impact of radioactive polluted outflows on nearby surface waters is proved, but far under the maximal permitted limit values. The whole area is part of the Sava river tributary system.

2. PRESENT WATER MANAGEMENT

There are three main objects of concern as sources of radioactive polluted effluents: the underground mine, the mine waste pile and the mill tailings. The effluents from these objects have been monitored in details since the start up of the ore production. Effluents from other minor sources like smaller mine spoil heaps, adits etc. have been monitored periodically. The annual effective dose contributed to the members of critical group by water pathway is negligible (0.015 mSv: U, Ra-226, Pb-210, Th 230). [IJS-1998] The data are shown for typical year 1998 with yearly rainfall of 1834 mm.

Present monitoring of the mayor mine effluents and the Brebovscica river and Todraski brook is going on since the start of the production in 1982. The flows are measured and sampled manually on daily basis. Monthly composites are made up of the daily samples and are analysed on : uranium, radium-226, ammonia, calcium, magnesium, iron, sulphates and chlorides. Table 1 shows yearly average values for contaminants in the surface waters. The sediments in the surface water flows are sampled, uranium and radium-226 are determined. Of course, underground waters are monitored regularly in the whole area even in alluvial sediments of the Brebovscica river (Figure 2). Periodicaly are monitored surface waters above the mine objects. Organisation of this work is responsibility of the Radiological Safety Department.Part of the sampling and monitoring is entrusted to the contractors Institute of Josef Stefan and Institute of Occupational Safety, Ljubljana.

2.1. Run off the Mine Water

The mine dewaters by gravity through the tunnel P-10 at the lowest point of the mine at 430 m. Average yearly mine water flow is 70 – 85 m^3/h (20 – 24 l/s) depending on the rainfall. The water is not chemically contaminated.

The mine water was treated mechanically (coagulation, floculation, filtering) at the water treatment plant during the mine exploitation. Normally, water with less than 5 mg/l solids was discharged into the Brebovscica river.

2.1.1. Water suppliers in the mine structures

Water suppliers in the mine structure are tectonically fractured sandstone's and conglomerates. Fractures as consequence of folding, appear in the south-western part of the ore deposit. We observe them in the apex of the folds in the shape of strongly clivaged rocks.

Another type of the water supplier is conglomerate from the third horizon, where carbonates prevail in the shape of limestone and dolomite pebbles, where a binder is composed of carbonates. This carbonate horizon is leached of in tectonic fractured faults, small caverns are created and washed out cracks.

2.1.2. Sources of Mine Water Pollution

Waters that inflows into the open mine rooms, are contaminated with uranium depending to the type of water supplier. It can happened during the way through the rock. In much more cases, they get contaminated when percolate over opened ore bodies due to leaching of uranium and its daughter's products.

Waters that spring contaminated from the rock are bound to the fractured zones, that cut and crush the ore bodies, drain from folded rock strata in the north-eastern part of the ore body. Bigger number of contaminated mine water sources are exploration boreholes that drain through ore horizons.

Additional contamination of the mine water is percolation through stopes and tunnels, where they cut the ore zones. The same mechanism applies to the waters that spring uncontaminated.

2.1.3. Mine Water Flows and Contamination

Different quantities of the mine water inflows into horizons referring the level.

On the highest horizon the mine exploitation started in 1982. We would expect bigger inflows due to surface proximity. This is not the case, however water inflow strongly depends on weather conditions. With lower horizons constructions this horizon became dry. The biggest mine water inflows are at the mine level 430 m that is the lowest and at the level of the Brebovscica river. Upper horizons grow up drier.

We get only 1.4 l/s water from all sources at the horizon 580 m. This water outflows through the drain boreholes and blind shafts to the lower horizon. Water contains only 26 µgU/l in average. Horizon 555 is small intermediate horizon that is practically dry. We can observe only small springs in faulted zones and trickled out pore water. This level contributes only 0.2 l/s with 769 µgU/l.

At the level 530, which is situated in the middle of the ore body, the waters from horizon 555 are collected and partially from horizon 530. These waters are joined by substantial quantities of seepage waters from this horizon. The contribution from this horizon is 2.9 l/s. They are not so contaminated, contain only 129 µgU/l.

Waters inflow to the horizon 480 is from drainage boreholes and from blind shafts at horizon 580 and spring waters. Contribution from this horizon is only 1.3 l/s and contains 129 µgU/l.

Horizon 430 m is the lowest in the mine and presents drainage area for the whole mine. Here are numerous springs from fractured zones, from stopes and inflows from boreholes. The contribution is 16,9 l/s in average. The water quality differs considerably. Contaminated water comes from water suppliers that cut ore bodies e.g. exploration boreholes that cut more ore bodies are the worst. Additional problems represent flooded stopes where the contaminants concentrations exceed 6,000 µgU/l. The dilution at this horizon is big enough so the average concentration is 209 µgU/l. See the table 1 and the figures 3 – 5 for details.

2.2. Mine Waste Pile Jazbec Effluents

Mine waste pile is situated in narrow ravine, where two background water flows from two smaller ravines confluence in the brook called Jazbec. The Jazbec culvert was built under the spoil heap on the bottom of the small ravine, to drain surface water from background area before the start of construction. There is approximately 1.5 Mio ton of mine waste including 50,000 ton of neutralised red mud from mill process and 15.000 ton of debris from demolished mill buildings.

All waters coming into the mine waste heap due to rainfall and from background (surface, surrounding underground) outflow through Jazbec culvert. Flow has torrential nature and varies from 1 to 25 m^3/h. The background surface water dilutes the seepage from the pile. Average concentration of uranium is 310 µgU/l and varies up to 575 µgU/l. See table 1 for details.

The minor part of contaminated water outflows as underground water that is not collected in the culvert. Maximal contamination of underground water in alluvial sediments is 15 µgU/l. Carstic nature of the pile ground complicates the situation with priority carstic water pathways. Figure 6 shows the contaminants average yearly concentration in the mine effluent since the start of monitoring.

2.3. Mill Tailings Borst Effluents

The mill tailings contains 620,000 ton of mill waste and 70,000 ton of mine waste. The surface is covered temporary by thin soil layer. Rainfall and some underground water together flow through the mill tailings and dissolve the contaminants. The effluent flows are mill tailings underground water (sampling point SDIJ), surface outflow via mill tailings pond Borst and in minor degree the underground drainage tunnel. The flow of the mill tailings underground water flow (SDIJ) decreased considerably after the construction of the drainage tunnel. The concentration of the contaminants rose by five times due to lack of dilution by the underground water.

Simplified water flows and the contaminants concentrations from the tailings are shown in the table 2.

2.4. Other Effluents

Other effluents, periodically monitored are:

- Tunnel P-9 run off mine water
- P-36 mine waste backfill weathering seepage water
- P-1 temporary mine waste heap weathering seepage water.

Their impact is negligible due to small flows and/or low contaminants concentrations.

3. PROPOSED SOLUTIONS

The limits for concentrations of the contaminants have been given by authorised limits or are stated in the existing regulative. These objectives are presented in the table 4, and have been taken into consideration for the design of the remediation actions. During the remediation works in the mine the water treatment plant will operate to minimise the emission of the solids into the Brebovscica river.

General request is the site monitoring period of 5 years after finishing of implementation which has been given by the Authorities.

3.1 Run off mine water

Objectives to minimise generation of the contaminants in the run off mine water will be achieved by engineered works:

- Caption boreholes for dewatering of the critical mine stopes and tunnels, to avoid water contacts with ore bodies.
- Isolation of flooded stopes at the lowest level, where is impossible to use and implement the boreholes.
- Implementation of drainage boreholes from level 430 m upwards opposite to the direction of decline of the strata and foulted zones. The test boreholes have proved this idea. Contaminated water flow from exploration boreholes decreased or ceased in total. See the figure 7.

The plan is to minimise concentration of uranium in mine water from 20 – 30 % with implementation of designed scope of work.

3.2. Mine Waste Pile effluents

Objectives to minimise generation of the contaminants water outflow respectively will be achieved by engineered works:

- Repair of a part the PEHD pipelines under the mine waste pile to minimise water inflow into the waste body. Leaching of the contaminants will be prevented partially this way.
- With engineered multi layers cover weathering will be prevented and side waters inflow will be prevented as well.
- With surface diversion of the Jazbec brook the flood waters will not endanger the pile.

With implementation of these measures the concentration of the contaminants will remain lower as it is prescribed in authorised limits.

3.3. Mill Tailings Borst Effluents

The designer of the mill tailings long-term remediation declared that there will be no seepage effluents from the tailings after consolidation of the tailing materials. This is the reason why authorised limits have not been given by the authorities.

3.4. Other Effluents

Relocation of all temporary waste piles into the central mine waste pile Jazbec has been planned. The areas will be cleaned and adequately recultivated.

4. CONCLUSIONS

We believe, the impact by the water pathway on the environment will be minimal, if not negligible, after the implementation of the listed measures, and much lower than requested by authorities.

Funding of the planned activities is rather slow and the last plan foresees the conclusion of the field works in the year 2005.

5. TABLES AND FIGURES

Table 1: Surface recipients average values for year 1998
[Source: JRO-1999]

Water course	Average flow	Uranium	Radium-226	Uranium	Radium
	m^3/h	$\mu g/l$	Bq/m^3	Kg/a	MBq/a
Brebovscica river	3368	15.5	4	332	101,5
Todraz brook	367	2.5	13	33	47

Table 2: Mine and waste pile effluents, averages for the year 1998
[Source: JRO-1999]

Effluent	Average flow	Uranium	Radium-226	Ammonia	Ca^{2+}	Mg^{2+}	Cl^-	SO_4^-
	m^3/h	$\mu g/l$	Bq/m^3	mg/l	mg/l	mg/l	mg/l	mg/l
Run off mine water	83	246	46	0.2	22	2.9	3.9	20
Mine waste pile Jazbec	34	309	21	0.8	81	29	7.2	246

Table 3: Mill tailings effluents, averages for the year 1998
[Source: JRO-1999]

Effluent	Average flow	Uranium	Radium-226	Ammonia	Ca^{2+}	Mg^{2+}	Cl^-	SO_4^-
	m^3/h	$\mu g/l$	Bq/m^3	mg/l	mg/l	mg/l	mg/l	mg/l
SDIJ	0.9	590	223	56	354	68	344	1163
Surface outflow from control pond	5.1	600	1461	13	206	25	87	569
Seepage outflow from drainage pond	0.2	544	423	4	217	26	87	528
Underground drainage tunnel	5.1	3.4	12	0.2	23	5.8	59	37

Table 4: Comparison of maximal permitted concentrations of contaminants for mine effluents and surface waters

Expected effluent flow after remediation		MPC for potable water		Authorised limits		Authorised limits Quantity/annum	
	Average flow	Uranium	Radium-226	Uranium	Radium-226	Uranium	Radium-226
	m^3/h	$\mu g/l$	Bq/m^3	$\mu g/l$	Bq/m^3	Kg/a	MBq/a
General		50	1000	-	-	-	-
Run off mine water	60 - 100	-	-	250	60	170	50
Mine waste disposal	34	-	-	510	40	85	25
Mill tailings SDIJ		-	-	No flow	No flow	No flow	No flow
Surface outflow from control pond		-	-	No flow	No flow	No flow	No flow
Seepage outflow from drainage pond		-	-	No flow	No flow	No flow	No flow
Mill tailings drainage tunnel	5	-	-	< 50	< 1000	-	-
Todrascica brook	367[1]	-	-	< 50	60	-	50
Brebovscica river	3368[1]	-	-	< 50	40	-	-

Note [1] : These are average hourly flows for the water courses in the year 1998.

6. SOURCES

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[JRO-1999] - Interoffice Report on Implementation of Monitoring in 1998, Jozef Rojc, Todraz, February 1999 (in Slovenian)

T. Begus - 3 D view of the Mine site (1999)

[IRGO-1996] - Cadez Franc: Hydrogeological and Geomechanical Characteristic of the Mine Waste Pile Jazbec and its Impact onto Groundwater, Ljubljana, 1996 (in Slovenian)

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2.1.2 Sava-Becken

Das Sava-Becken erstreckt sich nördlich des Flusses Sava in ost-westlicher Richtung über mehr als 50 km von dem Ort Moravče im Westen bis hinter die Stadt Laško im Osten (Abb. 1). Seine heutige Nord-Süd-Erstreckung beträgt aufgrund der starken tektonischen Einengung maximal 3 km. Dieser Wert wird im Bereich der Ortschaft Zagorje erreicht.

Das Sava-Becken ist wegen seiner Kohlevorkommen schon seit mehr als 100 Jahren Gegenstand geologischer Untersuchungen. Neben den Kartierarbeiten von BITTNER (1884) und Teller (1907) entstanden schon früh Arbeiten über die Makroflora (ETTINGSHAUSEN 1872, 1877, 1885) und Fauna (HOERNES 1876; TELLER 1886) der kohleführenden Schichten. Bis heute sind der komplizierte geologisch-tektonische Bau des Beckens (z.B. MUNDA 1953; KUŠČER 1967; KUŠČER & MITREVSKI 1979; GRAD et al. 1996) sowie die unsichere stratigraphische Stellung seiner Sedimente (z.B. ODIN et al. 1994; vgl. auch Kap. 5) Gegenstand zahlreicher Arbeiten.

2.1.1.1 Sedimentäre Abfolge

Wie im Becken von Gornji Grad beginnt die Sedimentation auch im Sava-Becken mit terrestrischen klastischen Ablagerungen. Diese werden nach JELEN et al. (1992) in Abgrenzung zu den eozänen Socka-Schichten (ROLLE 1858) als Pseudo-Socka-Schichten bezeichnet. Ein Kohleflöz untergliedert diesen Komplex in die unteren und oberen Pseudo-Socka-Schichten (Abb. 5 und 6), wobei erstere als fossilfreie Konglomerate, Sande und hellgraue Tone fluviatilen Ursprungs beschrieben werden

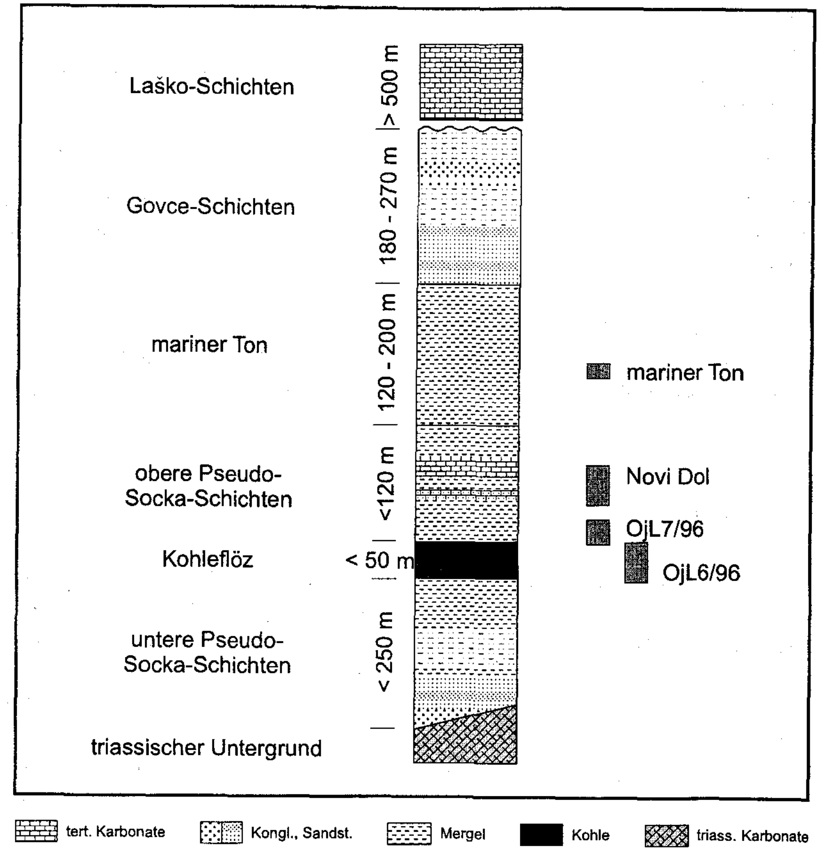


Abb. 5: Vereinfachtes Normalprofil der tertiären Abfolge im Sava-Becken und stratigaphische Lage der bearbeiteten Profile. Mächtigkeitsangaben nach MUNDA (1953) und ODIN et al. (1994).

(KUŠČER 1967; CIMERMAN 1979; ODIN et al. 1994). Zum Hangenden wird der Tonanteil dominanter und geht unter Zunahme des organischen Anteils in die Kohleablagerung über. Die unteren Pseudo-Socka-Schichten können eine Mächtigkeit bis zu 250 m erreichen (KUŠČER 1967; UHAN 1991; ODIN et al. 1994).

Die Kohle der Pseudo-Socka-Schichten ist als eine dunkle, harte Braunkohle mit relativ hohem Inkohlungsgrad vom Rang einer Matt- bis Glanzkohle ausgebildet (KUŠČER 1967; MARKIČ mündl. Mitt. 1996). Die auftretenden Lithotypen lassen sich nach STOPES (1919) überwiegend als Durain

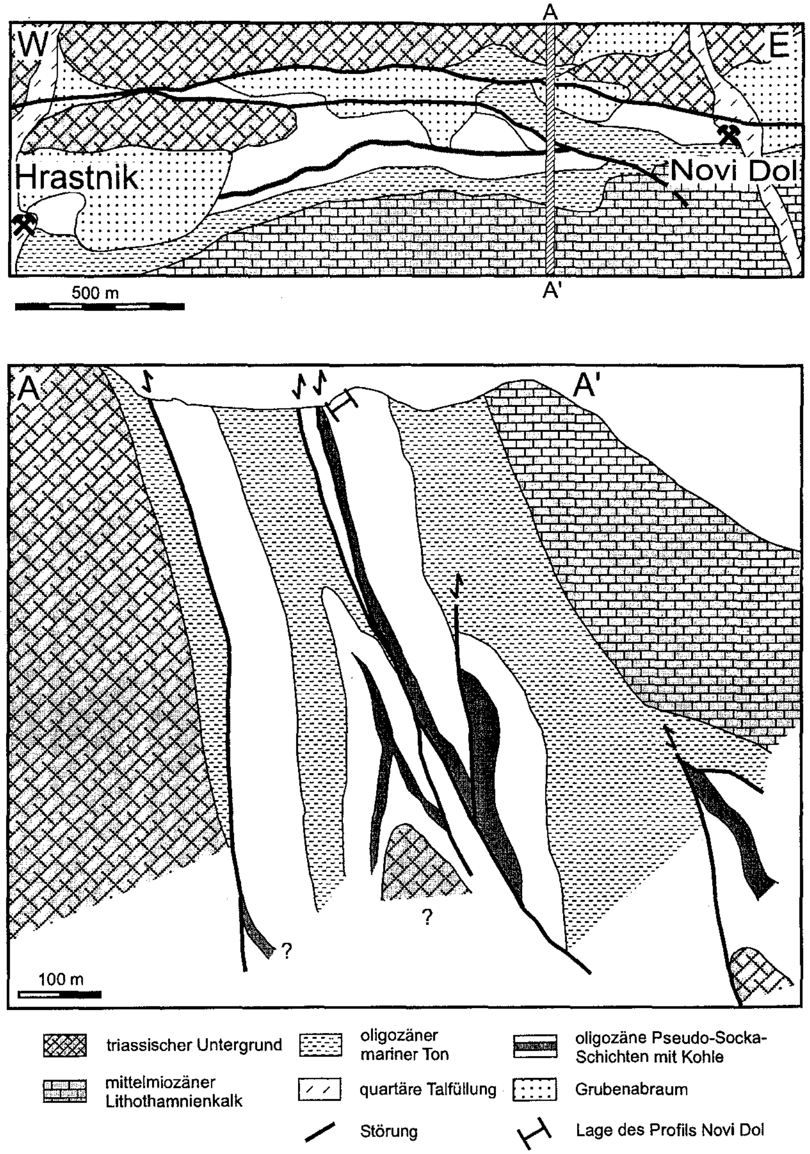


Abb. 6: Geologischer Aufbau des Sava-Beckens zwischen Hrastnik und Novi Dol. Das Profil Novi Dol befindet sich direkt auf der Profillinie A - A' (nicht überhöht; verändert nach KUŠČER & MITREVSKI 1979).

(Mattkohle) bis Clarain (Streifenkohle) mit zum Teil hohen Anteilen an Vitrain (Glanzkohle) einordnen (MARKIČ schriftl. Mitt. 1996). Der Brennwert der Kohle wird von KUŠČER (1967) mit durchschnittlich etwa 4500 kcal/kg angegeben. Die Abfolge innerhalb des Flözes geht vom Liegenden mit stärker tonigen Anteilen in einen von Karbonateinschaltungen dominierten Abschnitt über; nur der obere Teil des Flözes ist von besserer Qualität (KUŠČER 1967; UHAN 1991; HAFNER 1996). Über die gesamte Mächtigkeit treten vereinzelt bis regelmäßig vulkanoklastische Einschaltungen auf (z.B. RUMPF 1884; BUSER 1979; ODIN et al. 1994). An Fossilien sind aus dem Flöz des Sava-Beckens bereits seit dem letzten Jahrhundert Reptilien- und Säugerreste - vor allem von Anthracotherien - bekannt (HOERNES 1876; TELLER 1886; THENIUS 1959). Auch die Makroflora und ebenso die Süßwasserfauna der karbonatischen Zwischenmittel wurden früh beschrieben (ETTINGSHAUSEN 1872, 1877, 1885; BITTNER 1884). Jüngere vor allem palynologische Arbeiten blieben dagegen bis auf wenige Ausnahmen unveröffentlicht und beschränken sich meist auf die Angabe einzelner stratigraphisch wichtiger Taxa (MARKIČ et al. 1993; ODIN et al. 1994; GRAD et al. 1996; JELEN mündl. Mitt. 1996). Für das Kohleflöz wird meist eine Mächtigkeit von etwa 20 bis maximal 30 m angegeben (z.B. KUŠČER 1967; MIHAJLOVIC & JUNGWIRTH 1988; ODIN et al. 1994), wobei es zu den Beckenrändern hin ausdünnt und z.B. östlich von Laško (Abb. 1) nur noch wenige Dezimeter umfaßt (KUŠČER 1967; GRAD et al. 1996).

Die oberen Pseudo-Socka-Schichten werden im Becken geprägt von lakustrinen Kalksteinen und Mergeln in unterschiedlichen Anteilen und Mächtigkeiten. Der Übergang von der Kohle zum Hangenden ist stellenweise als bitumen- und diatomeenreicher Laminit ausgebildet, der in wechselnden Mächtigkeiten auftritt und als „Brennschiefer" oder „sapropelic overburden" bezeichnet wird (MARKIČ mündl. Mitt. 1998). KUŠČER (1967) erwähnt östlich von Zagorje ein Vorkommen feinlagiger Silikatschiefer, das möglicherweise diesem „Brennschiefer" entspricht. Aus den oberen Pseudo-Socka-Schichten wurde neben der Süßwassermolluskenfauna vor allem die Makroflora beschrieben (STUR 1871; BITTNER 1884; MIHAJLOVIC & JUNGWIRTH 1988). Außerdem sind Fischfossilien bekannt (GORJANOVIC-KRAMBERGER 1884, 1886, 1891, 1895 zitiert in KUŠČER 1967), welche als Hinweis auf zum Hangenden hin teilweise brackische Umweltbedingungen interpretiert werden (z.B. KUŠČER 1967; CIMERMAN 1979). Die Mächtigkeit dieser Ablagerungen wird mit 15 bis 120 m angegeben (UHAN 1991; ODIN et al. 1994).

Analog zur tertiären Abfolge bei Gornji Grad geht die terrigene Sedimentation auch im Sava-Becken zum Hangenden hin in marine Ablagerungen über. Flachmarine Ablagerungen, wie sie bei Gornji Grad regelmäßig anzutreffen sind, bilden hier jedoch eine seltene Ausnahme (KUŠČER & MITREVSKI 1979). Es dominieren graue Mergeltone, die mit dem Vorkommen von Foraminiferen, Dinoflagellatenzysten und Nannoplankton (z.B. JELEN et al. 1988/89; BRICL & PAVŠIČ 1991) vollmarine Bedingungen belegen. Die Tone sind tektonisch bedingt nur geringmächtig; ODIN et al. (1994) geben 120 bis 200 m Mächtigkeit an. Diese mergelige Abfolge wurde bisher nur informell beschrieben und findet sich in der Literatur meist als "oligozäne marine Tone" (z.B. KUŠČER 1967;

ODIN et al. 1994; GRAD et al. 1996). Zum Teil wird jedoch auch in Analogie zur ungarischen tertiären Schichtenfolge der Bergriff „Kiscell Clay" verwandt (z.B. CIMERMAN 1979; JELEN et al. 1992).

Die im unteren Teil der Abfolge reinen Tonmergel gehen zum Hangenden hin durch graduelle Zunahme der Sandfraktion in die Govce-Schichten über, die bereits ins Miozän gestellt werden (ODIN et al. 1994). Diese sind von klastischer Sedimentation mit Sandsteinen und Konglomeraten geprägt und erreichen Mächtigkeiten von 180 bis 270 m (ODIN et al. 1994). Die Abfolge wird diskordant von Kalken mit Corallinaceen-Biohermen überlagert, die nach PLACER (in ODIN et al. 1994) ins Baden datieren. Mit diesen sogenannten Laško-Schichten, für die MUNDA (1953) eine Mächtigkeit von mindestens 500 m angibt, endet die tertiäre Abfolge des Sava-Beckens.

SAVA-BECKEN ZUSAMMENFASSUNG

Die gute Erhaltung der relativ reichen Palynoflora der Profile des Sava-Beckens ermöglichte eine quantitative Auswertung sowohl in paläoökologischer als auch paläoklimatischer Hinsicht.

Mit Hilfe multivariater statistischer Methoden wurde die ökologische und fazielle Entwicklung im Ablagerungsraum rekonstruiert (Abb. 27).
Dieser läßt sich zunächst als von Taxodiaceen und Farnen dominiertes Braunkohlemoor beschreiben, in dem sich aufgrund schwankender Grundwasserspiegel als Folge wechselnder Subsidenzraten immer wieder kleinere Seen mit riedbestandenen Uferbereichen bildeten. Mit Beginn der Sedimentation der oberen Pseudo-Socka-Schichten etablierte sich ein limnisches Milieu. Nach der Ausbildung eines größeren Sees mit mehreren Kilometern Durchmesser veränderte sich die Vegetation. Die Taxodiaceen gingen zurück und Auenwälder dominierten, die mit zunehmendem Absinken des Grundwasserspiegels sukzessive von trockeneren Elementen des mesophilen Mischwaldes verdrängt wurden. Später wurde das Gebiet von der fortschreitenden Transgression erreicht, und die marine Sedimentation setzte ein.

Die paläoklimatische Auswertung mit Hilfe des Koexistenz-Ansatzes erbrachte folgende Ergebnisse:

- Jahresmitteltemperatur: 16 bis 19 °C
- Mittlere Temperatur des kältesten Monats: 6 bis 9 °C
- Mittlere Temperatur des wärmsten Monats: 25 - 28 °C
- Jahresniederschläge: 1100 - 1300 mm
- Niederschlag des wärmsten Monats: 70 - 90 mm
- Niederschlag des feuchtesten Monats: 175 - 180 mm
- Niederschlag des trockensten Monats: 20 - 50 mm
- Relative Feuchte: 72 bis 74 %.

Die mit dem Koexistenz-Ansatz erzielten Ergebnisse weisen auf große klimatische Stabilität während der Sedimentation der untersuchten Abfolge im Sava-Becken hin. Die Befunde sind in sich konsistent und zeichnen das Bild eines warmtemperierten, sehr humiden Klimas vom Typ Cfa mit nur geringen jahreszeitlichen Niederschlagsschwankungen. Längere Frostperioden erscheinen ausgeschlossen. Ein rezentes Analogon zu den klimatischen Verhältnissen im Sava-Becken während des Ablagerungszeitraums der Pseudo-Socka-Schichten bildet das Klimadiagramm von Ningpo/Ostchina (Abb. 31; WALTER & LIETH 1960/67).
Die Auswertung der statistischen Verteilungsparameter hinsichtlich ihrer Aussagekraft und Verwertbarkeit bezüglich der Charakterisierung des Paläoklimas erbrachte am Beispiel der Jahresmitteltemperatur eine sehr enge Korrelation mit der Anzahl der ausgewerteten Taxa, so daß diese Parameter nicht als zusätzliche Hilfsmittel der Klimaanalyse angesehen werden können.

Lediglich die Schiefe verhält sich als einziger der statistischen Parameter der Klimaaussage der Koexistenz-Intervalle entsprechend. Ob hier ein signifikanter klimabezogener Zusammenhang besteht oder methodische Einflüsse eine Rolle spielen, kann nur durch weitergehende Betrachtungen an Floren verschiedener Klimaprovenienzen geklärt werden.
Insgesamt dokumentieren die Ergebnisse der palynologischen Bearbeitung, daß im Oligozän des Sava-Beckens die beobachteten Vegetations- und Klimaentwicklungen unabhängig voneinander verliefen. Die Florenentwicklung war innerhalb des sehr einheitlichen warmtemperierten, humiden Klimas wahrscheinlich ausschließlich von der regionalen tektonisch-geographischen Entwicklung gesteuert.

PALÄOKLIMA IM OSTALPENRAUM

Die Auswertung von 25 obereozänen bis miozänen Palynofloren mit dem Koexistenz-Ansatz zeichnet ein relativ einheitliches Bild des klimatischen Geschehens im Ostalpenraum. Es wurden durchgehend Cfa-Klimate nachgewiesen. Darüber hinaus treten bestimmte Zeitabschnitte mit sich verändernden paläoklimatischen Verhältnissen deutlich hervor:

Eine deutliche Abkühlung und der Rückgang des Sommerniederschlags im Eozän/Oligozän-Grenzbereich ist nördlich der Alpen dokumentiert. Diese kann neben der globalen Tendenz zu einem kühleren Klima auf die erste Isolation der Paratethys zurückgeführt werden, die eine deutliche Abschwächung des ozeanischen Einflusses zur Folge hatte.

Ebenfalls in dieser Region zeigt sich ein Abschnitt im Bereich vom Unter- zum Mittel-Miozän (Ottnang bis Baden) mit einem Trend zu kühleren Temperaturen in den Winter- und Jahresmitteltemperaturen; die Sommertemperaturen ändern sich nicht, so daß hier auf Änderungen in der Saisonalität geschlossen werden kann. Hier scheint mit dem Rückzug der Paratethys aus dem Molassebecken bei gleichzeitiger Regression der Nordsee ebenfalls die Abnahme des ozeanischen Einflusses das Klima zu bestimmen.

Eine weitere signifikante Abkühlung ist vom Mittel- zum Ober-Miozän im pannonischen Raum zu verzeichnen. Ebenso weisen auch die Sommerniederschläge in abnehmende Richtung. Diese steht in Zusammenhang mit einer verstärkten Hebung der östlichen Ostalpen und der endgültigen Abschnürung der Paratethys von den Ozeanen.

Diese Ergebnisse werden durch die aus der oligozänen Palynoflora des slowenischen Sava-Beckens hochauflösend gewonnenen Klimadaten durchweg unterstützt.
Die beobachtete klimatische Entwicklung im ostalpinen Raum insbesondere der Temperatur ist stark von der regionalen Tektonik und der davon abhängigen Paläogeographie beeinflußt. Gleichzeitig wirken jedoch auch globale Veränderungen auf das komplexe System des regionalen Klimas. Die resultierende Land-Meer-Verteilung gibt dabei den entscheidenden Ausschlag über die Stärke der Saisonalität und damit der Kontinentalität des Klimas (Abb. 35).

AUSBLICK

Die in der vorliegenden Arbeit vorgenommenen Auswertungen von Palynofloren aus der Literatur geben einen Überblick über die klimatische Entwicklung im ostalpinen Raum im Oligo- und Miozän. Weitergehende Untersuchungen zur quantitativen Paläoklima-Rekonstruktion in diesem Zeitraum sollten sich hochauflösend vor allem auf die kritischen Zeitabschnitte des Grenzbereiches Unter-/Mittel-Miozän und des Ober-Miozäns konzentrieren, um die beobachteten klimatischen Veränderungen zeitlich noch genauer zu erfassen. Vor allem eine Auswertung von Profilen der südlichen Alpenregionen ist für eine Vervollständigung des Gesamtbildes sowie zur Erfassung der Entstehung des mediterranen Klimas dringend nötig.
Die mit dem Koexistenz-Ansatz gewonnenen quantitativen Klimaabschätzungen liefern darüber hinaus die Grundlage für computergestützte Modellrechnungen, welche eine Rekonstruktion der tertiären atmosphärischen Zirkulation, die ja im Grunde das eigentliche „Klima" ausmacht, ermöglichen.

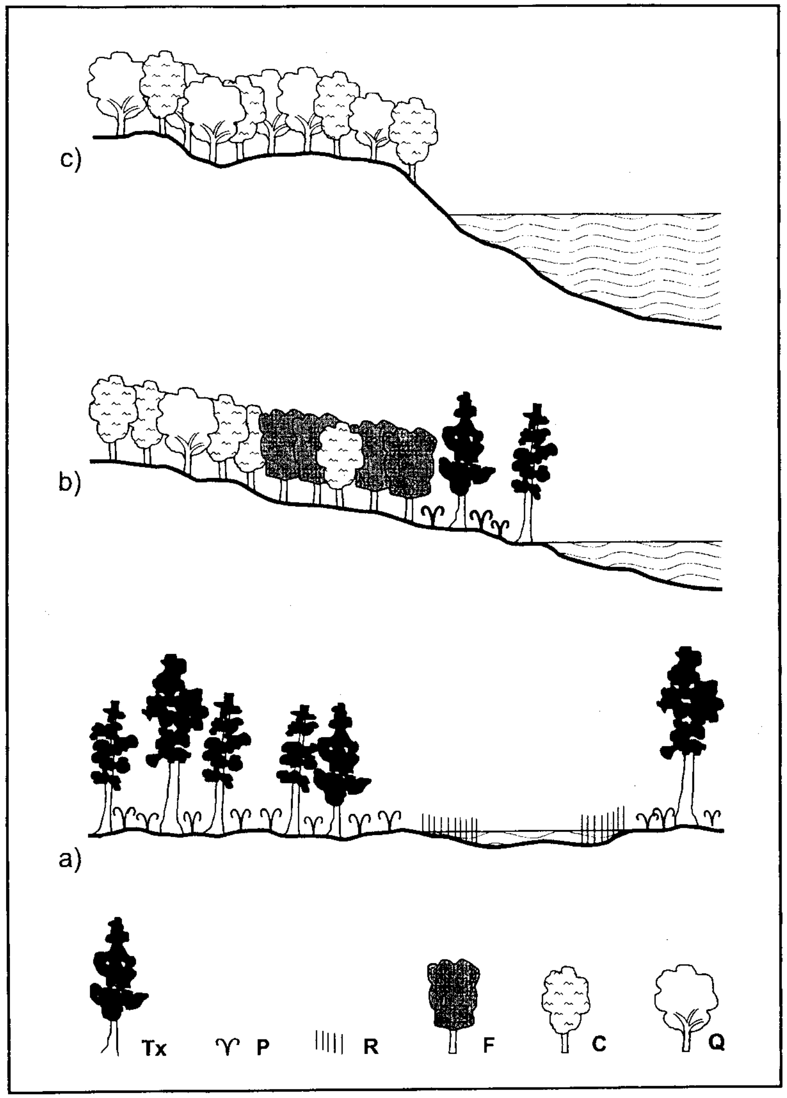


Abb. 29: Schema der Vegetationsentwicklung in den Profilen des Sava-Beckens.
a) OjL6/96 (Cluster 4): Taxodiaceen-Polypodiaceen-Moor mit Ried-Bewuchs an kleineren Wasserflächen;
b) OjL7/96 (Cluster 3): Auenwald-dominierte Übergangsvegetation an einem flachen See;
c) Novi Dol (Cluster 2): mesophiler Mischwald; durch steile Ufer unterdrückte Auen-Vegetation.
Repräsentativ sind die in der Palynoflora dominanten Taxa dargestellt: Tx: Taxodiaceen; P: monolete Sporen (Polypodiaceen); R: Ried-Vergesellschaftung; F: *Tricolporopollenites cingulum*-Gruppe (Fagaceen?); C: *Caryapollenites simplex* (Carya); Q: *Quercopollenites* spp. (Quercus).

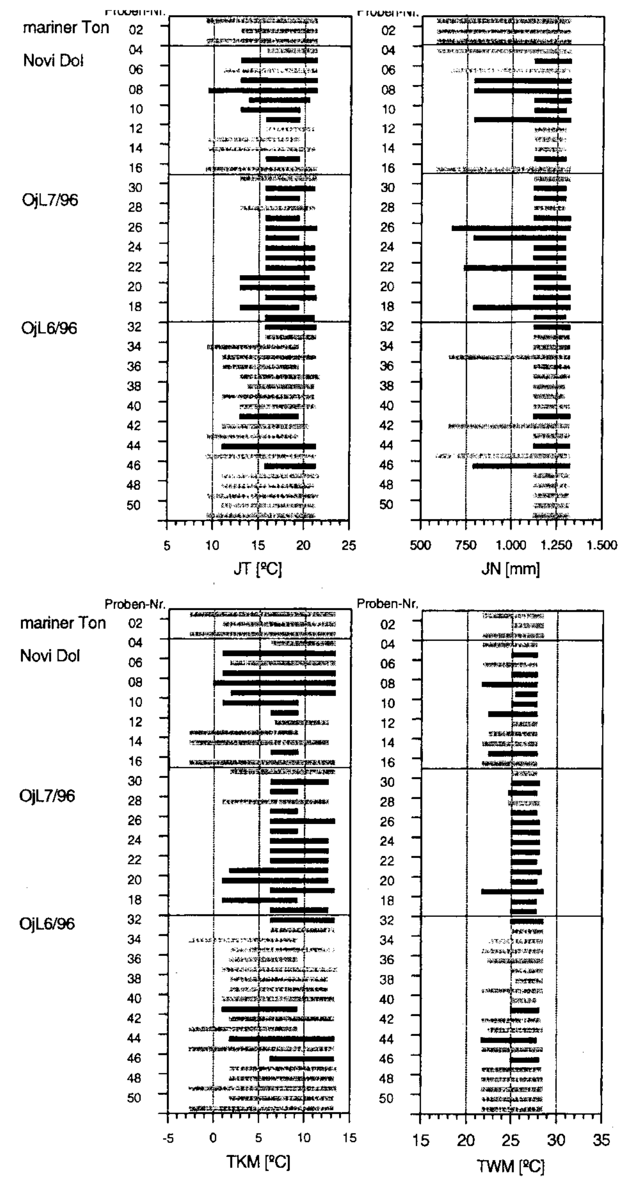


Abb. 30: Übersicht über die mit dem Koexistenz-Ansatz ermittelten Klimawerte für die einzelnen Proben der Profile des Sava-Beckens. Koexistenz-Intervalle, die auf einer Datenbasis von mehr als 10 Taxa beruhen, sind schwarz dargestellt.

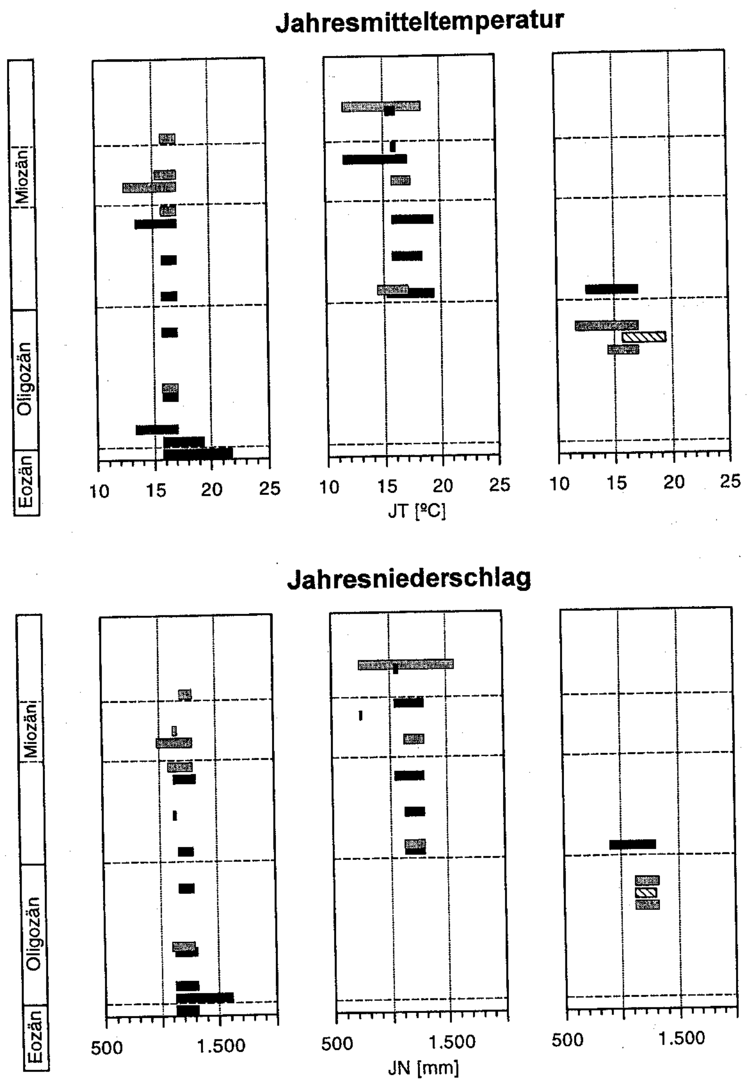


Abb. 34a: Koexistenz-Intervalle aller ausgewerteten Palynofloren.
Linke Spalte - nördlicher Alpenraum: grau - Deutschland; schwarz - Österreich.
Mittlere Spalte - pannonisches Becken: grau - Ungarn; schwarz - Slowakei.
Rechte Spalte - südlicher Alpenraum: grau - Italien; schwarz - Slowenien; schraffiert - eigene Ergebnisse.

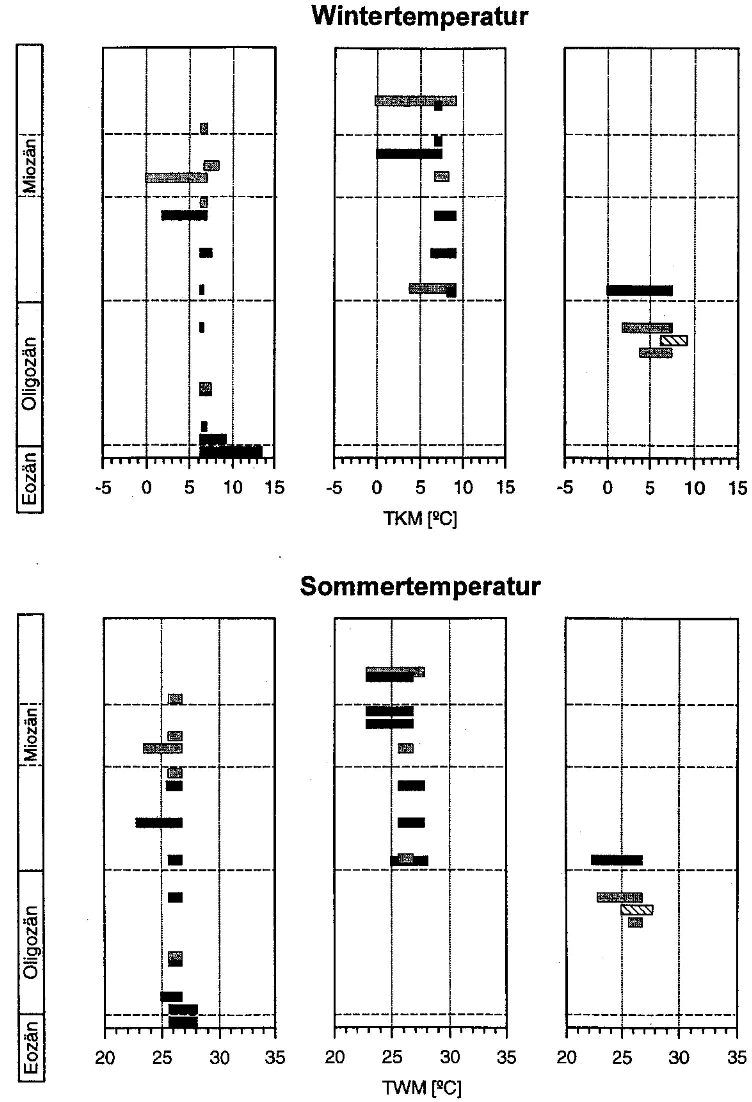


Abb. 34b: Koexistenz-Intervalle aller ausgewerteten Palynofloren.
Linke Spalte - nördlicher Alpenraum: grau - Deutschland; schwarz - Österreich.
Mittlere Spalte - pannonisches Becken: grau - Ungarn; schwarz - Slowakei.
Rechte Spalte - südlicher Alpenraum: grau - Italien; schwarz - Slowenien; schraffiert - eigene Ergebnisse.

The Uranium Deposit of Žirovski Vrh

Veselin Jokanović, Staniša Radošević, and Milan Ristić

SUMMARY

The Žirovski Vrh uranium deposit is situated about 30 km west of Ljubljana. The ore bearing rock is the grey Gröden sandstone of the Middle Permian age. Its basement is represented by dark Permo-Carboniferous shale, whereas it is overlain by Middle Permian red Gröden sandstone and Upper Permian limestone and dolomite.

The thickness of the grey sandstone is about 300 meters. The sequence of the red series is between 300 and 500 meters thick.

The grey sandstone has a variable grain size, from the very fine up to coarse ones. It is composed of sharp-edged quartz grains, K-feldspars and felsic plagioclases, and contains, as a rule, fragments and phenocrysts of volcanic quartz and feldspars, the fragments of usually recrystallized quartz-porphyry and keratophyre, the quartzite fragments and, less frequently, those of chert. The diabase fragments were also observed. The muscovite is frequent, and very frequent chlorite.

The cement of the uranium-bearing rocks is composed of quartz-clay-sericitic material, replaced partially by calcite. The calcite occurs in veinlets or it is dispersed throughout the rock. In addition to calcite, there are also small quantities of dolomite, ankerite and cerussite.

The uranium ore is confined to the zones in the grey series that contain the dispersed organic matter and anthracite aggregates.

As the most common uranium mineral pitchblende occurs, disseminated in the sandstone cement, or rarely associated with galena, pyrite, chalcopyrite, and anthracite.

The mineralized zones contain also sphalerite, tetrahedrite, chalcocite, bornite, realgar, marcasite, arsenopyrite, covellite, ilmenite, chrome-spinel, and pyrrhotite. Among the secondary uranium minerals the presence of autunite, torbernite, metatorbernite, dumontite, the minerals of the phosphuranylite-renardite series, gummites, arsenolite and beta-uranotile has been established. Limonite, malachite and azurite are also present.

The strata-bound uranium ore constitutes numerous unregular lenses of highly variable dimensions. The surfaces of the ore bodies are of the order of several hundreds to thousand square meters. Their thickness vary from 0,5 to 1,5 meters, attaining in most favourable cases several meters. The uranium contents varies most frequently in the interval of 0.05 to 0.23 % of U_3O_8. The ore itself is controlled by the stratification. The rocks, however, mostly do not show a well marked bedding. The most developed structure of the Gröden beds is the cleavage oriented at right angle to the bedding planes.

Determination of the origin of mine waters from Velenje mine on the basis of their chemical composition

(Summary)

N. MALI and M. VESELIČ

In the hanging and bottom wall strata of Velenje Mine exists a series of lithologically, hydrodynamically and hydrogeochemically differing aquifers.

A clear hydrogeochemical anomaly is surrounding the lignite seam, due to the substantial rise in the free CO_2 and HCO_3 content which gave way to the rise in mineralisation of the waters. It is believed that the CO_2 source was lignite itself during maturation, yet, this hypothesis was so far not proven.

The aquifers range from quaternary and pliocene sandy aquifers in the hanging wall strata to the pliocene sandy, miocene sandstone, oligomiocene tuffic and triasic dolomitic aquifers in the bottom wall strata. Further, within a marginal part of the seam are the pliocene sandy aquifers interbeded into the lignite seam and referred to as the pliocene interbeded sandy aquifers. Quaternary, pliocene and miocene aquifers have intergranular porosity and low to very low permeability. Hydrogeologicaly strictly speaking, a part of the pliocene and miocene aquifers should be classified among the semipervious strata. Yet, from the miner's point of view, they present, if not depressurised, a potentially dangerous source of water for a sudden inrush. Therefore they are considered as water bearing »aquifers«. Oligo-miocene and triasic aquifers are fractured aquifers. The first have very low permeability and represent no real water inrush hazard, while the later are partly karstified and have a definite inrush risk potential. Finally, some waters may exist even within the lignite seam itself due to it's local fracturation, however, they are mostly due to the past application of the flushed backfill. The aim of the study was to define the characteristical chemical composition of ground waters from the above aquifers and to provide us with the hydrogeochemical parameters that may be used for the determination of the origin of the water coming from anyone of these aquifers. The main problem was the selectivity of the parameters, which have to be as simple and quick to get as possible, if they were to be a useful tool to the miner for his operational decisions. Whenever a water inflow occurs into the mine, let it be through a borehole or directly into the mineworking a quick and certain evaluation of the risk potential of this inflow has to be made and the appropriate decisions adopted.

During this study all the existing data were analyzed. The initial data base consisted of 272 samples of unfortunately very unequal analytical quality. A preselection was therefore to be made that considerably reduced our data matrix. The analyzd hydrogeochemical parameters were basic analytical data Na^+, K^+, Ca^{2+}, Mg^{2+}, NH_4^+, Cl^-, HCO_3^-, SO_4^{2-}, Fe^+, pH, carbonate and total hardness, solid residue at 105° C and the $KMnO_4$ value. Other parameters, such as conductivity and total solids content were generally not analyzed and had therefore to be omitted from our analysis. We have checked the selectivity of the basic analytical data as well as some of the sinthetical hydrogeochemical parameters, that are advised in the literature[2,8]. Checks were performed by standard statistical methods – correlations, ^{2}test, Wilcoxon test. An inconclusive attempt of multivariate analysis was also realized, but is not discussed in the article.

The conclusion of our study is that some correlations do exist between the basic analytical parameters (Table 1) but very often, this parameters are not selective enough. Some of the sinthetical parameters proved to be selective when the origin of the ground water within the different triasic aquifers is considered (Tables 3 and 4) with symbols denoting V – aquifer; N – number of the analyzed samples; min, max, and x – minimum, maximum and mean value of the analyzed parameters; M – median; »z«-test – test value, S – lower triasic (skitian), a – middle triasic (anizian). To complete the picture, the mean values (median values, where the data sample is small) are given in the Table 2.

Aleksander Brezigar, Bojan Ogorelec, Lija Rijavec & Pero Mioč

Geologic setting of the Pre-Pliocene basis of the Velenje depression and its surroundings

Introduction

The Velenje depression is situated in the central part of northern Slovenia. The discussed area includes a part of the Karavanke Mountains and the northeastern outliers of the Savinja (Kamnik) Alps, both encompassing the Šalek valley.

The Pliocene beds of the Šalek valley harbor a thick seam of lignite which is being exploited in the Velenje colliery.

Previous investigations

Aleksander Brezigar

About 150 years ago, the geologists began to investigate the Velenje area. It was Keferstein in 1829 (cf. Rolle, 1860, 8) who provided its first geologic description. The most known investigators until 1914 were Morlot (cf. Rolle, 1857, 405), Rolle (1857 and 1860) and Teller (1898). Between 1914 and 1945, geological exploration stagnated. After 1945, the investigators concentrated mostly on partial lithostratigraphic problems. In 1976 appeared the regional geologic map at 1 : 100,000 scale, sheet Slovenj Gradec, edited by Mioč and Žnidarčič. Explanations to the map were issued two years later (Mioč, 1978).

Geologic description of the geotectonic units

Aleksander Brezigar and *Pero Mioč*

Six tectonic units can be distinguished in the area (Figs. 1 and 2). They are as follows.

The Podgorje-Vitanje tectonic depression is built up by the Helvetian Ivnik (Eibiswald) beds which consist of conglomerates, micaceous sandstones and marls (Fig. 3a).

The Velunja overthrust is a part of the greater tectonic unit of the northern Karavanke Mountains. It consists of Silurian-Devonian strata represented mostly by dark green and violet phyllitic schists with intercalations of crinoid limestone. Violet and gray quartz sandstones of Permo-Triassic age can also be found in places (Fig. 3b).

The central Karavanke Mountains, a constituent part of the Periadriatic lineament, extend as an elongated belt from the neighboring Austria. Its northern part is composed of granite and the southern one of tonalite, with a narrow metamorphic layer in between. Granite is of Variscan age, whereas tonalite resulted from the Alpine Oligo-Miocene magmatism (Fig. 3c).

The southern Karavanke Mountains are built up by young Paleozoic overthrusts, consisting mainly of quartz sandstones and conglomerates with intercalations of dark grey shales and lenses of limestone wiht fusulinids. Taking part in tectonic nappes are also white of pink crystalline limestones belonging to the Lower Permian. Near Hudi mlin occur erosional remnants of the red Trbiž (Tarvisio) breccia. The gratest part of this tectonic unit consists of Triassic rocks, among them of Scythian clastic and carbonate beds, the Anisian stratified and massive dolomite, and the Middle to Upper Triassic crystalline dolomite and limestone with intercalations of marly schists. In the southern Karavanke Mountains there are preserved, in places, the Middle Eocene fresh-water marls and sandstones with floral remains and intercalations of coal. The Oligo-Miocene andesites are found in some tectonic zones near the Smrekovec fault. The Miocene and the Pliocene Villafranchian strata are typical for the Velenje depression proper (Fig. 4).

The Velenje depression proper is situated between the Šoštanj fault and a near parallel tectonic line, the Velenje fault, this being an inverse tectonic contact of Triassic rocks with Oligo-Miocene beds. In the extension of the Velenje depression towards Dobrna near Vinska gora occurs the Oligocene (Rupelian) gray limestone with intercalations of conglomerates. Widespread in the area is the Oligo-Miocene (Egerian) sandy and marly clay, locally called »sivica« grey clay, as well as the Oligo-Miocene Smrekovec beds consisting of andesite, andesite tuff and tuffaceous clays and breccia. There are also the Lower Miocene (Burdigalian) sandy micaceous marls of Dobrna, and glauconitic sandstones with quartz grains of Govce. The Middle Miocene (Badenian) marine marl and sandy lithothamnian limestones follow upwards. The Pliocene and Villafranchian (Plio-Quaternary) beds with lignite are bound to the narrow center of the Velenje depression (Fig. 5).

The Gorenje-Šoštanj block belongs to the outlier of the Savinja Alps. The oldest member is a gray and black Upper Permian limestone intercalated with gray and black shale. Lower, Middle and Middle to Upper Triassic rocks follow, which resemble the beds in the southern Karavanke Mountains. There are also the Oligo-Miocene Smrekovec beds and the marly clay called "sivica", both occurring also in the Velenje depression proper. The uppermost part of the sequence are Lower Miocene sandy micaceous marls with dacite, and beds of dacitic tuffs (Fig. 6).

Pre-Pliocene basis of the Velenje depression

Morphologic description

Aleksander Brezigar

A number of boreholes penetrated the basis of the Velenje depression. The depression is about 11 km long and 4 km wide, its trough-like form elongated in the NW-SE direction. Morphologic characteristics are shown in Figure 7, and a cross-section, roughly across the middle of the depression, in Figure 8.

The slopes of the southern Karavanke Mountains descend toward the center of the depression under variable angles. Its basis is here about 1,100 to 1,200 m deep, the southern limb rising evenly until it meets the prolongation of the Šoštanj fault. Further on, the rise is stepwise.

The Pre-Pliocene basis can be separated into a northern part, consisting mostly of Triassic rocks, and a southern one, consisting of Oligo-Miocene and Miocene beds. The two parts are separated by the Velenje fault.

Triassic rocks

Bojan Ogorelec

The Triassic rocks of the Velenje depression have been thoroughly investigated in drill cores from the Gabrke-Ležen district. The rocks have been studied from the lithological, paleontological and sedimentological point of view in order to reveal their environmental characteristics, and to enable the stratigraphic and the tectonic correlations between boreholes (Fig. 9 and pls. 1 and 2).

The oldest rocks are of Scythian age. A gray dolomite prevails over limestone, both containing up to 10 per cent of detrital admixture of fine grained quartz and mica. There are intercalations of marly layers in the rocks. The pinkish and reddisch oolitic dolomite is the most characteristic lithological unit of the Scythian series, its colour occasioned by disseminated hematite.

The Anisian beds are represented by dolomites only, mostly of biomicritic texture. Fine laminated stromatolitic layers are discernible in places, indicating a littoral environment of deposition. The Anisian age of the succession is proved by the foraminifer *Meandrospira dinarica* (determined by L. Šribar).

The Middle and the Upper Triassic rocks are difficult to subdivide. The paleontological data (foraminifers *Involutina* sp. and *Triasina* sp.) point to the Norian-Rhaetian stage (the »Haupt-Dolomit«). Represented are thick beds of gray sparry dolomite with frequent stromatolitic layers, and biomicritic dolomites with shrinkage pores and solution cavities. Intervals of silty sandstone and slate might belong to the Carnian age, since they are lithologically comparable with the Carnian rocks of the Karavanke Mountains.

The Triassic carbonate sequence in the basis of the Velenje depression was tectonically affected by numerous faults and overthrusts. The inverse position of beds would indicate a rather strong tectonic activity during, or preceding, the formation of the Velenje depression.

Biostratigraphy of the Oligocene and Miocene beds

Lija Rijavec

The basis of the Velenje depression proper is formed by the Oligo-Miocene and Miocene beds, which are in turn overlain by Plio-Quaternary sediments. A new nomenclature, valid for the Paratethyan region, was applied in biostratigraphic analysis (Cicha et al., 1975b, a; Rögl, 1975; Steininger, 1975a, b; Stevanović, 1951).

The oldest Tertiary beds belong henceforth to the Egerian, that is to the Aquitanian and Chattian, the first evidenced by foraminifers, and the second devoid of them. The Eggenburgian beds (Lower Burdigalian) follow. They have been found near Črnova village east from Titovo Velenje, and in the borehole PT-14/74. A stratigraphic gap follows, since the Ottnangian and the Carpathian beds (Lower and Upper Helvetian) are missing. The sedimentation resumed in the Badenian (Tortonian) which is evidenced by typical foraminiferal fauna found near Šalek and in borehole PT-14/74.

Tectonics

Aleksander Brezigar

The Alpine and the Dinaric tectonic directions interfere in the discussed area. The boundary between the Alpides and the Dinarides is the Periadriatic lineament. The boundary between the Savinja Alps and the Karavanke Mountains pases in the middle of the Šalek valley and corresponds to the Velenje fault. In this region faults of the 1st, 2nd and 3rd order can be distinguished. Regarding the degree of tectonic affectedness of the Pliocene beds filling the Velenje depression, two Pre-Pliocene tectonic stages are evident (Fig. 1).

The Smrekovec and the Šoštanj faults are 1st order faults, the first a subvertical reverse fault dipping south, and the second a step fault dipping on the average 75° north-northeast (Fig. 8). Along the northern flank of the central Karavanke Mountains there is the Čofatij fault, a high-angle reverse fault dipping southwest.

There are two Pre-Pliocene tectonic zones of the first order: the reverse Velenje fault and the area of the Paleozoic overthrusts.

The Topolšica and the Dobrna faults (Fig. 7) are ranked as faults of the 2nd order. There are numerous other nameless faults belonging to this category, running in the NW-SE and SW-NE directions, all of them of neotectonic origin.

Faults of the 3rd order encompass a great number of faults of short extension and low significance.

RUDNIK LIGNITA VELENJE
HyG HIDROGEOLOŠKA SLUŽBA

KOHLENBERGWERK IN ŠALEK TAL

VELENJE, 1993

1. EINIGE BEMERKENSWERTE DATEN ÜBER DIE GESCHICHTE DER KOHLENGEWINNUNG IN ŠALEK TAL
2. ERFORSCHUNGEN
3. DIE KOHLE
4. TEKTONIK UND SEDIMENTATIONSMODEL
5. ENTWÄSSERUNG
6. GEOMECHANISCHE VERHÄLTNISSE
7. ENTWICKLUNG DER ABBAUMETHODEN

1. EINIGE BEMERKENSWERTE DATEN ÜBER DIE GESCHICHTE DER KOHLENGEWINNUNG IM ŠALEK-TAL

Unter Begebnisse, die als meistwichtige in der historischen Entwicklung des Kontaktes zwischen der Kohle in dem Šalek-Tal und den Menschen ausscheinen, steht der erste schriftliche Bericht aus dem Jahr 1767, in dem Pater Steitz über die Verbrauch der Kohle von Oberfläche berichtete sicher an der ersten Stelle.

Da die Infrastruktur dieses Gebietes damals noch sehr unentwickelt war, ist es nicht zu bewundern, dass es erst nach 100 Jahren zur fachlichen Erkennung der hiesigen Kohlen-verhältnisse kam. Dr. Friedrich Rolle, Geologe, hat sie im Bericht "Die Lignitablagerung des Beckens von Schönstein und ihre Fossilien" beschrieben und auf einer geologischen Karte dargestellt. Er vermutete, dass in der Teufe besseres und dickeres Flöz liegt.

Von 1873 bis 1875 hat Franz Mages als Investitor mit Untersuchungsbohrungen diese Vermutung bestätigt; damit war das Hauptflöz zum ersten Mal durchgebohrt.

Mit der Kohlengewinnung fangte Daniel Lapp an. Er hat auch die Forschungen erweitert und über die Kokerei erwägt.

Die ersten Methan-Schwierigkeiten tauchten schon im 1887 auf.

Die Kohle war der führende Grund für die Eisenbahnbau im 1891.

Im 1892 war der erste erfolgslose Streik.

Im Jahr 1893 hat das Methan sehr hohes Steuer verlangt: 32 Bergmänner starben. Weitere erfolgslose Streiks für mehr Geld und Deputat brachen im 1907 und 1909 aus.

Neue Schwierigkeiten traten mit dem Wassereinbruch aus triassischen Dolomit im 1918 ein.

Das Bedürfnis die Abbauverluste und Kosten für Bergbauschaden zu reduzieren, ergab schon im 1924, noch heute unrealisierte Idee, Hinterfüllung.

Grundrichtung zum heutigen Zustand wurde im 1927 mit den ersten Kraftwerk gegeben.

Nach dem 1955 wurden Metallausbau und hydraulischen Schildausbau eingeleitet.

Die Ideen über die Vergasung, die noch heute ein schönes aber weites und teueres Traum sind, waren zu jener Zeit (1961 - 1965) in der Realisierungsphase. Aber die Politik hat diese grosse, laufende Investition gewaltig beendet und die teuere importierte Ausrüstung hat verfallen.

Die Weltkrise der Kohlenindustrie zwischen 1965 und 1967, ist mit diesen Problemen zusamengefallen. 550 von 3700 Arbeiter waren entlassen und erst das neue Thermokraftwerk öffnete weitere Möglichkeiten für den Kohlenverbrauch.

Im 1973 war es sehr ernst wegen eines Wassereindranges aus triassischen Dolomit. Aber mutige Bergmänner haben auch Glück gehabt - es war endlich klar, wie man Entwasserung beherschen und auch die Kohle, die in Schutzpfeiler gegen Dolomit liegt, gewinnen kann.

2. FORSCHUNG

Zusammen mit dem Bedarf an grösseren Kohlenmengen tauchte auf auch der Bedarf an neuen Erkentnissen hinsichtlich des Flözes, des Wassers das das Abbauen bedroht, der Eigenschaften des Hangendes und Liegendes und der Nachwirkung des Abbauens in der Grube und auf der Oberfläche.
Es folgten dann immer mehr komplekse Labor-Analysen des Bohrkerns, geophysikalischen, geomechanischen, tektonischen, sedimentologischen Methoden und Studien in Verbindung mit physikal-mathematischen Analysen.
Die meisten bisher gesammelten Angaben stammten von den Ergebnissen des Tiefbohrens von der Oberfläche und aus der Grube. Diese Daten stellen eine Ausgangsstelle für weiteres Nachdenken vor und dienen gleichzeitig als Kontrolmittel bei anderen angewendeten Methoden.

Bis heute waren insgesamt rund 550 Bohrlöcher von der Oberfläche gebohrt (das bedeutet 172000m) und zusätzlich sind noch rund 1500 Bohrlöcher mit 70000m von Untertage zuzuzählen.

In den Grenzen des Exploitationsfeldes gibt es ungefähr 8km² des Landes, unter dem noch ungefähr 650mil. Tonnen der Kohle mit dem Heizwert über 4,2MJ/kg gibt. Von diesen Mengen gehört nur eine Hälfte zu den Bilanzvorräten, weil nur die Kohle mit dem Heizwert über 7.5MJ/kg abgebaut sein kann und 100 mil. Tonnen in den Schutzpfeilern bleiben müssen.

3. KOHLE

Trotz grosser Kohlenmengen, die bis zum 1950 abgebaut waren, bewerteten die Bergmänner hauptsächlich den Heizwert visuell. Im 1952 hat Hamrla eine petrografische Analyse gemacht und nannte hierige Kohle "Velenje-Lignit" der aus Moorkohle und Dunkelmoorkohle mit Xylit zusammengesetzt ist und untergeordnet ein bischen Fuzit enthält. Die Analyse von Nikolić & Dimitrijević ändert nichts besonderes: mit 60% Detrit und 40% Textit (manchmal mit einige % von Fuzit) ist es immer noch Moorkohle - Lignit oder Braunkohle gennant.
Seit dem 1950 gibt es sehr viele Angaben über chemische Zusammensetzung der Kohle. Die Bearbeiter haben schon früh festgestellt dass die analysierten Werte nicht den tatsächlichen Werten entsprechen. Gewisse lineare Abhängigkeiten zwischen chemischen Parametern der Kohle waren festgestellt und die Ergebnise der Laboranalysen wurden umgerechnet. Diese Rechnungsart war aber untauglich und theoretisch unbegründet.
Mit der Studie über die Klassifikation des Flözes wurde aber ein neues mathematisch unterstützes Mittel zur Umrechnung und Auswertung von Analysen eingeleitet.

4. TEKTONIK UND SEDIMENTATIONSMODEL

Velenje Einbruchstal befindet sich zwischen zwei regional bedeutsamen Bruchsystemen:

im Norden: Smrekovec Bruch (Störung)
im Süden : Šoštanj Bruch (")

und ist ein Teil der tektonischen Regionaleinheit, die Velenje-Dobrna Einbruchstal genannt ist (Bild 2, 3).

Mit den verschiedenen Methoden (Geophysik, Kartieren, Fotogeologie) wurden noch viele lokal-bedeutsame Bruche die verschiedenes Alter sind, festgestellt.
Im Velenje-Teil des Einbruchstales befindet sich unter anderen Sedimenten auch das Kohlenflöz, das 8.3km lang und 1.5 bis 2.5km breit ist und erreicht im Zentralgebiet maximale gewinnbare Mächtigkeit bis 170m.
Ein charakteristischer geologischer Querschnitt ist folgender (Bild 4, 5):
Die Grundlage des Einbruchstales ist im Norden triassisches Dolomit (Anissium - Ladinium, stellenweise auch Skitium), fast ohne Fossilien und deshalb nur nach Lithologie erkennbar. Im Süden bilden die Grundlage oligocän und miocän Schichten, meistens Andesit mit Tuff und stellenweise lithotamnische Kalksteine.
Über der Grundlage befinden sich erst Basalschichten, grüne Silte, sandige Siltsteine mit Sand, stellenweise sandige Töne und Ton im Norden auch roter und weisser Ton. Dann folgt direkt Liegendes mit ähnlichen Schichten, aber die Anwesenheit des Tones wird grösser.
Der Brandschiefer ist der Übergang zur Kohle, die allmählich besser wird, und bis zur Grenze mit dem Hangendes den Heizwert rund 12-14MJ/kg erreicht. Exploatiert wird die Kohle bis unteren Heizwert 7,5MJ/kg.
Mergel mit den Makrofossilien (Schnecken) bildet die Dachschichte, die maximal drei Meter dick ist. Oben folgt eine sehr dicke Schicht des Hangenden, gebildet aus Tegel mit Fossillblättern und wasserführenden Sandschichten. Weiter gibt es meistens grünen und grauen Ton mit Sand und Schotter. Zu diesen Schichten gehört auch die

Kohle die schon in der Vergangenheit exploatiert wurde, und ein wichtiges Fossil, Mastodont, der beim Dorf Škale gefunden war. Dann folgen noch gelborange sandige Schichten und endlich Aluvium mit Sand und Schotter.
Dieser Querschnitt zeigt uns einen kompletten Sedimentations-zyklus von der terrigene über Sumpf und See Phase wieder über Sumpf bis terrigene Phase, mit der Gesamtdicke über 1000m, was bedeutet über 1000m Senkung im Zentrum des Einbruchstalles.

Ähnliche Sedimentation ist in Literatur auch See oder Süswasser-typ der Sedimentation genannt.
Paleontologische Analysen stellen Kohlenentstehen in der Zeit des junges Terziars, an der Grenze zwischen mittel und ober Pliozän, was bedeuten kann, dass unsere Kohle ungefähr 2.5mil. Jahre alt ist.

5. ENTWÄSSERUNG

Die undurchlässige Isolierungsschichte zwischen Kohle und wasserführenden Sandschichten ist stellenweise sehr dünn d.h. unter 20m, und stellenweise finden wir Sandschichten gleich im Flöz. Dieses Wasser das unter Druck ist (20 bis 30 bar) bedroht unsere Abbaue, die in der Nähe sind, in Form Hangenddurchbruche des Schlammes. In letzter Zeit haben wir mit wissenschaftlichen Untersuchungen bedeutsame Ergebnisse auf diesem Gebiet erreicht. Erfolgreiche Zusammenarbeit von Geologen, Hydrogeologen, Geomechaniker und Bergbauingeneure hat uns bestimmte Kriterien gegeben, die das Abbauen unter dünne isolierungsschichten ermöglichen. Bessere Verhältnisse versicheren wir mit der Entwasserung des Gebietes durch zahlreiche (und sehr teuere) Brunnen (von Oberfläche gebohrt), die das bedrohte Gebiet umkreisen. In der Grube bohren wir auch zahlreiche Steckfilter um ein besseres Resultat zu erreichen.
Das zweite bedeutende hydrogeologische Problem war der triassische Dolomit, der viel Wasser enthält. Entwässerung ist Heute fast total beherrscht weil wir Strecken und lange Bohrlöcher im Dolomit hergestellt haben.
Insgesamt pumpen wir aus der Grube ungefär 5 mil. m' Wasser pro Jahr.
In der Zukunft werden grössere hydrogeologische Probleme wahrscheinlich noch immer die wasserführende Sandschichten vorstellen, die nicht nur über und gleich im Flöz sind, aber befinden sich auch im Liegendes.

Teilweise gehört der Vergangenheit auch das Problem, der durch Bodensenkung entstand. Vor mehreren Jahren konnte niemand mit Sicherheit sagen, dass das Wasser in den Mulden nicht gefährlich für die Grube war. Aber die Geomechaniker leisteten die Versicherung. Nach einigen Jahren der Untersuchungen wurde festgestellt, dass die Isolierungstonschichten zwischen der Kohle und den Seeboden dick genug sind und entsprechende geomechanische Eigenschaften haben.

6. GEOMECHANISCHE VERHÄLTNISSE

Die Syntheze der Resultate von der geomechanischen Eigenschaften aller Sedimenten heisst "geomechanisches Modell" des Velenje Einbruchstals und ist im 1984 fertiggestellt.

Ein weiteres geomechanisches Modell, das sich näher mit den Flözeigenschaften beschäftigt, ist in einer gesonderten Studie, mit dem Titel "Klasifikation des Kohlenflözes mit Rücksicht auf das Heizwert und der physikal-mechanischen Eigenschaften" dargestellt.

Der Vergleich zwischen diesen zwei Modellen und Sedimentations-model zeigt gute Korrelationen zwischen geomechanischen Eigenschaften und Sedimentationsbedingungen.

Abbauproblematik ist mit montangeologischen Verhältnissen im Flöz verbunden und stellt sich in folgenden Formen dar:

- Abbauen unter wasserführenden Sandschichten in Gebieten wo Isolierungsschicht dünn ist;
- Verhinderung der plötzlichen Gasausbrüche;
- Ausbaustabilität;
- Grossraumstabilität;
- Versicherung der Tagesanlagen und anderen Objekte;

Mit ersten ernsten Untersuchungen im Bereich Hydrogeologie und Geomechanik mussten Probleme bei Abbauen unter wasserführenden Sandschichten in Gebiete wo Isolierungsschicht dünn ist, aufgelöst sein.

Das Ziel dieser Untersuchungen war, gewisse "Kriterien", die Abbauen in solchen Bedingungen erlauben, festzulegen und damit das Abbauen unter Isolation die dünner als 20m ist, ermöglichen.

In den letzten Jahren waren auch umfassende in-situ Untersuchungen in den Strecken durchgeführt um die nötige Stabilität zu erreichen und optimale Ausbau einzusetzen. Solche Untersuchungen sind sozusagen schon ein Teil der Technologie geworden.

7. ENWICKLUNG DER ABBAUMETHODEN

Der wichtigste Beitrag in der Entwicklung der Abbaumethoden ist eine Tendenz nach möglichst geringe Abbauverluste.

Die Änderungen wurden durch ekonomischen, technologischen und auch politischen Grunden bedingt.

Die erste angewendete Abbaumethode war die Teilsohlen-schrägbaumethode, die in vier Varianten entwickelt wurde.

Die Methode, die bessere Sicherheit leistete, war aber nicht ekonomisch, war die stossbauartige Schrägbaumethode.

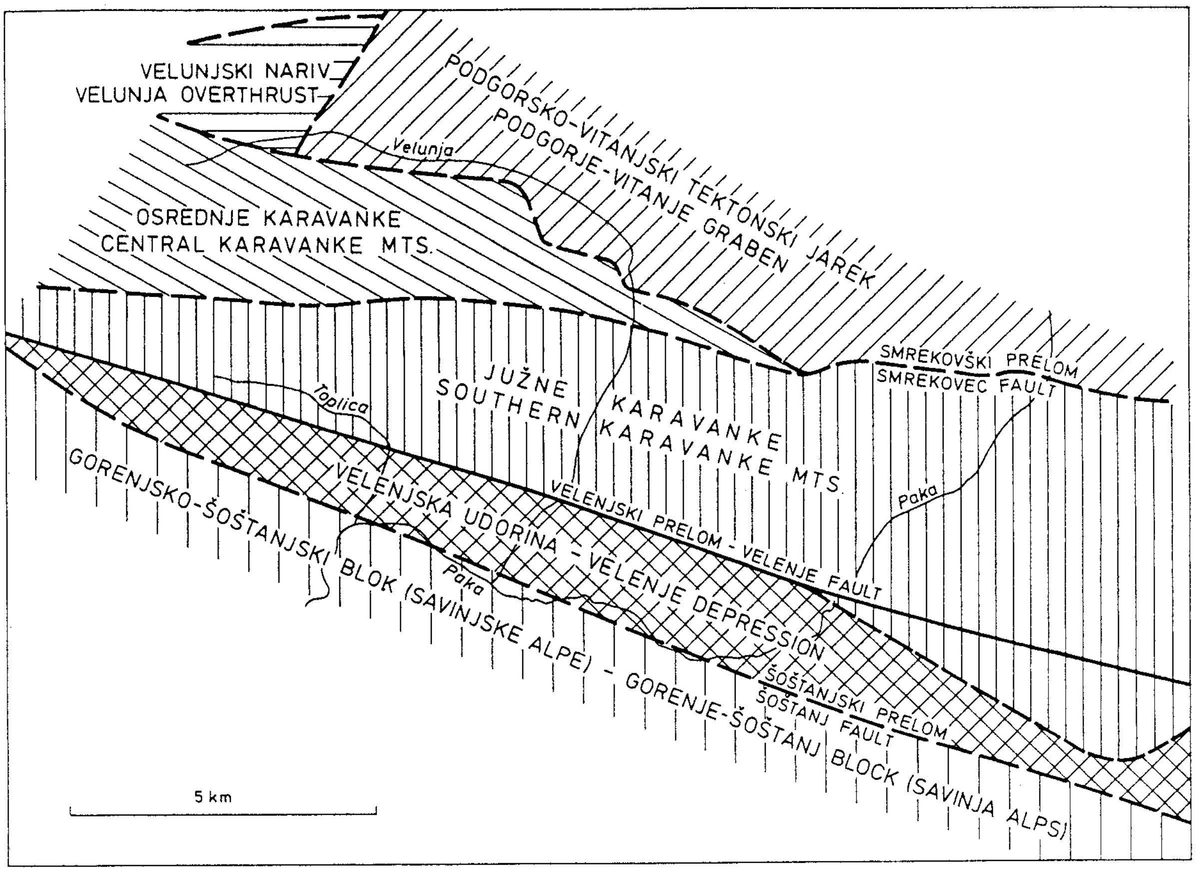
Aus der ersten Methode entwickelte sich die Pfeilerbaumethode mit Sicherheitspfeiler in verschiedenen Varianten.

Seit 1960 wird "Velenje Strebabbaumethode" (VOM), als eine gute Synthese aller positiven Eigenschaften bisher angewendeten Methoden, verwendet.

Schon seit einigen Jahren können wir in unseren Bergwerk über totalmechanisiertes Abbauen mit horizontaler und vertikaler Konzentration sprechen.

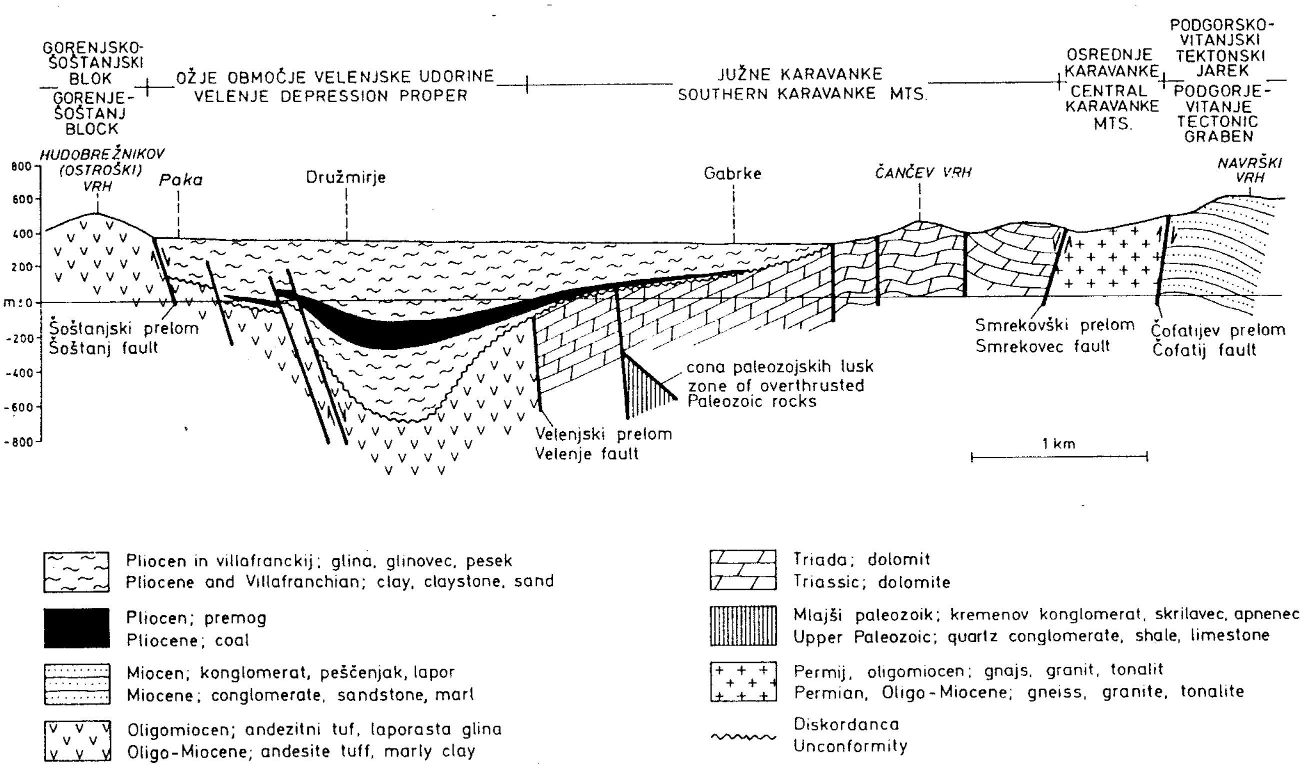
- Vertikale Konzentration ist Velenje-Strebabbaumethode mit Nachfallgewinnung mit Bruchbau (Streblänge 80 - 140m und Höhe der Abbauetage 7,5 - 11m)
- Horizontale Koncentration ist VOM, mit Streblangen 80 bis 100m und 3,2m hohe Abbauscheibe.

Aleksander Brezigar, Bojan Ogorelec, Lija Rijavec & Pero Mioč



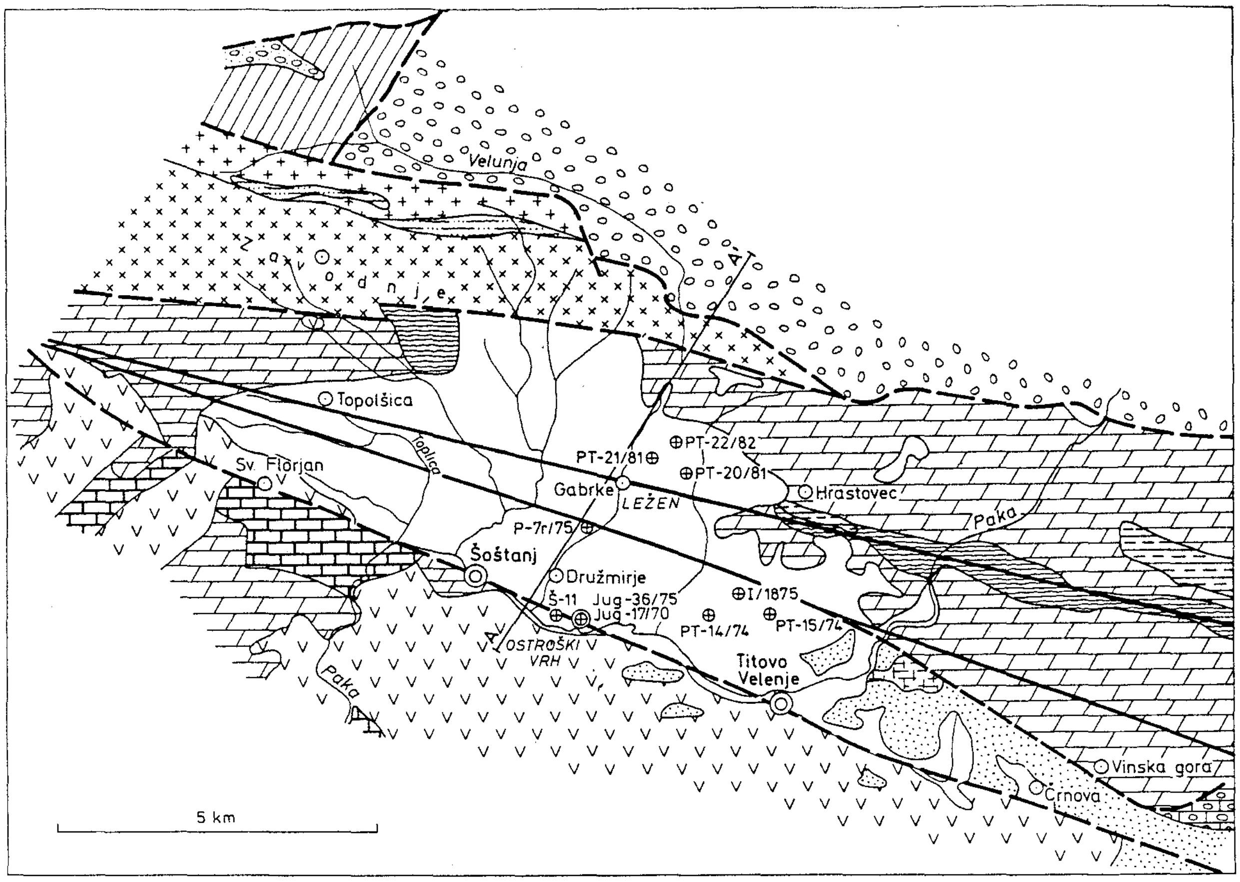
Sl. 2. Tektonske enote

Fig. 2. Tectonic units



Sl. 8. Geološki presek skozi Velenjsko udorino

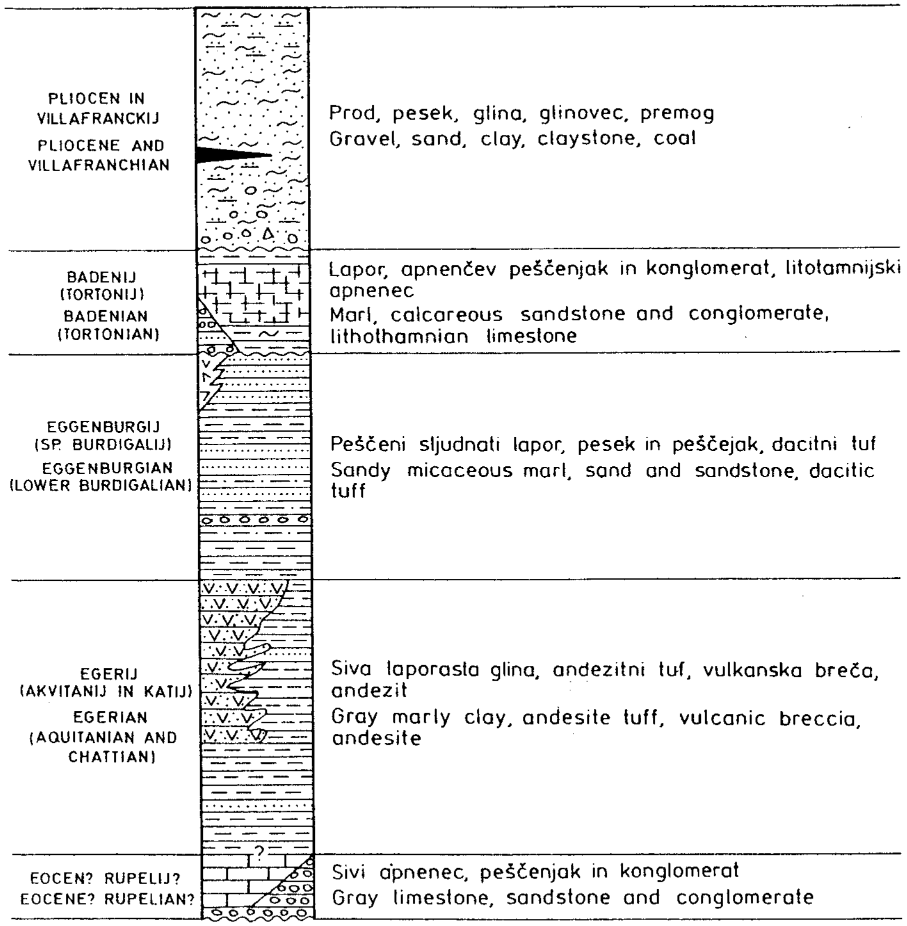
Fig. 8. Geologic cross-section across Velenje depression



Sl. 1. Geološka karta Šaleške doline in okolice

Fig. 1. Geologic map of the Šalek valley and its surroundings

- Pliocen in villafranckij: prod, pesek, glina, premog
  Pliocene and Villafranchian; gravel, sand, clay, coal
- Badenij (tortonij); litotamnijski apnenec
  Badenian (Tortonian); lithothamnian limestone
- Helvetij; konglomerat, peščenjak, lapor
  Helvetian; congomerate, sandstone, marl
- Eggenburgij (sp. burdigalij); peščenjak, lapor in dacitni tuf
  Eggenburgian (Lower Burdigalian); sandstone, marl and dacitic tuff
- Egerij; lapor, peščeni lapor, peščenjak, andezitni tuf, andezit
  Egerian; marl, sandy marl, sandstone, andesitic tuff, andesite
- Oligomiocen; tonalit
  Oligo-Miocene; tonalite
- Rupelij; sivi apnenec z vložki konglomerata
  Rupelian; gray limestone with intercalations of conglomerate
- Srednji eocen?; sljunati lapor
  Middle Eocene?; micaceous marl
- Triada; predvsem dolomit in apnenec
  Triassic; mostly dolomite and limestone
- Permotriada; vijoličasti in sivi kremenov peščenjak
  Permo-Triassic; violet and gray quartz sandstone
- Permij; granit
  Permian; granite
- Zgornji permij; sivi in črni apnenec, sivi dolomit
  Upper Permian; gray and black limestone, gray dolomite
- Zg. karbon in sp. permij; črni glinasti skrilavec, kremenov peščenjak in konglomerat temno sivi, svetlo sivi in rožnati apnenec
  Upper Carboniferous and Lower Permian; black shale, quartz sandstone and conglomerate, dark gray limestone, light gray and pink limestone
- Silurij, devonij; filitoidni skrilavec z vložki apnenca
  Silurian, Devonian; phyllitic schist with intercalations of limestone
- Gnajs s prehodi v blestnik
  Gneiss with transitions to mica schist
- Geološka meja
  Geologic boundary
- Prelom
  Fault
- Predpliocenska tektonska cona
  Pre-Pliocene tectonic zone
- Vrtina
  Borehole



Sl. 5. Geološki stolpec Velenjske udorine

Fig. 5. Geological column of Velenje depression

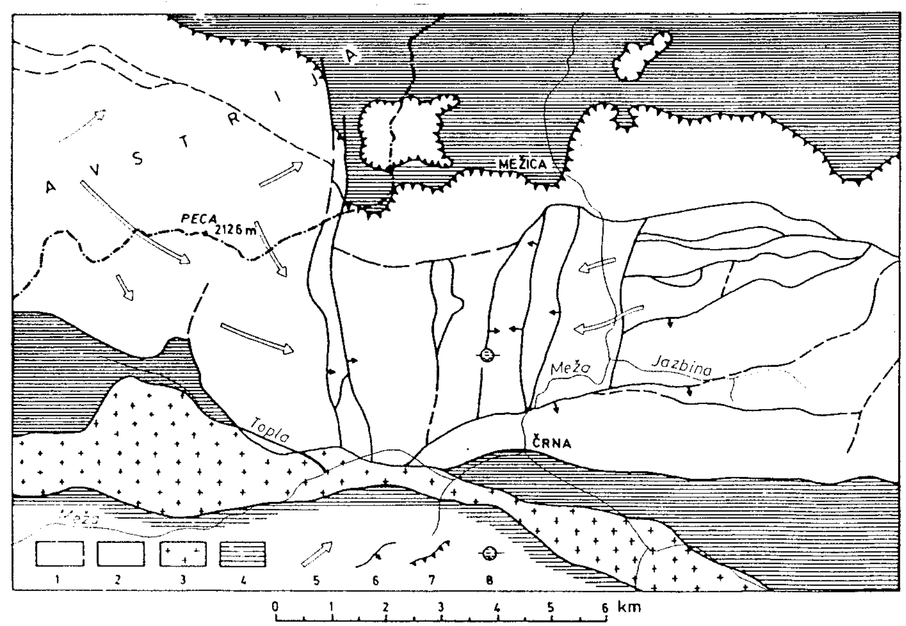
Ivo Štrucl

1 permeable (karstified) Wetterstein beds, *2* Upper Triassic and Jurassic carbonate rocks with impermeable beds of claystones and marls, *3* igneous rocks (granodiorite, granite porphyry, tonalite), *4* impermeable rocks (Paleozoic schists, Permian and Triassic beds, Miocene clays), *5* direction of the groundwater flow, *6* the most important dislocations, *7* the North Karavanke overthrust, *8* pumping station on the mine level + 300 m

Geological and geochemical characteristics of ore and host rock of lead-zinc ores of the Mežica ore deposit

The lead and zinc ores of the Mežica deposit are at the first look very similar. Under a somewhat closer look and scrutiny, however, they reveal considerable differences between them in structural and textural characteristics of ore and host rock, as well as in their geochemical and mineralogical composition. All these differing characteristics reflect obviously various conditions of genesis of individual ores and ore systems.

In the narrower area of the Mežica deposit the Pb-Zn ore occurs in general in carbonate rocks of the Ladinian-Carnian stage of Triassic, in the so called Wetterstein beds, and certain ore occurrences appear also in Carnian beds between the first and the second marker layers of shale. In the wider surroundings are mineralized also the Middle Anisian dolomite and Carnian beds above the third marker layer of shale. However, no direct connection was discovered up to now between the two mineralized sequences of the Triassic beds, not even in the case of ore occurring in younger tectonic structures.



Sl. 17. Hidrogeološka skica širše okolice mežiškega rudišča

Fig. 17. Hydrogeological sketch map of the broader surroundings of the Mežica mine

Stratigraphy of the Wetterstein sequence and its equivalents

The Ladinian stage and a part of the Carnian stage are developed in three facies: in the back reef, reef and fore reef facies. The back reef (see fig. 1) and reef facies (fig. 2) have been called for a long time (Teller, 1896) the Wetterstein beds, or the Wetterstein limestone, and the fore reef facies the Partnach beds. The first two facies almost completely consist of carbonate rocks — limestones and dolomites, comprising all transitional varieties, and the Partnach facies consists of clayey carbonate sedimentary rocks.

Until recently the entire profile of Wetterstein beds was attributed to the Ladinian stage. The age was determined by gastropods *Chemnitzia rosthorni* and *Chemnitzia gradata* (Teller, 1896). Wetterstein beds are in general poor in fossil material. Microfossils are much more abundant. In almost every sample which is not dolomitized or recrystallized, various algae, foraminifers or test fragments of various molluscs may be found. Very important was the find of the alga *Poikiloporella duplicata* (Pia) which is characteristic for the Cordevolian and Julian substages of the Carnian stage. With this find the boundary between the Ladinian and Carnian stage was moved downwards for more than 150 m. However, in practice, especially in mapping, this will not be possible to consider. Relatively often occurs also the alga *Thaumatoporella parvovesiculifera* (Raineri). An important part in the composition of the fossil material play also the foraminifers.

The reef facies is macroscopically hardly distinguishable from the Wetterstein limestone of the lagoon facies. The difference is only in fossil inventory and in microstructural and textural characteristics of the limestone.

In the reef belt which extends with interruptions from the Peca mountain to Razborje the following corals have been determined up to now: *Thecosmilia subdichotoma* Münster, *Thecosmilia badiotica* Volz, *Craspedophyllia alpina* Loretz, *Margarophyllia michaelis* Volz, *Margarosmilia septanectens* (Loretz) and *Omphalophyllia bittneri* Volz. Besides corals also sponges, foraminifers and algae were found.

In the Graben mining district and east of it beside the listed fossils also *Connophyllia alpina* Loretz, *Oppelismilia* sp. and *Microtubus communis* Flügel were found by us. On this basis a part of the reef belt is attributed to the Carnian stage.

South of the reef belt the Wetterstein limestones do not occur. In their place appear there black and dark grey shales which can be taken as an equivalent of the Partnach beds.

Lithological and sedimentological characteristics of the orebearing parts of the Wetterstein beds

The 1,000 to 2,000 m thick succession of the Wetterstein beds consists almost entirely of carbonate rocks. The lower part is predominantly dolomitic, and the upper part is calcareous. Locally also in the upper part occurs considerable dolomite, but having not much lateral extension. In the central pit of the Mežica mine the degree of dolomitization is highly variable even on short distances, either vertically or horizontally. It is interesting to note that dolomitization in the upper part is as a rule connected with the genesis of interstratified Pb-Zn ores, while the lower dolomite is barren. The Wetterstein beds are at the first look very uniform, but at a closer inspection they appear lithologically of very variable composition. Occurs a rapid interbedding of various microbreccias, macrobreccias, stromatolitic and oncolitic beds, loferites, dolomites of varying granularity and chemical composition, and aphanitic and phanerocrystalline limestones. Such is the situation in the cross section (fig. 3) of the upper 190 m of the Wetterstein beds on the 7th level of the Central zone, where 230 beds and sheets of the mentioned rocks were recorded.

By number predominate the stromatolitic beds. Their thickness varies from 1 cm to maximum 15 cm. They consist of calcite and dolomite in varying proportions. However, the predominant part of the succession of the Wetterstein beds was deposited in the subtidal area of sedimentation. Occur micritic, dismicritic and sparitic limestones with rare allochems and low energy index, and a low degree of dolomitization. Among the most extraordinary beds belong the so called black breccias (fig. 3—6) which occur in the Mežica ore deposit at levels about 12 m, 25 m, and 60 m below the Cardita shale. In spite of their small thickness from 5 to 15 cm they are of a considerable regional extension.

The reef limestone consists of very fine intraclastic and bioclastic material. However, in practically any sample of unaltered limestone remains of the reef fauna may be found. The reef belt in the Graben mine district consists of intrasparite and intrabiosparite, i. e. of sediments which were deposited in the very shallow sedimentation basin.

Sedimentological characteristics indicate that individual sediments of the Wetterstein beds were deposited in the following environments:

— the micritic, dismictritic and sparitic limestone in the subtidal area,

— the stromatolitic and oncoidal limestone in the intratidal area,

— the dolomites, the black and other breccias, and limestones with a high energy index in the intratidal and supratidal areas. To these belong also the reef limestones.

In the region of the Mežica deposit can be observed sequences similar to those described by Bechstädt (1974) in the Bleiberg deposit, and even at approximately equal distances from the 1st Carnian shale. Some of these are shown on figure 5. If assuming that the green marly beds represent residual sediments, then occur in the upper part of the Wetterstein sequence 8 to 12 horizons which indicate shorter or longer interruptions of deposition, and also of karst erosion. Most of these horizons are characterized by breccias, and some of them have also increased contents of Zn and Fe.

Geochemical characteristics of the ore-bearing rocks

There are probably few rocks that were geochemically so extensively and in detail investigated as these parts of the Wetterstein beds. Only from the Mežica mine and the surroundings more than 300,000 samples were analyzed, most of them, certainly, on Pb and Zn. In Table 1 the composition of both main components is shown. Even if the composition refers to one of the least altered, i. e. dolomitized sections, the pure limestone is relatively rare. As a rule limestone always contains some dolomite, either in the form of disseminated crystals and crystal aggregates, or in the form of diagenetic cement in pores and fissures. Often also the inverse situation occurs, the groundmass being dolomitic, and pores and fissures filled with calcite. The dolomitic component is predominating especially in the Navršnik mine district where also the levels of stratiform ores are the most abundant. The Wetterstein limestone contains generally very low free SiO_2 (0.12 to 0.2 %).

Table 2 shows the composition of the main components of the reef limestone. The calcareous part is representative mostly of the barren rocks, and the dolomitic of the mineralized rocks. The proportion of the insoluble residue is very low, from 0.04 to 1.32 %, on the average 0.20 %. Since the ZnS ore sometimes contains from 2 to 4 % SiO_2 in the form of euhedral and subeuhedral quartz, it is assumed that silica was introduced later in the process of the ore genesis.

Although there are geochemical data for the entire area of the Mežica deposit, for the presentation of distribution of lead and zinc in the upper part of the Wetterstein succession the mine districts Navršnik and Srednja cona were selected. The reason is in the existence in both districts of mainly older, Triassic mineralizations: in the Navršnik district layered and 8-hours veinlike ores, and in the Srednja cona district only layered ores. From data in fig. 8 and tables 3 and 4 it is obvious that average contents of both metals are much higher in Navršnik than in the Srednja cona, although the part of the Wetterstein succession is the same. Reasons for it are several, the most important being:

1. In the Navršnik district the ore occurs at 3 or 4 distinct horizons, the lowest being at about 90 m from the 1st Carnian shale, while in the Srednja cona district (see fig. 9) a single horizon is mineralized, and this horizon occurs at about 140 m from the shale.

2. The country rock of the stratiform ores in Navršnik is medium grained late diagenetic dolosparite, and in the Srednja cona a relatively little altered limestone.

3. The ore in the Navršnik district is considerably more oxidized, and therefore also the secondary dispersion is most probably higher than in the Srednja cona district.

In the reef limestone appears the ore only in the case if the rock is dolomitized (see table 5). This, however, does not mean that ore will be found in any dolomite.

In table 6 appears the elemental composition of trace elements in 33 samples from various levels of the Wetterstein sequence. Sampling was done at a predetermined grid 1 by 1 km. Samples were analyzed at the Geologische Bundesanstalt in Hannover, West Germany.

Fluorine belongs in the eastern alpine Pb-Zn deposits to typical trace elements. It occurs in fluorite which mostly crystallized during the cementation stage of diagenesis. It appears most commonly in shaly sediments or close to them.

The composition of trace elements in carbonate rocks of the reef facies is shown in the table 7. Analytical data indicate that the nonaltered reef limestone is very low in trace elements, while the dolomitized limestone is much higher in them, especially in lead and zinc.

Geological and mineralogical characteristics of Pb-Zn ores

In the sequence of the Wetterstein limestone occur several kinds of Pb-Zn mineralizations which may be subdivided according to structural and textural characteristics of ore and country rock, and especially according to their form and their spatial — stratigraphic, lithologic and tectonic — position into two systems: the concordant and the discordant one.

Concordant are all ores which occur more or less parallel to the bedding or to the paleogeographic relief, and the discordant ores occur in fissures, along faults and fault zones, or appear without clear stratigraphic-lithologic spatial elements. Concordant ores were formed mainly before the mountain-building tectonic orogeny, and the discordant ores before mountain-building tectonics during it, and after it.

Concordant or interbedded ores occur in various, but quite well defined horizons of the Wetterstein limestone. These horizons are situated at the following distances from the 1st Carnian shale: 10 to 15 m, 20 to 25 m, 50 to 60 m, 90 m, 130 to 150 m, and 650 m. While the lowest horizon was until present observed only in the Union district, other horizons have larger extensions. However, all horizons are not everywhere mineralized. Orebodies do not have the shape of a bed, or of a layer in the strict sense of the word, but rather shapes of narrow and very irregular lenses, tubes or channels, hollows and nests. Their boundaries or contours are seldom sharp, except towards the footwall where often funnel-like hollows occur filled with ore deposition. The country rock is mainly fine to medium grained xenotopic dolosparite in which pores and vugs are in part or entirely cemented by coarse grained, mainly idiotopic dolomite. Structural and other characteristics of dolomite indicate the late diagenetic character of dolomitization of the prevailing part of the orebearing sediment. However, a part of the sediments, e. g. several ore rhythmites and stromatolites, show pecularities of the primary dolomite which was formed during the early diagenesis. Interstratified ore occurs also in more or less pure limestone. This holds especially for ores in the Srednja cona district which occur at 140 m from the 1st Carnian shale. In the predominating calcareous rock occur also the interstratified ores in the Moring mine district. Mainly three kinds of ore appear: the metasomatic ore, the ore rhythmites, and the ore breccias.

Metasomatic ores are the most abundant, they contribute above 90 % to the total ore mass. No wonder, then, that for decades investigators of Mežica were mislead by this abundance to attribute the Mežica deposit to the group of magmatogene telethermal metasomatic deposits of Tertiary age. The metasomatic ore is as a rule quite rich, and it appears usually in very picturesque structures and textures (fig. 11 and table 2). The ore consists mainly of galena, pyrite, marcasite, melnikovite-pyrite, dolomite and calcite in highly variable proportions. The metasomatic processes of ore minerals are mostly connected, except in a few instances (in the Srednja cona district and in Moring), with the process of the late diagenetic dolomitization.

The ore rhythmites (table 3) occur in interstratified ores very frequently, almost regularly, in places very abundantly, and in others in hardly notable appearances. Mostly they are found in the basal parts of the orebodies, but they appear also in their centers.

The mineral composition of ore rhythmites practically does not differ of that of metasomatic ore. Departures are mostly manifested in structural and textural patterns of ore and barren minerals. The ore rhythmites most often consist only of sphalerite, but also rhythmites with galena and sphalerite are no rarity in the Mežica deposit. According to the composition of the gangue components several groups of the ore rhythmites are distinguished: dolomitic, calcitic and dolomitic-calcitic. Along with major components is highly variable also the SiO_2 contents, which occurs either in the form of authigenic or terrigenic quartz, or in the form of clay substance. Relatively frequent is also fluorite (Table 4, figs. 1 and 3).

The base of the ore rhythmites consists of dolomite or calcite of variable grain size in layers or laminae of millimetric thicknesses. The grain diameter varies between 0.004 and 0.2 mm. In individual microlayers or laminae graded bedding may be observed which can be often false, the result of varying conditions of diagenetic crystallization. Laminae (or part of them) of pure dolomite or calcite, without clayey admixture or with very small amounts of it, consist as a rule of medium to coarse grained dolosparite or calcite, while the laminae containing higher amounts of clay matter are fine grained to very fine grained. Sulfides are usually not in proportion with the carbonate grains, neither by mass nor by size. A certain dependence is indicated only by the fact that the conditions for crystallization and growth of sulfide grains in layers of more pure, medium to coarse grained dolomite were more favorable than in the fine grained clayey-carbonate sediment. By direct precipitation and sedimentation perhaps only the smallest grains having the order of magnitude of framboids, from 3 to 20 μm, were formed, but even in this case remains the question of the chemical nature of the precipitates. In pyrite and in marcasite (Table 4) often occur very fine sphaleritic globules which represent probably the oldest, or the original form of at least a certain proportion of zinc in the sediment.

Grains of galena are as a rule larger than those of sphalerite, their diameter varying from 0.15 to 1 mm. Galena crystallized and grew during the diagenesis of the sediment. The metasomatic processes played an important part during the genesis of galenitic concentrations, either high or low grade ones. A typical mineral of the ore rhythmites is also fluorite, although it is not present in each rhythmite.

Pyrite appears in two forms, the crystal and the framboidal form. The major part of it occurs very fine grained, the diameter of grains varying between 0.003 and 0.03 mm, i. e. of dimensions which are characteristic of its early diagenetic phase. Although some authors maintain that the pyritic framboids may be formed also under hydrothermal conditions, it is possible to almost conclude, on the base of microscopic examination of several hundred samples from the Mežica deposit, that the form is typical of the early diagenetic mineralization.

In figure 12 is shown the paragenetic succession of minerals in the ore rhythmites.

The ore breccias of interstratified ores differ from each other in petrologic and mineralogic characteristics, and also in their genesis. The sulfide minerals occur mostly concentrated in the cement, and only locally they are present also in fragments. Most interesting and also economically the most important are the ore breccias in the Graben mine district, where they occur between the reef limestone and in the bituminous dolomite (fig. 13). Even if occurring in the same paleogeographic horizon, their petrologic and mineralogic composition is highly variable even on short distances. Highly variable is also the size of fragments which diameter ranges from millimeters to a few meters. Fragments have mostly sharp edges. Since sorting is very poor, the structure of the breccia is very chaotic. The majority of fragments consists of medium grained reef dolosparite, and occur also dark fragments of bituminous dolomicrite and dolosparite which are, however, considerably smaller than the fragments of reef dolosparite.

The dark fragments are often mineralized. They contain disseminated grains of pyrite (very often in framboidal form) and sphalerite. Grain size of dolomitic grains in the cement varies from 0.004 to 0.2 mm. Concentrations of sulfide minerals in the cement are very variable; most abundant is galena, follow by amount sphalerite, pyrite and marcasite.

Lithological characteristics of ore breccias offer indications that they are younger than the reef dolomite, and also the bituminous dolomite. On the basis of typical diagenetic indices (e.g. stylolitic sutures, cementation of pores and fissures, dolomitization, etc.) it can be deduced that the breccia is a product of epigenetic processes which may be best imagined as a combination of dissolution and postsedimentary deformation processes. Next to ore bearing intrastratified deformational breccias and the monomictic dolomitic (dissolution) breccias within the reef limestone, occurs in the Graben deposit a number of other breccias. Especially frequent are breccias in which matrix consists of shale (fig. 14), and fragments of dolomite or limestone. The genesis of breccias cannot be generalized, nor can their genesis be ascribed to a single process. The ore breccias occur also in the interstratified ores of the Central deposit, but they are, however, more rare, and not so pronounced and typical as in the reef limestone. An exception is presented by the orebody in the base of the Union mine district, between the 13th level (+ 410 m) and the height + 320 m. There two types of breccias occur, one of the typical dissolution type having the cement of coarse grained calcite, galena and sphalerite of cocade structures (table 6, figs. 3 and 4), and breccia of the second type, having the cement of fine layered fine grained ore sediment (table 6, fig. 1). It follows from the composition of fragments, composition of the country rock, and the chaotic structure in the ore sediment, that in the second instance the breccia is of the collapse type. Since in the orebody dissolution breccias prevail, also the genesis of collapse breccias can be attributed to dissolution processes in the hanging wall rock. In the sample on table 3, fig. 4 these deformations can be seen in miniature. At this point the questions may be asked on the time and place of the genesis of the sediment, before the deposition of covering sediments or after it, on the bottom of the depositional basin or in a karst cavity, consequently either externally or internally. Since only one instance of such orebody in this level of the Wetterstein succession (at 650 m below the Cardita shale) is known, the explanation by the deposition in a karst cavity seems perhaps the most acceptable.

Discordant ores

Discordant ores may be subdivided into the following groups:

1. The 8 hours veinlike ores or fillings of subvertical, the so called 8 hours, or 120^g (NW-SE) fissures,

2. Ores of the Union system, or veinlike, vein-impregnation and metasomatic ores along the post-Triassic faults and fault zones, and

3. Irregular metasomatic orebodies without clear stratigraphic-lithologic and tectonical spatial elements.

The problematics of the 8 hours ores is complex, and is not yet reliably solved. The author's personal opinion is that they were deposited about at the same time as the interstratified ores, that their genesis is consequently associated with the Triassic paleokarst processes. The 8 hours ores occur only in the upper part of the succession of the Wetterstein beds, and practically in the same horizons as the interstratified ores. As a rule they are connected with the horizons of the black breccia.

The ore of the 8 hours ores consists predominantly of galena, limonite and cerussite. Sphalerite is very subordinate, it appears only locally, disseminated in the limestone, and very seldom in fissures along with galena. Marcasite is in general entirely altered into limonite. The content of Pb in ore is largely dependent on the thickness of the galenite vein which is highly variable, from 1 cm to 3 m, and mostly from 10 to 50 cm. The veins are not always continuous. The ore appears often also in the form of irregular nests.

The country rock consists mainly of limestone, dolomite is very rare. Characteristical for the country rock is the almost total absence of any alterations as they are typical for the major part of interstratified ores along which the country rock is mostly strongly dolomitized.

The system of the ore bearing Union faults extends at a surface of about 2 km^2. The depth from the Carnian shale is about 600 m, according to the recent knowledge. The general direction of strike of the Union faults is north-south. In the Central deposit most of these faults dip towards the west. The dip angle varies between 25 and 80^g. In their upper parts the faults tend to be steeper (50 to 80^g). The ore occurs directly along the fault or the fissure, but often it reaches also some distance into the country rock. The horizontal length of the orebodies varies between 5 and 100 m, and their thickness from 0.5 to 10 m. The orebodies have very irregular shapes, and they rise gently (15 to 25^g) along faults towards the northeast.

The ore grade varies much even on short distances, and so does the ratio of lead to zinc. No regularity of distribution of the two metals with depth appears to be present.

There is an abundance of faults and fissures of the Union system, but relatively few of them are mineralized. The most mineralized Union faults do not count much in the tectonical sense, since the shifts along them were minimal, if compared to other faults. The Union ores are indubitably younger than the interstratified ores. The basic condition, the space for deposition of ore components, was created by tectonic processes, but the ore was subjected later to a number of tectonic deformations, too. There is much evidence for it, the most obvious being the so called lead tectonic mirrors, and the galena with the lead tail structure. Most proof is furnished by microscopic examinations which give indications on several phases of fracturing, especially in the ore breccias. Besides the tectonic predisposition must have ruled in the Union system area also certain special geochemical conditions due to which ore components were deposited from the aqueous solution. One of the possibilities is perhaps the change of the country rock which was permeated by groundwater. In the western part, in the Navršnik and Three hour deposit, the country rock of the highly oxidized ores is dolomite, but in the area of the Union system it is a relatively pure limestone. That ores of the Union system were deposited from hydatogenous solutions of meteoric origin, and not of juvenile origin, follows also from the inclusions of galena, pyrite, shale, clay or limonite in calcite. Also the isotopic analyses of sulfur indicate that in mineralizations of the Union system occur secondary, remobilized enrichments of sulfide minerals (D r o v e n i k and others, 1970, 1980). Characteristic is the narrow range of δS^{34} which is an indication of the homogenization of sulfur, and with it also of remobilization of the ore components.

The irregular metasomatic ores occur in the entire deposit. In places a certain connection with one of the above described systems of ores may be ascertained, but in most instances this is no more possible. Very often occur more or less monomineral mineralizations, especially the zinc, resp. the sphaleritic ones. Among the most typical belong the zinc ores in Graben and Moring, and the lead ores in the Stari Fridrih mine districts and in the eastern part of the Graben. In the Graben deposit occur largely zinc ores in dolomitized reef limestone, and the lead ores in the lagoon dolomite. According to origin there are consequently two entirely different country rocks, and besides, there is no indication of any connection between the two dolomites. Everywhere occurs between them a several tens of meters thick belt of highly deformed shale, clayey-dolomitic breccias and dolomite (fig. 14). In this belt appear also considerable amounts of gypsum and anhydrite. The differences between the two groups of ore are shown in the summary comparison on table 8. The origin of the ore in both instances may be explained only by voluminous metasomatic processes. Mineralization took place in several phases. The succession of mineralization in the reef limestone is shown in fig. 15. A similar succession holds also for ore in the lagoon dolomite, the difference being only in the diagenetic alteration of the country rock. Mineralization (dolomite, sulfides and quartz) penetrated into the reef limestone from an other part, or horizon of the succession of beds (most probably from the younger one), while in the lagoon sediment the mineralization may have been present in one form or another already at the very beginning. In the second instance there is, moreover, the possibility of the presence of metals originally in the clayey sediment, of their migration during diagenesis into the dolomite, and of their accumulation there in ore.

The irregular metasomatic orebodies occur locally in larger extent also in the Central mine of the Mežica deposit and in the Mučevo mine district. Similarly as in Graben they differ from each other in mineral composition (mainly in proportions of mineral components) and in the country rock. In the Moring and Mučevo mine districts the country rock is generally limestone (in places without a trace of dolomitization), in the Fridrih, Stari Fridrih and Ravšarjevo mine district dolomite or dolomitized limestone. In the first two mentioned mine districts occur mainly zinc ores, and in the last three districts mainly lead ores with few zinc.

Geochemical characteristics of the Pb-Zn ores

The Triassic ores in the Northern Karavanke and Gailthaler Alps contain generally very few amounts of trace elements, which holds especially for galena. From one point of view this is economically favorable, since from ore without much trouble relatively pure lead with four nines (99.99 %) can be produced, but from the other side the ore does not contain silver, or other commercial elements or metals, and has therefore a lower price.

It can be seen from table 9 that galena contains all typical trace elements, but in low and variable amounts. Sphalerites (tables 10, 11) are much higher in trace elements, but still quite low in comparison with Paleozoic deposits in Slovenia and with other Yugoslav deposits, especially in contents of copper and iron. The latter occurs at levels from 0.1 to 2.5 % only. Sulfides of the interstratified ores are as a rule higher in trace elements than sulfides of discordant ores, with the exception of molybdenum which appears in considerable abundances especially in the Union system. The clear difference in the composition of trace elements is an additional piece of evidence against the rôle of Union fissures as supply channels of other Triassic Pb-Zn ores, since in such a case they should be as a rule richer in trace elements, especially in copper and iron.

In table 12 is shown the chemical composition of several typical ore rhythmites from the mine district where they are the most frequent. As seen, they vary considerably, either in principal components or in ore and trace elements.

Oxidation of Pb-Zn ores

The degree of oxidation is highly variable in the Mežica deposit. In places, for example in Mala Peca, Helena, Igrče and Navršnik mine districts, the individual orebodies are 50 to 90 % oxidized, in other places, in Graben, Moring, and Union districts not even 5 to 10 %. It is interesting that depth does not play the dominant part in it. Highly oxidized ores are not found only in the upper parts of the deposit, or above the primary level of groundwater, but also in lowest parts, 300 m and more below that level. The variation of oxidation is shown by frequency distributions in figure 16. While studying the degree of oxidation of ore in individual systems one gets the impression that the ores had to be subjected to oxidation already in Triassic, at the time of their deposition, or shortly after it. This idea is suggested especially by data on the oxidation of the interstratified ores, and especially of the 120° veinlike ores. Many among them, particularly those which are situated at 50 to 60 m from the 1st Carnian shale, are namely very profoundly oxidized regardless of their present depth.

In table 13 are presented data on the degree of oxidation in individual mine districts. It can be seen that the Graben deposit is the least oxidized, although it is situated closest to the surface.

From the geological sketch (fig. 17) and cross section (fig. 18) it may be seen that the meteoric waters arrive into the Central deposit mainly from the Mount Peca area where the Wetterstein limestone is outcropping in a relatively extended surface. Due to large altitude differences between the sinkholes on Peca and the resurgences in the valley, and due to the high frequency of fissures and high degree of karstification of the limestone the circulation of groundwater through the deposit was always very intensive. At present, when the mine workings arrived to the heigth + 300 m, the difference of altitudes amounts to 1,800 m, while it was before the beginning of mining activities from 1,540 to 1,600 m. It is understandable that these conditions varied much during the times from Pliocene until now. The tectonic structure, however, does not give any evidence that conditions also in more distant past were not much the same. The groundwater level did not change during the given period of time only due to climatic conditions, but also due to morphologic changes in the recharge and discharge areas. In the past undoubtedly intensive mixing of groundwaters occurred which led to establishment of geochemical barriers in the deposit. Isotopic analyses show that the time of mixing of the meteoric with the ground water is actually about 5 years. The chemical composition of waters from the Wetterstein limestone is shown in table 15. The first three analyses are of waters from the Mežica mine, and the three others of waters from the surroundings. Differences are obvious, especially in contents of Pb, Zn and SO_4^{2-}. The mine water contains on the average 0.01 mg/l Pb and 0.05 mg l Zn. By considering only these values, and the discharge of water from the mine, which is about 40 m³/min, it is possible to estimate that the deposit loses yearly about 210 kg of lead and five times that much (1,050 kg) of zinc.

The Mežica mine has been known since long by wulfenite. Less known are other oxide minerals. Although the oxidation affected more or less the entire deposit, appear higher abundances of several minerals, for example wulfenite, hydrozincite, hemimorphite and descloizite, only in particular parts of the deposit, mostly in the ores of the Union system, i.e. in Igrče, Helena and Union. Of economic importance is only cerussite which occurs as a rule in the ore together with galena with which it is commonly intensively overgrown (table 7). Smithsonite occurs usually in a highly dispersed state and can be commonly determined only under microscope, or by chemical analysis. It occurs locally also in somewhat higher concentrations, particularly in higher levels of the deposit. Its mode of occurrence is variable, it appears either alone, or in association with hydrozincite, hemimorphite, cerussite and gypsum (table 9). A very important mineral of the oxidation zone in the Mežica deposit is wulfenite. In traces it can be found in the entire deposit, but in higher abundances only in younger fissures of the Union system. From about 80 wulfenite finding places, which are indeed since long mined out, only 8 were connected with the system of interstratified ores, and even of those more than half were recorded only as mineral showings.

It follows from data in table 16 and 17 that within the ore bearing Wetterstein limestone sequence there was available for crystallization of wulfenite enough molybdenum, most probably in the form of finely disseminated jordisite. It is more and more obvious that in fissures and along faults of the Union system occurred deposition of secondary Pb-Zn ores which are, among others, characterized also by higher contents of molybdenum.

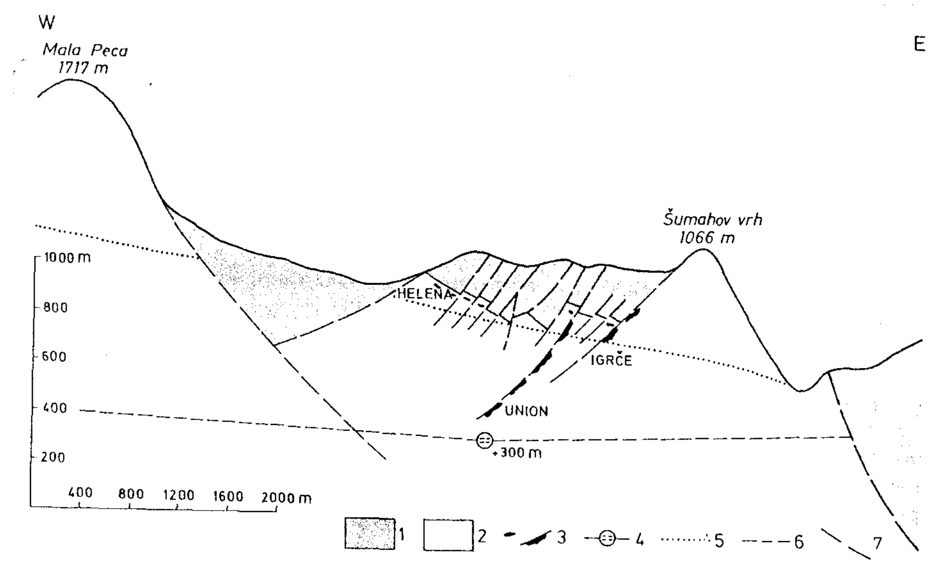
Conclusive remarks on the genesis of the Pb-Zn ores in the Mežica deposit

It follows from all above explanations that the Mežica deposit was formed in several phases, and that it was subjected to a number of secondary alterations. It makes no sense to look in each particular type of ore evidence for the primary genesis, because it will not be found as a rule. An even more serious mistake would be to generalize such ideas on the genesis. Therefore the present author discussed his views and reflections on the genesis progressively, while discussing particular groups of ores. In figure 19 the main phases of the deposit are schematically shown. It can be seen that the predominant part of the deposit was formed during the late diagenetic and epigenetic processes, and only a small part during the early diagenesis. The ore rhythmites cannot be considered by any means as the source material of all other ores. They are of relatively subordinate abundance in the Wetterstein limestone, in total they make lessthan 1 % of the entire ore mass of the interstratified orebodies. Also during their deposition they probably were not much more abundant. However, they may be useful in explaining several phenomena in the Triassic ores. It follows from the paragenetic evolution of sulfide minerals in the ore rhythmites that in them collective crystallization and metasomatic processes occurred, and with them also considerable ore concentrations, particularly in the pure carbonate beds. If this may be established at the millimeter scale, then the same phenomenon may be inferred to have occurred also in several decimeter or several meters thick beds in which the conditions for metasomatism and collective crystallization were obviously even more favorable. A considerable influence in this had certainly also dolomitization during which the porosity may be increased up to 13 %.

The problematics of the source of the ore components is still to a high degree unclear. The author discussed the question in the paper on the Anisian deposit of Topla (Š t r u c l, 1974), and because no new, more solid evidence was discovered since then, those suppositions should remain in vigour.

In the schematic presentation the ore rhythmites of the Graben deposit may have at the first look a somewhat unusual position, but they are internal ore sediments in the reef limestone, which means that they were deposited in vugs and other karst cavities of the already solidified reef limestone. Perhaps this holds also for a part of ore rhythmites in the Wetterstein limestone, but here many questions are not clear yet.

It also follows from the paragenetic presentation that the Pb-Zn ores have been formed all the time, practically up to the present day. We do not know, to be sure, what happened to the deposit between Triassic and Miocene. It is, however, almost certain that the deposit was not conserved, especially if taking into consideration that due to the cover of 1,500 to 2,000 m of overlying younger beds the temperatures and pressures must have changed considerably within the orebearing sedimentary beds. A considerable contribution to alterations within the deposit was undoubtedly supplied by the tectonic processes of the Alpidic orogeny. A more clear evidence on changes and deposition of younger ores is offered by post tectonic supergeneous processes. These processes did not only alter the appearance, composition and mineralogical and physico-chemical properties of the Triassic ores and country rocks, they also contributed much to the genesis of new Pb-Zn ores.



Sl. 18. Shematski geološki profil skozi mežiško rudišče
Fig. 18. Schematic geological cross-section of the Mežica ore deposit

1 Upper Triassic rocks, *2* Wetterstein beds, *3* Pb-Zn ore bodies, *4* pumping station in the Union district, *5* ground water level before opening of the mine, *6* the present ground water level, *7* faults

Thermal and mineral waters in north-eastern Slovenia

Peter Kralj · Polona Kralj

Abstract The Mura basin in north-eastern Slovenia is made up of two depressions, developed during the Late Neogene and Early Pliocene all within a widespread system of Pannonian basins. Both depressions are characterized by the occurrence of thermal waters of somewhat different hydrogeochemical character. Radgona depression is in the northern part of the basin and reaches depths of about 2 km. Thermal waters are generally dominated by sodium-bicarbonate, not related to the age of an aquifer, its wallrock composition, the type of porosity or total concentration of dissolved solids. Locally, sulphate-rich waters are encountered, and they are related to the presence of gypsum in the rocks of pre-Tertiary basement. The adjacent Ljutomer depression is over 4 km deep and comprises compartments with stagnant or semi-stagnant aquifers. Herein saline waters predominate, even in the aquifers of carbonate composition and abundant CO_2 gas. In shallower, unconsolidated, intergranular aquifers sodium-bicarbonate waters predominate. Thermal aquifers of this type are very important to the economy of the region, but they are also subjected to overexploitation which is reflected in time-dependent changes of dynamic pressures, temperature, conductance, salinity, pH and concentration of major ions, trace elements, dissolved gasses, and total organic carbon. Mineral waters occur in shallow aquifers or springs in marginal areas of the Radgona depression. Bicarbonate waters are dominated by calcium, or both calcium and sodium. Some mineral waters are formed mainly by penetration of CO_2 gas into shallow aquifers and consequent water-rock interaction. Composition of some mineral waters indicate their possible evolution from thermal waters which have risen from central parts of the Radgona depression along deep-seated faults, and have been modified by cooling and mixing processes.

Key words Sedimentary aquifers · Thermal water · Mineral water · Water chemistry

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Introduction

North-eastern Slovenia is characterized by an abundant occurrence of thermal and mineral waters. During the last five decades, the area has been extensively explored to discover new resources of oil and gas, however wells commonly tapped thermal water instead.

Until the present, only low-enthalpy resources have been exploited. Thermal water, with a temperature of 50–70 °C, is abstracted from an intergranular aquifer of the Upper Pliocene age, named Termal I. It is widely used in balneology and, in the town of Murska Sobota, also for local district heating. Because of its importance, hydrodynamic properties and water chemistry have been monitored in some exploitation wells more or less regularly since the beginning of production. The results indicate that Termal I is subjected to overexploitation, reflected in a constant decrease of static pressures, and in Murska Sobota also in time-dependent regular changes of hydrodynamic pressures. Efficient re-injection of thermally used water seems to be the only solution to preserve this natural resource for future generations.

Mineral waters are also important to the economy of north-eastern Slovenia. Radenska bottling company is renown in many European countries as a producer of high-quality mineral and potable waters. However, Radenci is not the only location in NE Slovenia where mineral waters occur, but also many other smaller sources exist, and some of them might be interesting for bottling.

High-enthalpy resources also exist in north-eastern Slovenia, but they have not yet been exploited. In a deep well, Ljut-1, located at Ljutomer, a brine having the temperature of 173 °C, has been captured in the pre-Tertiary carbonate basement. The studies have shown that this aquifer is a potential source for future production of electric power from geothermal steam (Kralj 1994).

The present contribution deals mainly with the geological occurrence of thermal and mineral aquifers in north-eastern Slovenia, the water types or hydrogeochemical facies encountered, and the changes in chemical properties of composite water, which are related to overexploitation of the Sob-1 well in the town of Murska Sobota.

Geological setting

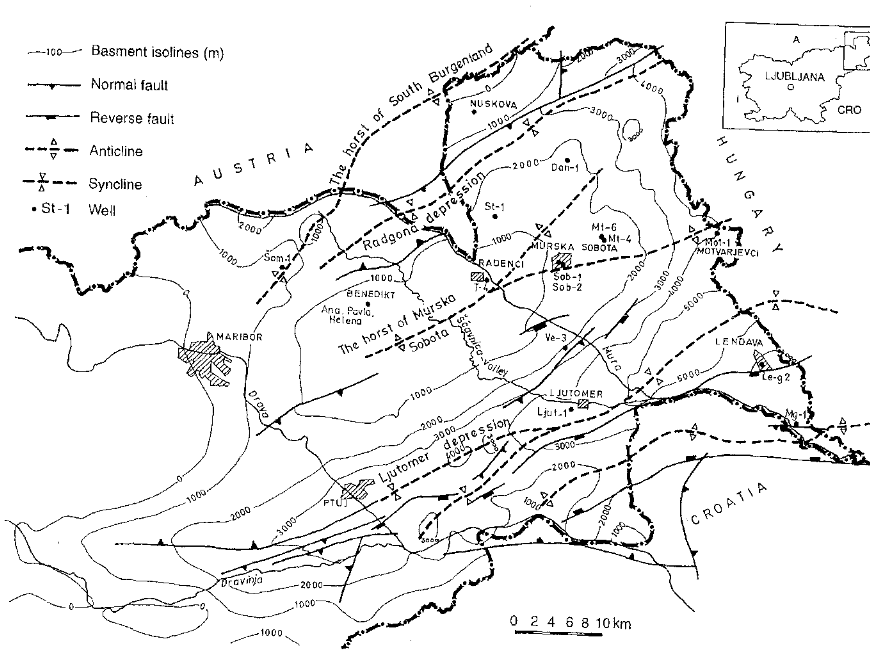
North-eastern Slovenia (Fig. 1) is a transitional region between Pannonian lowland in the east, and Southern Alps in the west. The most important tectonic structure is the Mura basin, which is infilled with clastic sediments of the Tertiary and Quarternary age. The Mura basin forms a part of a much larger Zala basin, which extends from south-western Hungary to northern Croatia, and belongs to a widespread system of Pannonian basins (Royden 1988).

Although the formation of Mura basin began as early as the Carpathian stage of the Tertiary age, the main subsidence occurred during Late Pliocene and Quarternary. This subsidence was closely related to tectonic activity which produced deep-seated strike-slip faults. Two of them are particularly important: the northeast-southwest trending Radgona fault in the north, and the east-west trending Ptuj-Ljutomer fault in the central part. Along the faults two depressions developed, separated by the horst of Murska Sobota (Fig. 1). They were named after the faults – the Radgona and Ljutomer depressions.

The major part of the Radgona depression is situated in Austria, and only southern margins extend on the territory of north-eastern Slovenia. In the north, it is separated from the adjacent Graz basin by the horst of South Burgenland, where the pre-Tertiary metamorphic basement outcrops. In the Radgona depression, the basement consists of Mesozoic carbonates overlying metamorphic rocks at a depth of about 2 km (Oberhauser 1980). The carbonates are a thermal aquifer with mineral water of essentially sodium-dominated bicarbonate type.

On the horst of Murska Sobota, the pre-Tertiary metamorphic basement rises to depths of about 500 m below the surface (Fig. 2). In the north-easterly direction, the horst spreads, but also deepens. Away from the horst of Murska Sobota, towards the Ljutomer depression, the

Fig. 1
Structural map of north-eastern Slovenia



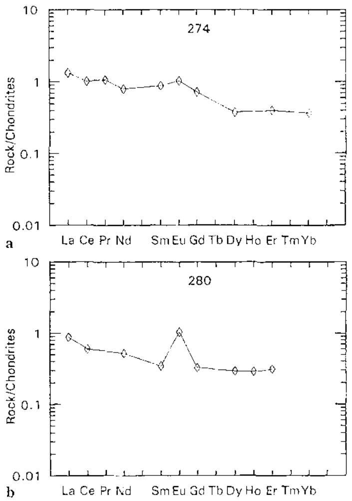


Fig. 3
Distribution of REE abundances normalized to chondrite values for mineral waters from the Radgona depression. a Sample from the T-4 well in Radenci, b sample from a shallow well in Stavešinci

The deep Ljut-1 well at Ljutomer, penetrated Mesozoic dolomites and dolomite breccias at a depth of 4004 m. The well tapped a stagnant, overpressurized aquifer with the fluid having the temperature of 173 °C, and mineralization amounting to 22,448 mg/l. Carbon dioxide was abundant.
Despite carbonate composition of the aquifer and abundant CO_2, the water was a brine (Table 5). Sodium and chloride ions amounted to almost 90% of total concentration of dissolved ions. The water is possibly marine in origin, being leached into the pre-Tertiary basement from the overlying marine sediments of the Murska Sobota formation, and later, modified by complex hydrogeochemical processes. The presence of carbon dioxide cannot substantially enhance mineralization of brines as saturation of carbonates is reached, and they tend to precipitate from the solution (Mazor 1991).

Aquifers in the Murska Sobota formation

The Murska Sobota formation includes stagnant aquifers, and confined aquifers with some phreatic parts. They bear thermal and mineral waters of rather diverse chemical composition.
A stagnant-type aquifer was tapped in the deep well Mot-1 at Motvarjevci, between 2828–2832 m in depth (Table 5). The water was a brine with total dissolved ions amounting to 26,995 mg/l. The dominant ions were sodium and chloride, with very subordinate bicarbonate and sulfate. In deper levels of the same well Mot-1 (3626.5–3630.5 m), another aquifer was encountered, with thermal water of the same Na-Cl type, but with lower total concentration of dissolved ions amounting to 15,750 mg/l. Water of similar mineralization and type was also tapped in the well Mg-6 (Murski gozd) in depths between 3726.7–3743.5 m (Table 5).
In Moravci spa, the Mt-4 well tapped some aquifers of Sarmatian and Badenian age, composed of fractured sandstones, which bear thermal water with the temperature of 71 °C, and abundant CO_2 gas. Concentration of total dissolved solids amounts to 15,520 mg/l. The water is dominated by sodium and chloride ions, although bicarbonate amounts to about 30% of the total dissolved anions (Table 5).

Table 5
Composition of water from deep-seated aquifers in the Ljutomer depression

Well depth (m) Formation, rock type	Units[a]	Ljut-1 4005–4023 Carbonate basement	Mot-1 2828–2832 Murska Sobota	Mot-1 3626–3630 Murska Sobota	Mg-6 3727–3744 Murska Sobota	Mt-4 1176–1263 Murska Sobota
Na^+	mg/l	8214	10037	5700	4435	4960
	meq/l	350.4	436.3	247.93	192.91	215.7
	%	97.5	96.4	96.4	90.9	94.5
K^+	mg/l	230	138	318	185	250
	meq/l	5.77	3.53	8.13	4.73	6.39
	%	1.6	0.8	3.2	2.2	2.9
Ca^{2+}	mg/l	36	210	38	260	95
	meq/l	1.8	10.49	0.97	12.97	4.74
	%	0.1	2.3	0.4	6.1	2.
Mg^{2+}	mg/l	13	29	1.65	20	16.7
	meq/l	1.06	2.38	0.14	1.64	1.37
	%	0.1	0.6	<0.1	0.8	0.6
Cl^-	mg/l	11735	15619	8288	5404	5574
	meq/l	324.3	440.46	233.46	152.41	157.0
	%	90.5	97.1	90.8	71.3	67.9
HCO_3^-	mg/l	2082	607	805	2474	4249
	meq/l	33.48	9.96	13.2	40.56	69.99
	%	9.3	2.2	5.1	19.	30.3
SO_4^{2}	mg/l	128	146	505	1001	196
	meq/l	2.66	3.04	10.52	20.84	4.08
	%	0.2	0.7	4.1	9.8	1.8
TDI	mg/l	22448	26995	15750	14210	15520

[a] Percentages refer to separate sums of cations and anions

Aquifers in the Lendava and Mura formations

Aquifers in the Lendava and Mura formations are characterized by the dominance of sodium-bicarbonate hydrogeochemical facies. However, none of the wells in the Pomurje region abstracts only the water from Lendava formation, and for this reason, the exact chemistry is unknown. It can only be estimated from the composition of mixtures with the water from Termal I; in general, concentration of total dissolved solids and the temperature are higher, and CO_2 abundantly occurs as undissolved gas.
The aquifer – Termal I – is composed of several water-bearing sandy layers, interbedded with silts and clays, up to 60 m thick. Concentration of total dissolved solids averages to 1276 mg/l for 46 of analyzed samples (Table 6). In the water from Le-g2 well, located at Lendava, the average sodium concentrations amount to 280 mg/l, which means 96.7% of the total dissolved cations, and in the water from Ve-3 in Banovci spa, to 363 mg/l or 97.9% of total dissolved cations. Concentrations of bicarbonate average to 856 mg/l and 970 mg/l or 99.3% and 97.2% of total dissolved anions, respectively.
The wells Sob-2 and Sob-1, located in the town of Murska Sobota, also abstract the water from Termal I, but also some water from the Lendava formation. Consequently, concentrations of total dissolved solids considerably increase, as well as the amount of CO_2 gas (Table 6). The wells are about 317 m apart and are hydraulically interconnected. Sob-1 penetrated about 151 m of the Lendava formation, and Sob-2 only 129 m due to tectonic displacements. The presence of the water from the Lendava formation in the abstracted composite water, increased total concentration of dissolved solids to 2736 mg/l in Sob-2 and to 3189 mg/l in Sob-1. Sodium is still the dominant cation, averaging 733 mg/l in Sob-2, and 755 mg/l in Sob-1, and bicarbonate the dominant anion, averaging

Table 6
Composition of water from Termal I (Mura formation). Admixtures of waters from the Lendava fromation increase concentrations of almost all ions and trace elements

Well depth (m) Formation Samples	Units[a]	Le-g 2813–1493 Mura 3	Ve-3 1111–1467 Mura 18	Mt-6 720–974 Mura, Lendava 25	Sob-2 600–854 Mura, Lendava 46	Sob-1 557–856 Mura, Lendava 71
Na^+	mg/l	280	363	335	733	755
	meq/l	12.18	15.79	14.55	32.85	33.71
	%	95.2	96.6	96.7	94.4	89.3
K^+	mg/l	8	9	7	44.0	71.0
	meq/l	0.2	0.24	0.18	1.14	1.8
	%	1.6	1.6	1.3	3.3	4.8
Ca^{2+}	mg/l	5	5	5	10	32
	meq/l	0.25	0.25	0.25	0.5	4.2
	%	1.9	1.5	1.7	1.4	1.6
Mg^{2+}	mg/l	8	1	1	4	8
	meq/l	0.66	0.08	0.08	0.33	0.66
	%	1.3	0.3	0.3	0.9	1.7
Cl^-	mg/l	3	18	132	122	149
	meq/l	0.09	0.46	3.72	3.44	4.2
	%	0.6	2.7	24.5	10.1	10.6
HCO_3^-	mg/l	856	970	696	1898	2125
	meq/l	14.03	15.96	11.41	31.12	34.83
	%	99.1	97.2	75.4	89.8	87.8
SO_4^{2-}	mg/l	2	<5	<5	<5	32
	meq/l	0.04				0.67
	%	0.3				1.6
TDI	mg/l	1173	1468	1187	2736	3189
CO_2	mg/l	15	178	227	411	550
pH		7.30	7.96	7.9	7.03	6.85
T	°C	58.3	54.5	58.8	47.6	49.0

[a] Percentages refer to separate sums of cations and anions

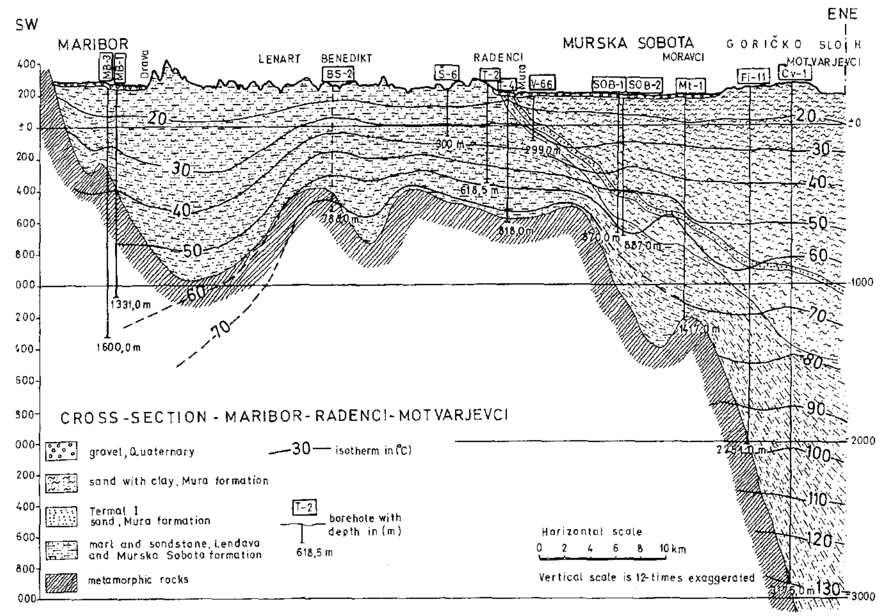


Fig. 2
:alized cross-section through Mura basin in WSW-ENE ·ection

e-Tertiary metamorphic basement deepens rapidly, and :ains a depth of about 4 km in its central part. Here, me remains of Triassic dolomites overlie metamorpic cks, forming an aquifer containig a brine and abundant)₂ gas.
·rtiary sediments in the Radgona depression were de- ·sited in a marine environment during Carpathian, Bad- inan and Sarmatian stage (Pleničar 1968). Except for .denian, they are developed as clastics – clays, marls, ts and sands. During Pannonian and Early Pontian, akish conditions prevailed. In Late Pontian and Quar- ·nary, the environment changed into continental – flu- ıl and limnic. Pliocene and Quarternary deposits are latively thin, and probably, extensively eroded. CO_2 gas abundant in marginal areas of the Radgona depression, netratrating along deep faults from the pre-Tertiary sement. Nuskova, Radenci, Benedikt, and the Ščavnica lley are the sites of mineral water occurrences, either in allow aquifers or as natural springs. CO_2 enters aquif- s, mixing with, and dissolving in the water enhancing agressiveness, and consequent water-rock interaction. 1 the horst of Murska Sobota and in the Ljutomer depression, Tertiary sedimentation began in the Sarmatian stage in a marine depositional environment. A thin layer of basal breccia is overlain by the sequences of interstratified clays, marls, shales, sands and sandstones (Fig. 2). Sarmatian sediments are united into the Murska Sobota formation. They are moderately to well lithified by compaction and cementation processes. Aquifers are commonly of poor capacity, unless fractured.
The overlying Pannonian and Lower Pontian sediments are fine-grained clays, silts and silty sands, deposited in a brakish environment. Their thickness attains up to 100 m. The sediments are united into Lendava formation. They are well compacted and partially lithified. The aquifers have poor capacity, but may be locally fractured, and characterized by the presence of CO_2 gas.
Upper Pontian and Quarternary sediments are continental and united into the Mura formation. Owing to rapid subsidence of the Radgona and Ljutomer depressions, rapid sedimentation occurred, the transport direction being from northwest to southeast. In the northern margin of the Radgona depression, along the horst of South Burgenland, systems of alluvial fans developed, and further on, they evolved into braided rivers. In the river channels, sands and pebbly sands accumulated, whereas in the adjacent flood basins, fine-grained sediments and organic matter deposited. During burial, the sediments stacked in horizontal and vertical directions forming a widespread

thermal aquifer – Termal I. Termal I underwent some compaction, nevertheless, it still preserved much of the primary porosity. For this reason, CO_2 does not occur as free gas, but only penetrates in the aquifer from the underlying formations, and dissolves in the water forming the set of inorganic carbon species.
The Radgona and Ljutomer depressions can be regarded as small artesian basins. Under compaction, waters rise from the depression centers towards the marginal areas, undergoing modifications due to elevated temperature and pressure conditions. Elevated lithostatic pressure may exceed hydrostatic pressure, and pore waters will tend to squeeze out through the low permeability horizons eventually producing an ion filtration (Albu and others 1997). The presence of CO_2 may cause considerable changes in chemical composition due to the enhanced agressiveness of the water. Finally, tectonic displacements which are more abundant in marginal areas of both depressions, can be responsible for the passage of water from different aquifers, producing the effects of mixing.

Hydrogeochemical facies

Hydrogeochemical facies, encountered in the thermal aquifers of the Mura basin, are shown in Table 1. The division is based on over 400 chemical analyses performed during hydrodynamical and hydrogeochemical monitoring of the aquifer – Termal I. Some data (G. Barič, unpub. data), obtained during oil and gas exploration are also incorporated. At first glance, it can be seen that sodium is the prevalent cation, whereas anion composition is variable, comprising chloride, bicarbonate or sulfate ions.
Mineral waters show the opposite compositional trend; they are essentially bicarbonate waters, dominated by calcium or calcium and sodium cations. Hydrogeochemical facies, encountered in mineral aquifers of the Mura basin are shown in Table 2. The division is based on 18 chemical analyses.

The Radgona depression

Thermal aquifers in the basement

Composition of water, abstracted from the pre-Tertiary carbonate basement in the Slovenian part of the Radgona depression, is generally dominated by sodium and bicarbonate. However, sulphate ions may become abundant locally, particularly if the carbonate rocks contain gypsum. Chloride is present in subordinate concentrations with respect to bicarbonate (Table 3).
The aquifers were tapped by deep oil wells St-1, Dan-1 and Šom-1, located along margins of the Radgona depression in the NE-SW direction (Fig. 1). The well St-1, Strukovci, penetrated the pre-Tertiary carbonate basement at a depth of 1645 m. Water, abstracted from the depth interval between 1645–1660 m, contained 6551 mg/l of total dissolved ions, and belongs to the $Na\text{-}HCO_3$ hydrogeochemical facies (Table 3). Concentrations of chloride ions were less than 1% of dissolved anions. The Dan-1 well, located at Dankovci, penetrated the pre-Tertiary basement at a depth of 2000.5 m. Water abstracted from the depth interval between 2188.5–2000.5 m contained 9858 mg/l of total dissolved ions, and belongs to $Na\text{-}HCO_3\text{-}SO_4\text{-}Cl$ hydrogeochemical facies (Table 3). Chloride amounts to 12.8% of the total anions. In the Šom-1 well, located at Šomat, the pre-Tertiary basement occurs at a relatively shallow depth of 895 m. The basement consists of carbonate, metamorphic and clastic rocks. Water, abstracted from the 895–914-m depth-interval, contained 5495 mg/l of total dissolved ions, and belongs to $Na\text{-}SO_4\text{-}HCO_3\text{-}Cl$ hydrogeochemical facies. Chloride amounted to 17.8% of the total dissolved anions.

Table 1
Hydrogeochemical facies recognized in thermal aquifers of the Mura basin

Na-Cl	Sodium – chloride
$Na\text{-}HCO_3$	Sodium – bicarbonate
$Na\text{-}Cl\text{-}HCO_3$	Sodium – chloride – bicarbonate
$Na\text{-}HCO_3\text{-}SO_4\text{-}Cl$	Sodium – bicarbonate – sulphate – chloride
$Na\text{-}SO_4\text{-}HCO_3\text{-}Cl$	Sodium – chloride – sulphate – bicarbonate

Table 2
Hydrogeochemical facies recognized in mineral aquifers of the Mura basin

$Na\text{-}Ca\text{-}HCO_3$	Sodium – calcium – bicarbonate
$Ca\text{-}(Na)\text{-}HCO_3$	Calcium – sodium – bicarbonate
$Ca\text{-}Mg\text{-}(Na)\text{-}HCO_3$	Calcium – magnesium – bicarbonate

Thermal and mineral aquifers in Badenian and Sarmatian sediments

Thermal water abstracted from Badenian and Sarmatian sediments is characterized by the dominance of sodium and bicarbonate. Mineralization is strongly dependent on the CO_2 gas available, which substantially increases water–rock interaction. In marginal parts of the Radgona depression CO_2 gas is abundantly encountered in thermal and mineral aquifers, but also in moffetes and underground traps.
The T-4 well, located at Radenci spa, penetrated the pre-Tertiary basement at a depth of 800 m. Thermal water is abstracted from the aquifers in Badenian and Sarmatian sediments between 400–450 m in depth; the water temperature is 43 °C, and dissolved ions amount to 10,946 mg/l (Table 3). The composition of water is dominatad by sodium and bicarbonate. Chloride and sulphate are relatively low, amounting to 2.9% and 0.8% of the total dissolved anions, respectively.
Shallow aquifers in Badenian and Sarmatian sediments commonly yield mineral water. The waters are dominated by calcium or calcium and sodium bicarbonate. In Benedikt (Fig. 1) three shallow boreholes – Helena, Pavla and Ana, reached a depth of 30 m, 60 m and 100 m, respectively. The chemical composition of abstracted water (Ta-

Table 3
Composition of thermal water in the aquifers of Radgona depression

Well depth (m) Formation, rock type	Units[a]	St-1 1645–1660 Carbonate basement	St-1 1652–1655 Carbonate basement	Dan-1 2188–2000 Carbonate basement	Šom-1 895–914 Carbonate basement	T-4 400–540 Murska Sobota
Na^+	mg/l	1414	750	2550	1570	2087
	meq/l	61.51	32.6	110.92	68.29	90.72
	%	78.6	90.6	90.5	91.2	72.1
K^+	mg/l	122	11	125	39	440
	meq/l	3.12	0.28	3.2	1.0	11.25
	%	4.0	0.8	2.61	1.3	9.1
Ca^{2+}	mg/l	181	42	145	66	233
	meq/l	9.03	2.1	7.24	3.29	11.63
	%	11.5	5.8	5.9	4.4	9.2
Mg^{2+}	mg/l	57	12	14	28	147
	meq/l	4.65	0.99	1.14	2.3	12.1
	%	5.9	2.8	0.9	3.1	9.8
Cl^-	mg/l	5	149	567	479	133
	meq/l	< 0.	4.2	16.0	13.5	3.75
	%	< 0.	11.6	12.8	17.8	2.8
HCO_3^-	mg/l	4199	1915	4874	1512	7633
	meq/l	68.82	31.4	79.9	24.78	125.13
	%	95.2	86.6	63.8	32.8	93.6
SO_4^{2-}	mg/l	203	31	1410	1795	233
	meq/l	4.32	0.65	29.3	37.37	4.85
	%	5.8	1.8	23.4	49.4	3.6
TDI	mg/l	6551	2669	9858	5495	10946

[a] Percentages refer to separate sums of cations and anions

ble 4) shows an increase in total concentration of dissolved ions with respect to the borehole depth ranging from 951 mg/l in Helena, to 2391 mg/l in Ana. The most obvious is the increase in calcium and bicarbonate, but the other cations – magnesium, sodium, potassium and amonium – also become more abundant. Trace elements – silicon, barium, cesium, rubidium, lithium and strontium – increase in waters from deeper aquifers. Chloride ion is low, but tends to decrease with depth, and it is probably leached from the soil horizons.

The borehole Helena in the shallows has significant recharge, and aquifers are subjected to pollution from the surface. The water from the borehole contains up to 0.03 mg/l of nitrite, and a part of sulphate, boron, arsenium, bismuth, cobalt, copper, chromium, tungsten and zinc was derived from recharge waters. Traces of some organic compounds as octyl-, and nonil-phenoles, phtalates and many others, undoubtedly originate in the surface (Vončina, unpub. data). The borehole has been capped.

Waters from mineral springs are rather diverse in total concentration of dissolved solids, which range from 2–5 g/l. The water composition is dominated by calcium and bicarbonate, although some types may also contain sodium in equal or higher amounts as calcium. The sodium-rich mineral waters commonly contain substantially higher amounts of chloride than the others, indicating possible partial origin in highly mineralized thermal waters that underwent cooling and mixing processes during their rise to the surface. Rare earth element (REE) distribution normalized to chondrite values for thermal water from the T-4 well shows a flat curve indicating rather limited fractionation of heavy (HREE) and light (LREE) rare earth elements, and very small positive europium anomaly (Fig. 3a). All analyzed mineral waters from Benedikt and the Ščavnica valley show a pronounced positive europium anomaly; furthermore, the normalized europium values are practically the same as in thermal water from T-4, whereas LREE and HREE are considerably lower (Fig. 3b). When trivalent REE can undergo fractionation process due to precipitation, induced by the change in Eh, pH and the temperature. A great part of europium may persist in dissolved divalent state according to the reaction:

$$Eu^{3+} + Fe^{2+} = Eu^{2+} + Fe^{3+}$$

This can happen if the reaction equilibrium is shifted to the right side in a solution containing higher concentrations of Fe^{2+} (Michard and Albarede 1986) what is the case in all studied samples of mineral and thermal water.

The Horst of Murska Sobota and Ljutomer depression

Thermal aquifers in the basement

Aquifers in the pre-Tertiary basement can be stagnant and diverse in wallrock composition, nevertheless, Na-Cl hidrogeochemical facies predominates.

Table 4
Composition of mineral waters captured in shallow wells in Benedikt, Nuskova and Ščavnica valley

	Benedikt, Helena	Benedikt, Pavla	Benedikt, Ana	Ivanjševci	Očeslavci	Stavešinci	Nuskova	Špindler
Amount (mg/l)								
NH_4^+	0.52	1.74	4.98	3.07	0.90	0.86	0.19	0.44
Na^+	11	36	51	104	685	162	276	30
K^+	1	8.8	21	15	65	13	3	4.8
Ca^{2+}	172	420	800	487	417	375	328	570
Mg^{2+}	80	94	180	203	69	32	47	23
Fe^{2+}	0.99	8.4	7.2	6.66	1.22	2.67	0.92	0.84
Mn^{2+}	0.610	0.340	0.170	0.143	0.178	0.359	0.428	0.540
J^-	< 0.01	0.05	< 0.05	0.02	0.21	0.05	0.02	< 0.01
F^-	< 0.01	0.13	0.04	< 0.1	0.78	0.22	0.40	0.22
Cl^-	14	5.0	3.5	7	170	25	32	8
N[a]	0.03	< 0.01	< 0.01	< 0.01	< 0.01	< 0.01	< 0.01	< 0.01
N	< 2	1.3	1.3	< 2	< 2	< 2	< 2	< 2
HCO_3^-	643	1800	3400	2590	2970	1690	1790	1620
SO_4^{2-}	26	14	23	2	118	19	68	37
CO_2	143	1918	1830	2500	3800	3300	3300	2600
P	0.034	0.015	< 0.015	0.016	0.058	0.023	0.041	0.180
SiO_2	5	27	43	18	15	17	11	30
TOC	2.4	1.7	1.3	0.9	0.8	0.6	0.9	0.8
TDI	951	2391	4536	3420	4499	2321	2547	2295
pH	6.82	6.00	6.37	6.22	6.22	6.02	6.00	6.22
Amount (ppb)								
As	4.8	3.6	0.2	0.1	0.7	0.5	0.5	1.9
B	200	60	80	100	1400	200	1400	34
Ba	97	230	520	640	63	210	62	170
Be	0.2	0.1	0.4	0.5	0.3	0.2	0.1	0.2
Bi	0.05	< 0.01	< 0.01	0.02	< 0.01	< 0.01	< 0.01	< 0.01
Cd	0.08	0.04	3.1	0.21	0.13	0.01	0.05	1.3
Co	9.4	2	2	0.8	0.5	1.1	0.8	< 0.1
Cr	1.7	1	0.4	6.7	5.5	0.7	0.7	0.3
Cs	0.06	0.13	1.5	0.88	11.5	0.01	0.29	8.3
Cu	4.2	9.1	2.2	< 0.1	10	1.4	0.5	5.4
Ga	0.21	0.02	4.4	0.01	< 0.01	0.04	0.02	0.09
Ni	26	14	24	32	20	25	32	1.9
Pb	0.08	0.36	0.06	0.22	0.12	0.01	0.01	0.04
Rb	2.6	24.8	106	53.4	346	61.2	27.7	213
Sc	12	7.7	13.4	25.9	23.2	9.3	9.6	1.9
Se	< 0.1	0.9	0.5	0.7	9.4	1.8	3.4	2.1
Sn	< 0.01	0.01	0.02	0.04	0.07	0.01	0.02	< 0.01
Sr	358	1120	2330	8180	1090	2170	1000	876
U	0.75	0.5	0.2	< 0.1	1.8	0.2	0.7	0.1
V	2.1	0.5	0.2	< 0.1	1.8	0.2	0.7	0.1
W	1.1	< 0.01	< 0.01	0.01	0.01	1.4	< 0.01	0.23
Y	1	0.87	0.24	0.7	0.03	1	0.28	0.02
Zn	62	7.6	2.8	3.5	3.5	5.1	4.6	2000
Zr	0.1	1.9	1.6	0.1	0.1	0.1	0.3	0.2
Pd	0.3	0.1	0.7	7.5	0.8	0.2	0.1	< 0.1
La	0.75	0.29	0.07	0.02	< 0.1	0.1	0.11	< 0.01
Ce	1.25	0.52	0.14	0.01	0.01	0.15	0.19	< 0.01
Pr	0.19	< 0.01	0.02	< 0.01	< 0.01	0.02	0.02	< 0.01
Nd	1.06	0.33	0.08	< 0.01	0.09	0.12	0.1	< 0.01
Sm	0.18	0.07	0.06	< 0.01	0.02	0.02	0.02	< 0.01
Eu	0.04	0.08	0.17	0.21	0.04	0.08	0.03	0.03
Gd	0.16	0.09	0.01	0.01	< 0.01	0.05	0.02	< 0.01
Tb	0.02	< 0.01	< 0.01	< 0.01	< 0.01	0.01	0.01	< 0.01
Dy	0.11	0.1	0.02	< 0.01	0.01	0.08	0.02	< 0.01
Ho	0.3	0.02	< 0.01	< 0.01	< 0.01	0.02	< 0.01	< 0.01
Er	0.06	0.07	0.3	0.01	0.01	0.07	0.04	< 0.01
Yb	0.08	< 0.01	0.02	< 0.01	< 0.01	0.05	0.02	< 0.01

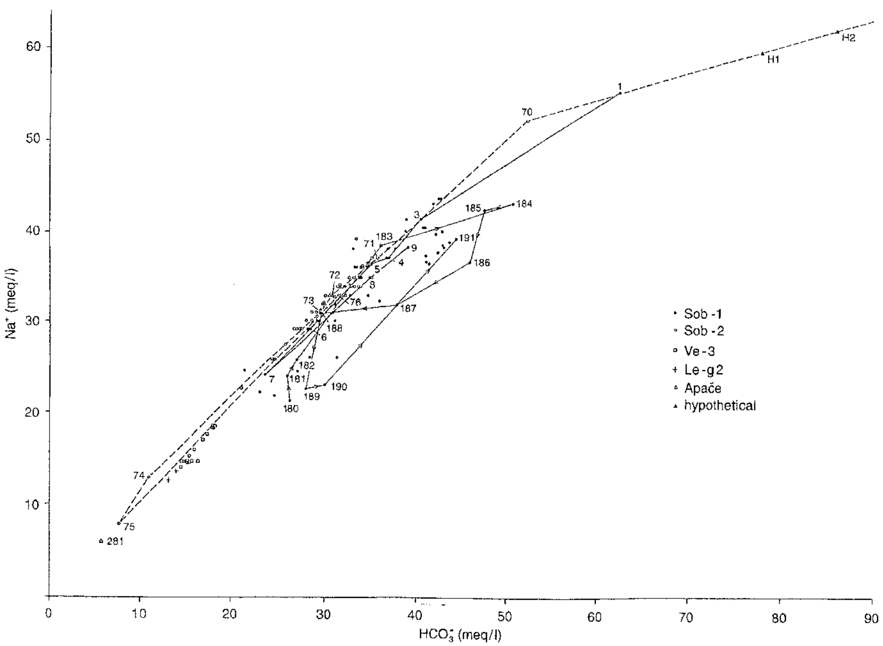
[a] N as nitrite

1898 mg/l, and 2125 mg/l, respectively. With the increasing proportion of water from the Lendava formation, potassium and calcium tend to increase, along with chloride, sulphate and many other ions and trace elements. The composite character of abstracted water is particularly important in an aquifer subjected to overexploitation. In Fig. 4, the relationship between two major ions, Na^+ and HCO_3^- is shown for the studied water samples from the wells Le-g2 (crosses), Ve-3 (open squares), Sob-2 (solid circles) and Sob-1 (open circles). The majority of samples is clustered in a straight line which extrapolates to the zero points, and indicates dilution of relatively high concentrated sodium-bicarbonate waters with a fresh-water end member. The second, broken line connects the samples 1 and 70 which represent water composition in the beginning of exploitation of Sob-1 and Sob-2. Calculated from these values are H1 and H2, two possible compositions of intermixing water from the Lendava formation. Intitial concentrations of sodium and hydrogen-carbonate are the highest recorded, and have never been attained during the well operation. The reason is in the largest proportion of water from the aquifers of Lendava formation, they have been overpressurized in the beginning of exploitation due to the presence of undissolved CO_2 gas. The Sob-1 began with operation in December 1987, and the Sob-2 in June 1988. In both wells sodium and bicarbonate have been in constant decrease until October 1992 (the samples 7 and 75), when they reached the lowest concentrations. After this period they increased in both wells, but started to vary. The samples from 180 to 192 show variations in water composition within 70 min, recorded in November 1997.

Variations in water composition caused by overexploitation of the Sob-1 well

Changes of dynamic pressures and temperatures in the Sob-1 well have been monitored by Leutert PT gauge

Fig. 4
Correlation of sodium with bicarbonate for the waters of Termal I. *Thicker solid line* connecting the samples 1–9 represents the trend of constantly decreasing concentration of Na^+ and HCO_3^- since the beginning of operation in December 1987 until January 1993 when they increased, but also began to vary. The *thinner solid line* connecting the samples 180–191 shows the change in concentration within 70-min cycle observed in November 1997. The *thicker broken line* connecting the samples 70–76 and represents the trend of constantly decreasing concentrations of the two ions in the well Sob-2 since the beginning of operation in June 1988 until November 1992 when they increased significantly. H1 and H2 are two hypothetical compositions of water from aqifers of the Lendava formation



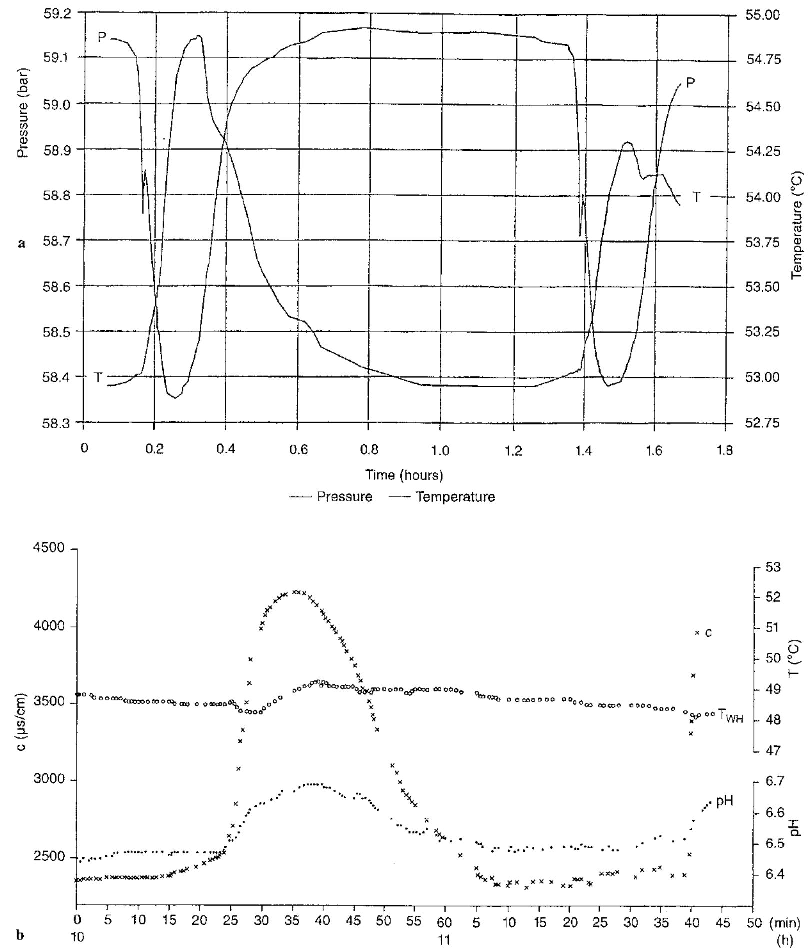
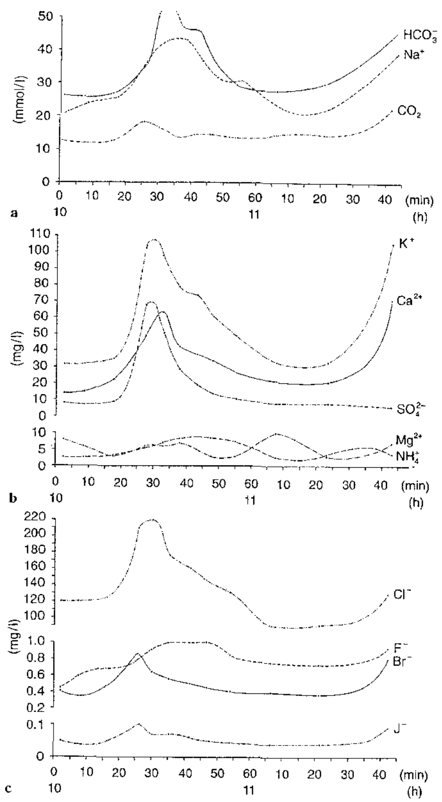


Fig. 5a
Time-dependent variations in pressure and temperature in the Sob-1 well, **b** the changes in conductance, salinity, pH and the water temperature at the well-head

during a one week period four times a year since the beginning of exploitation. The measurements have been taken every 10 s with computer-managed data output. Water samples were collected in the same 1-week period. The water level has been in constant decrease since the beginning of exploitation. The water pressure varies regularly, most commonly within a time amplitude of about 70 min (Fig. 5a). Under more intensive exploitation, the time periods tend to be shorter and amount to about 30 min. When the pressure increases, the temperature decreases and when the pressure decreases, the temperature increases. The maximum difference in pressure amounts to 0.8 bar, and the maximum difference in temperature to 2.5 °C. Conductance, salinity and pH of water increase



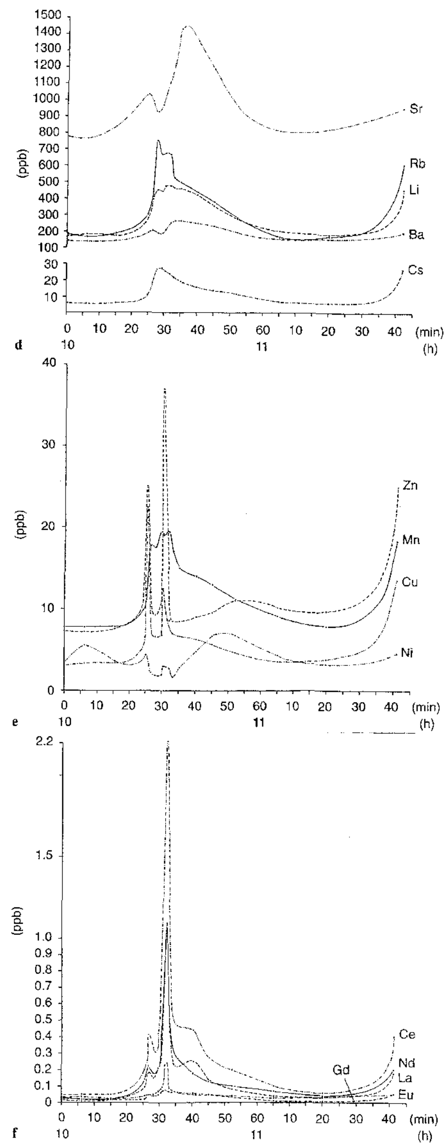


Fig. 6
Variations in abundances of various ions, trace elements and undissolved gasses in water from the Sob-1 well in a 70-min time interval in November 1997 **a** Na^+, HCO_3^- and undissolved CO_2, **b** K^+, Ca^{2+} and SO_4^{2-}, **c** Cl^-, Br^-, J^-, **d** Sr, Rb, Li, Ba, Cs, **e** Zn, Mn, Cu, Ni, **f** REE

proportionally with the temperature (Fig. 5b). The lowest measured conductance value is 2300 μS/cm, and the highest 4400 μS/cm. Salinity increases from 1.1 % to 2.2%, and pH from 6.34 to 6.69. The increase in temperature, conductance, salinity and pH in the abstracted composite water is related to a higher proportion of the water from the underlying Lendava formation. When the pressure in the aquifer – Termal I – decreases, the amount of water from the Lendava formation increases in the abstarcted composite water. When the pressure in the aquifer –Termal I – recovers and supplies more water

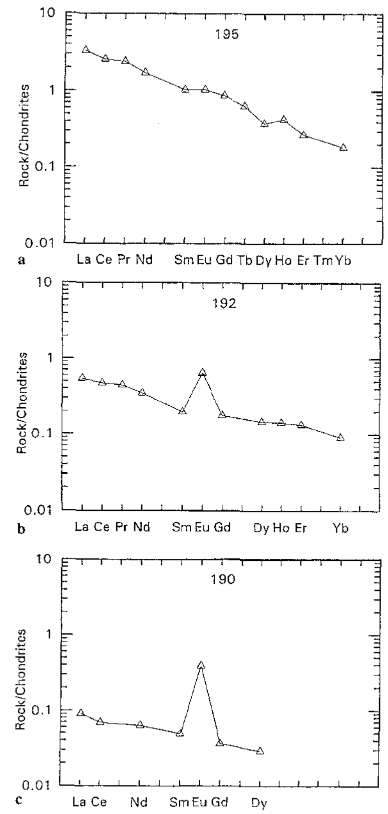


Fig. 7
Rare earth element abundances normalized to chondrite values in the water from the Sob-1 well, **a** water mixture with the highest mineralization, **b**, **c** water mixtures with lower mineralization

with a lower mineralization, the proportion of water from the Lendava formation becomes lower, as well as the overall chemical composition of the abstracted composite water.
The water from the Lendava formation is highly mineralized and even small amounts influence appreciably chemical composition of the abstracted composite water. An increase in concentration of almost all ions, dissolved gasses and trace elements – Na^+, HCO_3^- and CO_2 (Fig. 6a); K^+, Ca^{2+}, SO_4^{2-} (Fig. 6b); Cl^-, Br^-, J^- (Fig. 6c); Sr, Rb, Li, Ba, Cs (Fig. 6d); Zn, Mn, Cu, Ni (Fig. 6e); and REE (Fig. 6f) – occurs simultaneously with the decrease in pressure. Monitoring of the chemical composition within 70-min or 30-min cycles has shown, that the plots of changes in concentraton versus time are continuous and regularly repeating wave-like curves.
The maximum increase in concentration with respect to the lowest values is not the same for all of the ions and trace elements. For example: in a 70-min cycle, sodium concentrations increase from the lowest value of 490 mg/l to the highest value of 990 mg/l, which means about twice. At the same time, potassium increases from 32 mg/l to 104 mg/l, which is over three times; calcium increases from 14 mg/l to 63 mg/l, which is over four times, and sulphate increases from 8 mg/l to 68 mg/l, which is over eight times. A similar high increase in concentration was observed for light rare earth elements, particularly cerium (over eight times) and lanthanum (over ten times). The abundances of rare earth elements, normalized to chondrite values clearly indicate dilution patterns (Fig. 7). The only exception is europium, which is retained in the solution, and in more diluted samples strong positive europium anomalies are observed.

Conclusions

Tertiary sediments and sedimentary rocks in the Mura basin include aquifers with thermal and mineral water. Thermal waters from the Radgona depression are dominated by sodium and bicarbonate, although some waters may be sulphate-rich. Mineral waters are abundant in the marginal area of the Radgona depression, and occur in shallow aquifers or springs. They are bicarbonate waters, dominated by calcium, or calcium and sodium.
In deeper compartments of the Ptuj-Ljutomer depression, saline waters predominate regardless of the aquifer wall-rock composition and abundance of CO_2 gas. Aquifers in the Mura formation are characterized by intergranular porosity and thermal water dominated by sodium and bicarbonate, and also, by insignificant amounts of undissolved CO_2 gas.
Overexploitation of the Sob-1 well which abstracts composite water from Termal I and the aquifers of the Lendava formation is reflected in time-dependent changes in pressure, temperature, conductance, pH, salinity and overall chemical composition. At the beginning of exploitation, concentration of total dissolved solids constantly decreased due to sufficiently high hydrodynamic pressures in Termal I, and consequently higher inflow of its waters to the well. From the beginning of exploitation, the amounts of abstracted water were to high for the aquifer – Termal I – to recover. In the first 5 years from the beginning of exploitation, the mineralization of absracted water has been constantly decreasing. After this period, an intensive change in the chemical composition occurred. The changes are related to the changing hydrodynamical pressures in the aquifer – Termal I – which

occur regularly in a 70-min or 30-min cycle. The pressure decrease in the aquifer enables more intensive incursion of the highly mineralized water from the underlying Lendava formation. The overall mineralization of abstracted composite water increases. When the pressure in the aquifer recovers, the influx of less mineralized water begins and the overall mineralization decreases. Plotted changes in chemical composition versus time form a continuous wave-like curve. We beileve the process will lead to well collapse in the near future. Exploitation of thermal water from the intergranular aquifer - Termal I - in the Mura basin should be planned carefully and the used water reinjected from the beginning of well operation.

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Christian Wolkersdorfer

Der Weg zum guten Bericht

Was ist ein Bericht

Berichte stellen wissenschaftlich-technische Sachverhalte systematisch dar.

Zu den wichtigsten Berichten, die in Ihrem Leben eine Rolle spielen, zählen Versuchsberichte, Exkursionsberichte, Kartierberichte, Projektberichte oder Abschlußberichte. Aber auch Ihre Diplom- oder Doktorarbeit zählen zu den Berichten.

Wissenschaftliches Schreiben muß erlernt werden. Deshalb haben sich bereits viele Wissenschaftler angestrengt, um brauchbare Anleitungen zu verfassen. Eine kleine Literaturauswahl finden Sie am Ende dieser Zusammenfassung.

Die vorliegende Anleitung wird Ihnen hauptsächlich dann helfen, wenn Sie einen Exkursionsbericht verfassen wollen.

Grundlage eines Berichts

Grundlage Ihres Berichts ist die Untersuchung und Aufzeichnung einer wissenschaftlichen Neuigkeit. Dazu haben Sie Ihre Idee, das Feld- oder Laborbuch und Ihr naturwissenschaftliches Handwerkszeug.

Als zweiter Punkt folgt das Feld- oder Laborbuch. Dort notieren Sie alle Beobachtungen die Sie im Gelände oder im Labor anstellen. Manchmal mag Ihnen eine Beobachtung unwichtig erscheinen, und erst später erkennen Sie eine Regelmäßigkeit in dem entdeckten Sachverhalt. Schreiben Sie lieber zuviel, als zuwenig auf, denn einen anstrengend erreichten Aufschluß nochmals aufzusuchen ist oftmals sehr mühselig. Hier sei daran erinnert, daß nicht nur das geschriebene Wort eine Aufzeichnung darstellt, sondern gerade in unserem Beruf die Zeichnung oder Skizze. Zeichnen Sie, wo immer sie etwas wichtiges entdecken. Oftmals können komplizierte Sachverhalte mit einer Zeichnung anschaulich und einfach dargestellt werden.

Ihr Betreuer wird Ihnen dankbar sein, wenn sie statt der komplizierten Auflistung einer Deponiebasisabdichtung eine kleine Skizze beilegen. Ganz nebenbei bemerkt freut sich auch Ihr Betreuer über jede Auflockerung Ihres Berichts!

Gliedern

Beginnen Sie Ihren Bericht erst, nachdem Sie eine Gliederung entworfen haben! Für eine Exkursion könnten Sie beispielsweise folgende Strukturierung verwenden:

Titelblatt
Einleitung (z. B. Exkursionsziel)
Geologische Verhältnisse
Aufschlußbeschreibungen
Literatur

Selbstverständlich steht es Ihnen frei, die Gliederung jederzeit abzuwandeln und anzupassen. Wichtig ist lediglich, daß sie einen roten Faden haben, an dem Sie sich entlangarbeiten können. Es empfiehlt sich, auch bei kurzen Berichten eine Gliederung anzufertigen! Verlieren Sie nicht den Zusammenhang aus den Augen, für den Sie den Bericht schreiben. Schließlich sollen vor allem Sie von Ihrem Bericht profitieren!

Ein Beispiel dafür, wie allgemeingültig obige Gliederung ist, zeigt die folgende beispielhafte Gliederung für einen paläontologischen Exkursionsbericht:

Titelblatt
Einleitung (Thema und Ziel der Exkursion)
Geologisch-stratigraphische Grundlagen
Faunen: Aufschlußbeschreibungen
Systematische Einordnung, Morphologie
Taphonomie, Palökologie
Literatur

Die Gliederung eines Kartierberichts sollte folgendermaßen aussehen:

Titelseite

1 Zusammenfassung der Ergebnisse
2 Einführung
3 Ergebnisse der geologischen Kartierung
3.1 Stratigraphie und Petrographie
3.2 Tektonik
3.3 Mineralvorkommen und deren Nutzung
4 Interpretation der Ergebnisse
5 Anhang

Beachten Sie, daß die Kapitelüberschriften nicht zum eigentlichen Text gehören, Sie sollten nicht schreiben:

Öttinger Steinbruch

Im Steinbruch ist Suevit außerhalb des Kraters aufgeschlossen. Bunte Breccie ist auch zu finden.

Sondern besser:

Steinbruch Otting

Der Steinbruch Otting liegt am westlichen Stadtrand von Otting, 3.5 km außerhalb des Kraterzentrums. Er schließt Suevit und wenig bunte Breccie auf.

Inhalt des Berichts

Am Anfang Ihres Berichts stehen Ihr Name, der Titel, das Berichtsdatum und die Exkursionsleitung. Beispielsweise könnten Sie schreiben:

Helga Stein
Bericht zur Geologischen Exkursion nach Südengland
vom 27.08.94 bis 04.09.94
Friedrich-Alexander-Universität Erlangen-Nürnberg
Leitung: Prof. H. Tonstein
Dipl.-Geol. S. Faltenachser

Bei kürzeren Berichten können Sie diese Angaben an den Anfang der ersten Seite schreiben, bei längeren hingegen sollten Sie ein separates Titelblatt verwenden. Bedenken Sie bei allen nachfolgenden Fakten, die Sie im Bericht beschreiben, folgendes:

- So kurz wie möglich
- So ausführlich wie notwendig

Die Einleitung zu einer Exkursion in den Jungschen Steinbruch könnten Sie so formulieren:

Der Jungsche Steinbruch liegt im Westharz, an der Bundesstraße B 242, zwischen Bad Grund und Clausthal-Zellerfeld, wenige hundert Meter nordöstlich der Abzweigung nach Wildemann. Er befindet sich an einem nach SW geöffneten etwa 120 m hohen Prallhang der Innerste und schließt eine Wechselfolge kulmischer Grauwacken und Tonsteine auf.

Ziel der Exkursion war es, einen Einblick in die stratigraphische Abfolge des Viséum cd3 β und γ zu erhalten. Darüber hinaus wurde der Rutschungsmechanismus der Steilwand oberhalb der 2. Sohle diskutiert.

Beachten Sie, daß die Länge eines Exkursionsberichts (2 ... 10 Seiten) unter der eines Kartierberichts liegt (10 ... 30 Seiten). Daher muß es Ihr Ziel sein, die Länge Ihrer Unterpunkte der Gesamtlänge des Berichts anzupassen. Hätten Sie im Jungschen Steinbruch einen Kartierkurs abgelegt, oder Ihre Diplomarbeit dort durchgeführt, dann müßten Sie die jeweiligen Unterpunkte ausführlicher darlegen. Im vorstehenden Beispiel konnten Sie sehen, wie Einleitung und geologische Verhältnisse zu einem Kapitel verschmolzen wurden.

Den wichtigsten Teil Ihres Berichts machen Ihre Aufschlußbeschreibungen aus. Mit detaillierten Aufschlußbeschreibungen fällt Ihnen die Ausdeutung Ihrer Forschertätigkeit leichter, als mit lieblos dahingeschriebenen Stichpunktsammlungen. Die prinzipielle Gliederung einer Aufschlußbeschreibung sieht so aus:

Wo befindet sich der Aufschluß

Was ist dort zu sehen

Wie kann das Phänomen erklärt werden

Selbstverständlich ergänzt eine Skizze Ihre Beschreibung! Auf keinen Fall sollten Sie Ihre Erklärungen und Beschreibungen miteinander vermischen. Sie sind Wissenschaftler, kein Prophet!

Im folgenden Beispiel ist die vorgenannte Gliederung eingehalten:

Ediacara-Mine

Die Ediacara-Mine befindet sich am östlichen Ufer des Lake Torrens, etwa 200 km nördlich von Port Augusta (Südaustralien). Sie ist der Locus typicus der Edicara-Fauna.

*In der Umgebung der verlassenen Kupfermine steht ein feinkörniger Quarzit an, der oberflächlich ockerbraun verwittert. Im frischen Bruch weist das Gestein eine weißliche bis hellgelbe Farbe auf. Typisch für den Quarzit ist seine Verwitterung in zentimeterdicke Platten, die maximal 50*50 cm groß werden. Gelegentlich finden sich auf den Schichtoberseiten Fossilien, die Würmern, Quallen und Farnen ähneln.*

Für den guten Erhaltungszustand der präkambrischen Fauna ist das Ablagerungsmilieu ursächlich zuständig. Nach der Sedimentation des Quarzsandes und dem Absinken der toten Tiere wurden diese innerhalb kürzester Zeit von Tonen bedeckt. Die Weichteile der Tiere wurden in den noch weichen Sand gedrückt und die Abdrücke konnten sich trotz Diagenese und Orogenese bis heute erhalten.

Zu einer guten Aufschlußbeschreibung gehört eine Lageskizze, ein Profil oder eine Aufschlußskizze. Haben Sie Mut! Eine schlecht gelungene Skizze ist besser als gar keine.

Aus Ihrer Zeichnung müssen Höhen- und Längenmaßstab sowie die Himmelsrichtung hervorgehen. Bäume oder Sträucher erleichtern zwar das Erfassen der Größenordnung, ersetzen aber keinen Maßstab. Daneben dürfen Sie nicht die Legende vergessen.

Sollten Sie in Ihrem Bericht bis hierher gekommen sein, dann prüfen Sie jetzt Ihren sprachlichen Ausdruck.

Wissenschaftliche Sprache

Nicht immer gelingt Ihnen auf Anhieb, sich so auszudrücken, wie Sie es ursprünglich vorhatten. Schreiben ist eine Kunst, daher bedarf es der Übung und Anleitung. Vor dem Beginn Ihres Berichts haben Sie sich überlegt, für welchen Personenkreis Sie Ihren Bericht schreiben. Vergessen Sie bitte nicht, daß gerade an Sie als Wissenschaftler besonders hohe Anforderungen gestellt werden. Dies gilt genauso für Ihren Umgang mit der Sprache und die Verwendung von Fachausdrücken.

Sie müssen sich

- klar
- unmißverständlich und
- korrekt

ausdrücken, um verstanden zu werden.

EBEL & BLIEFERT (1991) geben einige Kriterien für guten sprachlichen Ausdruck:

- Denken Sie nach und – schreiben Sie was Sie denken

- Verwenden Sie keine zu langen und zu komplizierten Sätze mit mehrfach ineinandergefügten Satzteilen!
- Ein Wechsel von kürzeren und längeren Sätzen bringt Rhythmus und Spannung in die Sprache.
- Benutzen Sie deutsche Fachwörter anstelle englischer, wo immer angängig.
- Wägen Sie jedes Wort ab und prüfen Sie, ob es gebraucht wird.

Daneben gibt es noch eine Anzahl weiterer Kriterien, die Sie beachten sollten und die Sie bei EBEL & BLIEFERT (1991, 1993) nachlesen können.

Häufige Fehler

In geologisch orientierten Texten tauchen die nachfolgenden Fehler regelmäßig auf. Prüfen Sie Ihren Text daraufhin, ob Sie nicht ähnliche Formulierungen verwendet haben:

👎 *Die Geologie im Nordharz ...*
👍 *Die geologischen Verhältnisse im Nordharz ...*

👎 *Durch aus von mir nicht erkannten Ursachen,*
👍 *Durch Ursachen, die nicht von mir erkannt ...*

Vermeiden Sie Sätze mit „man“. Es gibt Verlage, die in wissenschaftlichen Beiträgen kein unpersönliches „man“ zulassen.

👎 *Daraus kann man die starke Erosion erkennen.*
👍 *Daraus ist die starke Erosion erkennbar.*

Machen Sie sich den Unterschied zwischen „hier“ und „dort“ klar! „Hier“ gibt Ihren Standort wieder, „dort“ einen über den Sie schreiben:

👎 *... steht Höttinger Breccie an. Hier wurde von AMPFERER ...*
👍 *... steht Höttinger Breccie an. Dort wurde von AMPFERER ...*

aber:

... wurden hier, an unserem Institut, umfangreiche ...

Beginnen Sie nicht jeden Satz mit einem Artikel:

👎 *Die Lokalität Klimpan befindet sich oberhalb des kleinen Sees, der von Marmor umgeben ist. Das dortige Gestein weist Einschlüsse von Granaten auf und ist stark metamorph überprägt. Der Granat konnte als Almandin identifiziert werden.*

Gleiches sollten Sie beim Wort „diese“ bzw. „dieses“ beachten. Besonders wichtig ist der Bezug auf vorangegangenes, der durch „dieses“ hergestellt wird. Beginnen Sie keinen Absatz oder ein Kapitel mit „dieses“, denn am Kapitel- oder Absatzanfang gibt es normalerweise nichts, worauf Sie mit „dieses“ Rückbezug nehmen könnten.

Fossilnamen müssen korrekt wiedergegeben werden. Keiner verlangt von Ihnen, die Internationalen Regeln der zoologischen Nomenklatur (IRZN) auswendig zu können, dennoch muß es heißen

👍 *Pseudophillipsia (Carniphillipsia) ogivalis javornikensis G. & R. HAHN, 1977*

und nicht

👎 *pseudophillipsia Javornikensis (HAHN).*

Allgemeine Regel: *Gattung (Untergattung) art unterart* ERSTBESCHREIBER, Jahr.

Auch bei stratigraphischen Bezeichnungen gibt es Regeln, die Sie beachten müssen:

👍 *... werden als Obere speciosus-Schichten bezeichnet ...* (Artname klein)

👍 *... im unteren Devon ...*

👍 *... die Posidonienschiefer neigen zur ...* (Gattungsname groß)

Abschließend werfen Sie einen Blick auf Ihre Zeichensetzung.

- Nach einem Satzzeichen folgt ein Leerzeichen.
- Hinter der öffnenden und vor der schließenden Klammer wird kein Leerzeichen gesetzt (da gibt es keine Ausnahme).
- Unterscheiden Sie zwischen Bindestrich (ohne Leerzeichen), Gedankenstrich (mit Leerzeichen) bis-Strich (mit Leerzeichen) und Strecken-Strich (ohne Leerzeichen). Darüber hinaus weisen die Striche im Computersatz unterschiedliche Längen auf.

  Für die NW—SE-streichende Lagerstätte wird heute – zumindest von einigen Wissenschaftlern – eine sekundär-hydrothermale Entstehung bei 120 — 140 °C angenommen.

  (In vielen wissenschaftlichen Texten wird, der Empfehlung in DIN 1338 Beiblatt 2 folgend, anstatt des „bis"-Strichs das Erstreckungssymbol ... verwendet:

  bei 120 ... 140 °C).
- Einheitenzeichen werden mit Leerzeichen hinter die Zahl gestellt: 2,3 %, 123 m, 15 °C, 2,1 g/L. Beachten Sie die Großschreibweise des Einheitszeichens L (Empfehlung des CIPM – Comité International des Poids Mesures).
- Verwenden Sie das = Zeichen nur bei mathematischer Gleichheit.

  Orogenese = Gebirgsbildung dürfen Sie auf keinen Fall verwenden! Aber: $E = 1285\ kN/m^2$.

Danksagung

Dank gilt allen Kolleginnen und Kollegen, die mit Tips, Kritik und Ergänzungen zum Gelingen dieser Anleitung beigetragen haben.

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Ebel, H. F. & Bliefert, C. (1993): Diplom- und Doktorarbeiten: Anleitungen für den naturwissenschaftlichen Nachwuchs. – 218 S.; Weinheim (VCH).

Duden Taschenbücher (1988): Wie verfaßt man wissenschaftliche Arbeiten. – 2. Aufl.: 216 S.; Mannheim, Wien, Zürich (Dudenverlag).

Lang, H. D., Rabien, A., Struve, W. & Wiegel,E. (1976): Richtlinien für die Verfasser geowissenschaftlicher Veröffentlichungen. – Stuttgart (Schweizerbart).

Anmerkung: Vorstehende Zitierweise entspricht den in den Richtlinien für die Verfasser geowissenschaftlicher Veröffentlichungen (1976) nachlesbaren Empfehlungen. Anlaß für die Herausgabe der Richtlinien war die uneinheitliche Zitierweise in den verschiedenen geologischen Publikationen.

Selbst heute halten sich die geowissenschaftlichen Fachverlage nicht alle an die sogenannten „Bonner Richtlinien", sondern verwenden jeweils Ihre eigene Zitierweise. Entsprechendes gilt für Werke, die außerhalb der geologischen Wissenschaften veröffentlicht werden. Dieses Manko kann den Austausch von Artikel oder Literaturzitaten erheblich erschweren, daher wird von verschiedenen Verlagen seit geraumer Zeit ein vereinheitlichtes Zitiersystem angestrebt. Es handelt sich dabei um die Vancouver-Konvention (1968, 1978, 1987). Sie wird allen Anforderungen an korrektes wissenschaftliches Zitieren gerecht, kann in allen Fachgebieten und Sprachen eingesetzt werden und verwendet ausschließlich den Punkt um die bibliographischen Merkmale voneinander zu trennen. Ihre Übersichtlichkeit gestattet es, jedes Werk leicht und wiederauffindbar zu zitieren. Eine Vereinheitlichung auf der Basis einer allgemein anerkannten Konvention kann dem Austausch von Wissen sicherlich weiter helfen!

Beispiel für Zitierung nach Vancouver:

Ebel HF, Bliefert C. Diplom- und Doktorarbeiten: Anleitungen für den naturwissenschaftlichen Nachwuchs. Weinheim: VCH; 1993. 218 S.

Anhang

Beispiele gelungener Aufschlußzeichnungen. Die Abbildungen 1 und 2 sollen das Prinzip des geologischen Zeichnens demonstrieren. Daher fehlen sowohl Himmelsrichtungen als auch Größenangaben.

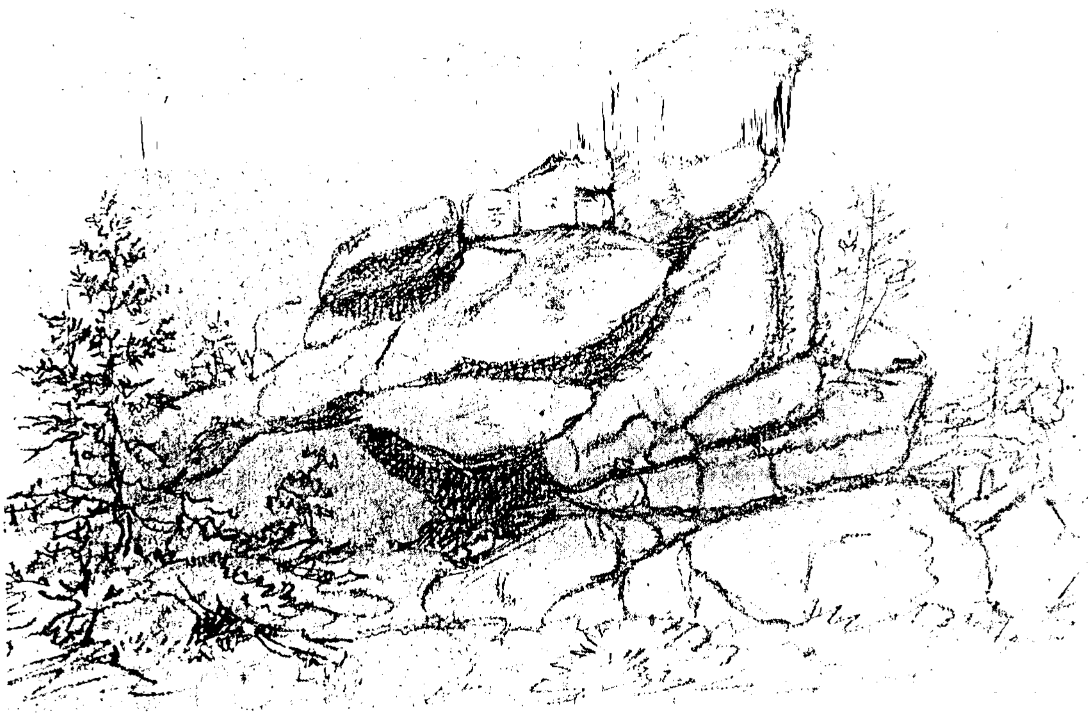

Abb. 1: Granitklippen im Brockengebiet (Johann Wolfgang von Goethe).

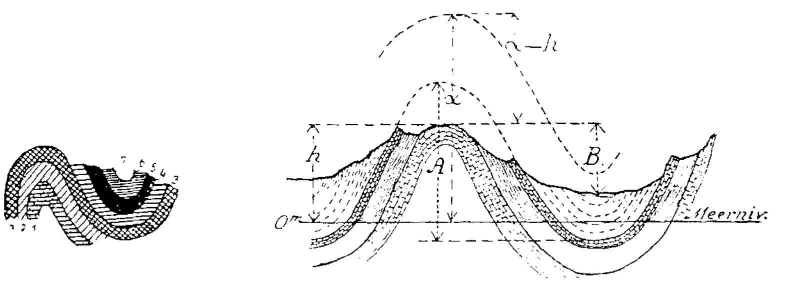

Abb. 2: links: Sattel und Mulde in schlechter, weil strukturwidriger; rechts: Sattel und Mulde in vorbildlicher Zeichnung (aus Hans CLOOS (1938): Geologisches Zeichnen. – Geol Rdsch **29**, S. 599—604).

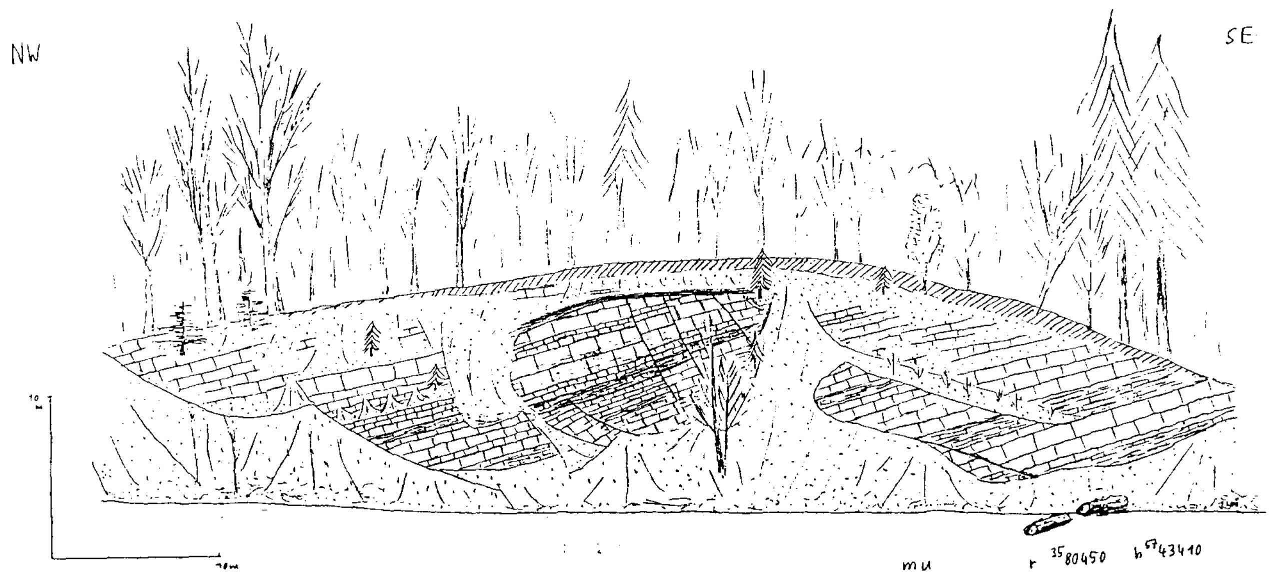

Abb. 3: Aufschluß im Muschelkalk (Ludger Feldmann).