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From Ground Water to Mine Water

Environmental Hydrogeology in Mining

Introduction | Historical Background

Prof. Dr. Christian Wolkersdorfer (云村)

Finnish Distinguished Professor – Lappeenranta University of Technology
South African Research Chair for Acid Mine Drainage Treatment

From Ground Water to Mine Water

Contents

- **Introduction, Historical Background**
- Mining Methods, Technical Terms
- Water and Water Inrushes
- Dewatering methods; Recharge
- Mine Flooding
- Mine Water Geochemistry
- Prediction of Mine Flooding
- Mine Water Treatment

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Introduction	Subjects involved
<ul style="list-style-type: none">• Mining: Mine Geometry, Mining Methods• Geology: Rocks, Tectonics, Strata• Mineralogy: Genesis of Deposit• Hydrogeology: Water• Chemistry: Analysis, Reaction• Biology: Microorganisms, Plants, Animals• Statistics: Data Evaluation• Economy: Operational, Remediation Costs• Legislation: Laws, Regulations• Mathematics: Modelling	

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Introduction	Mine Water: The Good and the Ugly
	

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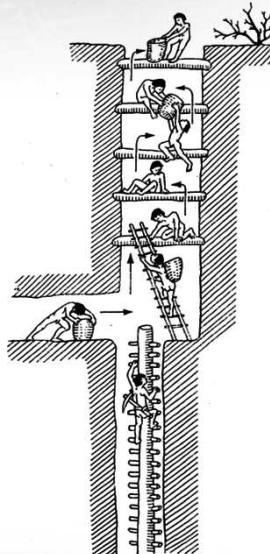
Introduction History of Mine Water

- Water inflow ⇒ dewatering drainage, drainage
 - Manuel bucket or sack water-raising (bailing)
 - Water wheel (3rd cent. BC, 14th cent. AD)
 - Archimedes' Screw (Egypt 3rd — 2nd cent. BC)
 - Dewatering Adit, drainage ditches
 - Horse winch (Tyrol, Harz 14th—15th cent.)
 - Wooden pumps (Rammelsberg/Goslar 15th Jht.)
 - Metal pumps (Schemnitz 1749: Joseph Hell)
 - Electric mine water pumps (20th cent.)

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History Dewatering Techniques

- Bailing
 - Manuel bucket or sack water-raising

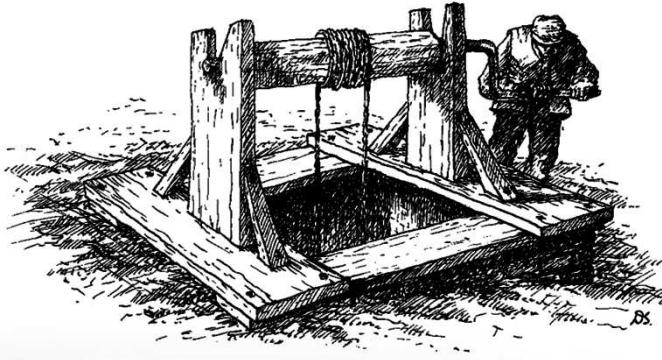


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from Rebrik 1987

History Dewatering Techniques

- Whinches
 - Manual bucket or sack water-raising

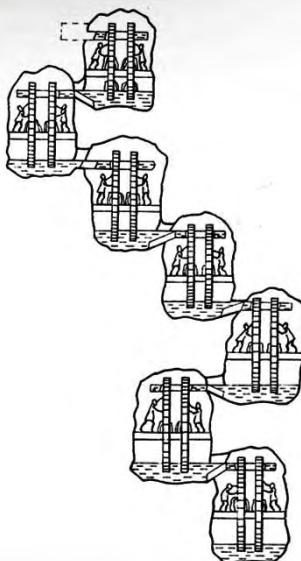


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Cowman & Reilly 1988

History Dewatering Techniques

- Man powered Water wheels
 - Egypt
 - Man power



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from Rebrik 1987

History Dewatering Techniques

- Archimedes' screw
 - Egypt
 - 3rd—2nd cent. BC

The diagram illustrates the historical use of Archimedes' screw for dewatering. On the left, a vertical screw pump (1) is shown with a chain drive at the top. A person (2) turns the screw, which rotates and lifts water from a lower level into an upper channel. The screw is labeled with numbers 3, 4, and 5, corresponding to specific parts of the mechanism. The background shows a landscape with a body of water and a distant structure.

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from Rebrick 1987

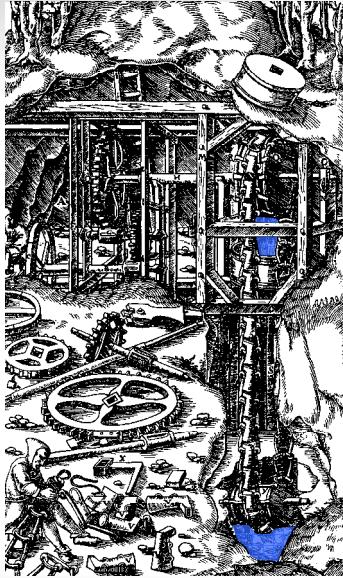
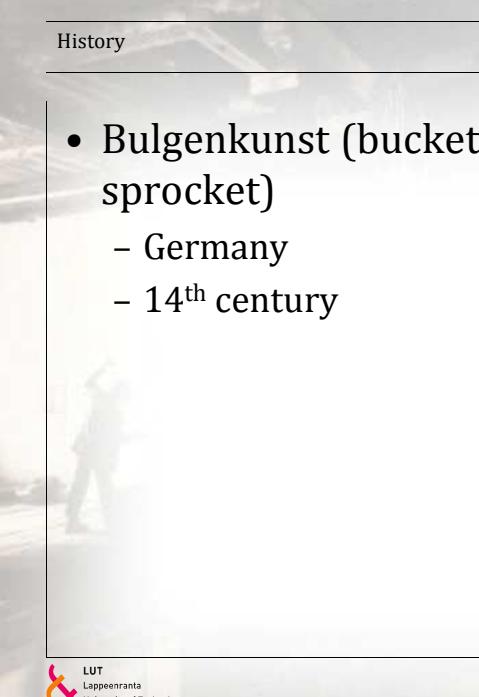
History Dewatering Techniques

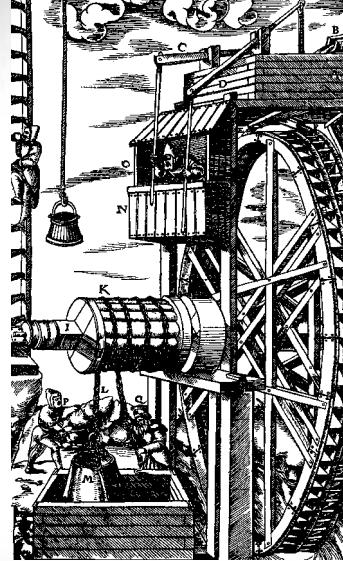
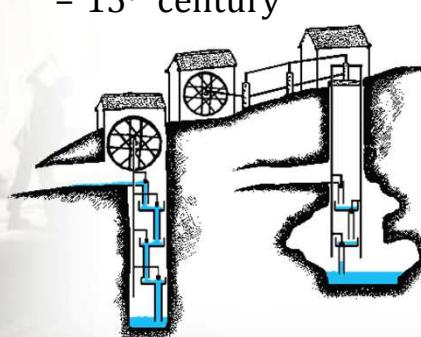
- Archimedes' screw

A black and white historical photograph showing two horses harnessed to a wooden frame, pulling a long metal screw (Archimedes' screw) through a field. The screw is partially submerged in a body of water on the left, and its end is in a drainage ditch on the right. The horses are pulling on a long wooden beam attached to the screw's frame.

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SLUB | Deutsche Fotothek | df_h_0000134

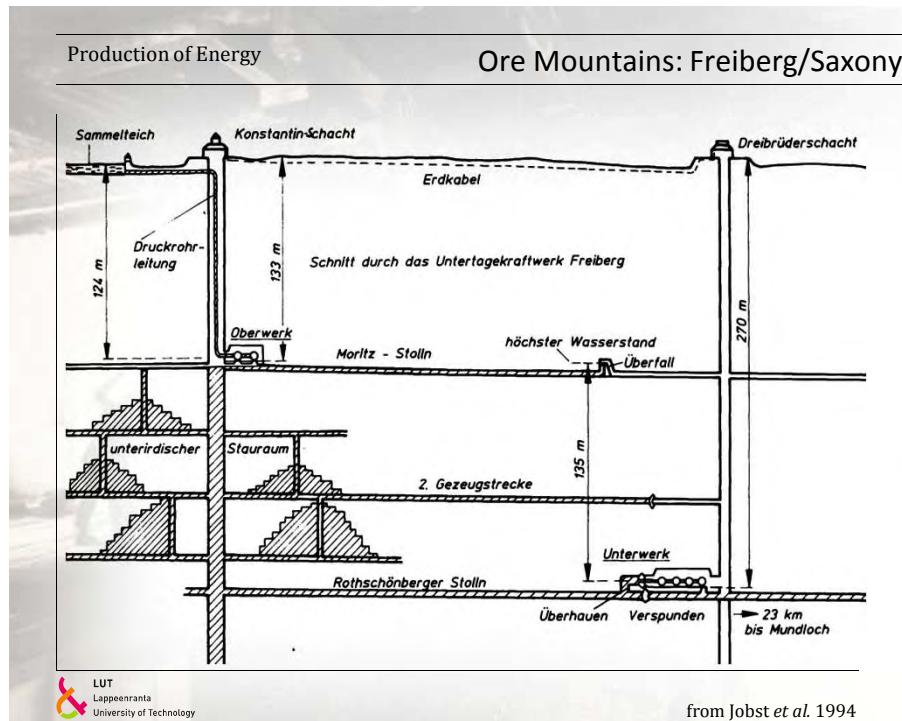
History	Dewatering Techniques
<ul style="list-style-type: none">• Bulgenkunst (bucket sprocket)<ul style="list-style-type: none">– Germany– 14th century	
	<p>from Agricola 1556</p>

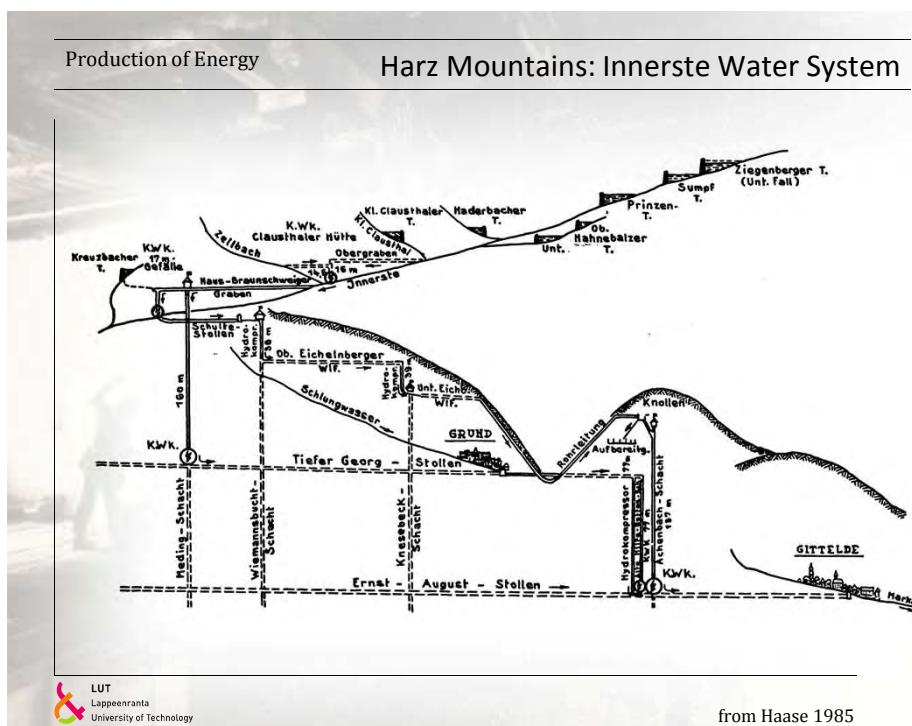
History	Dewatering Techniques
<ul style="list-style-type: none">• Water wheel<ul style="list-style-type: none">– Germany– Rammelsberg– 15th century	
	<p>from Agricola 1556</p>

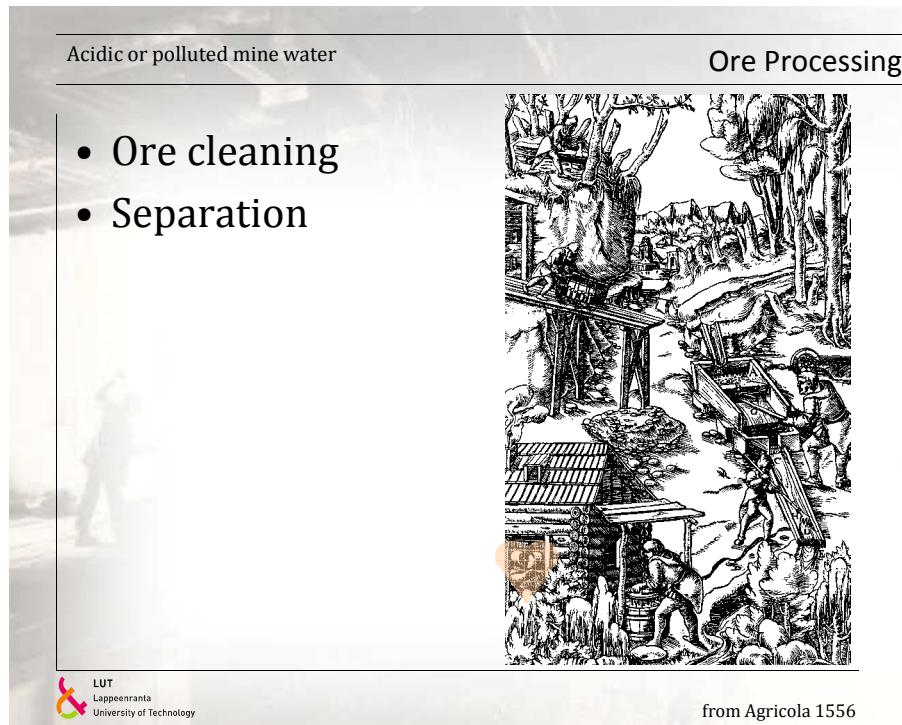
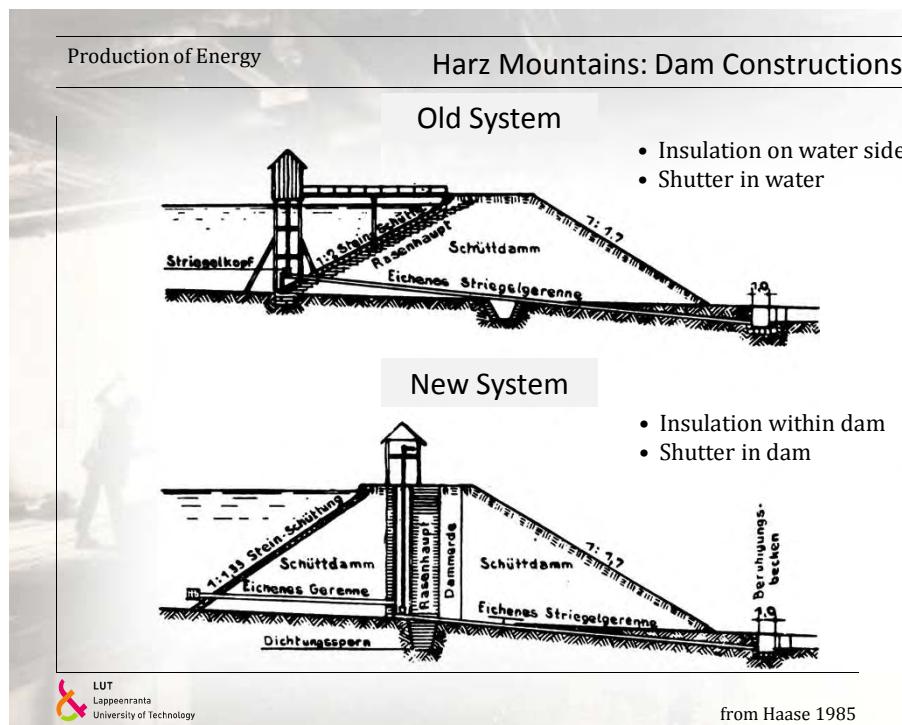
Introduction Water: The Good and the Ugly

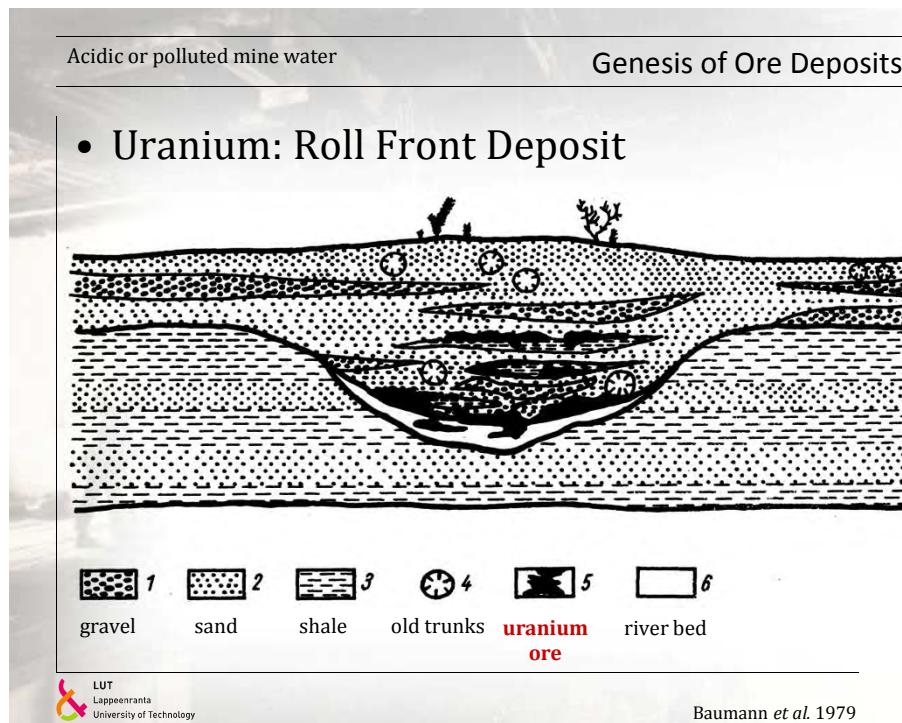
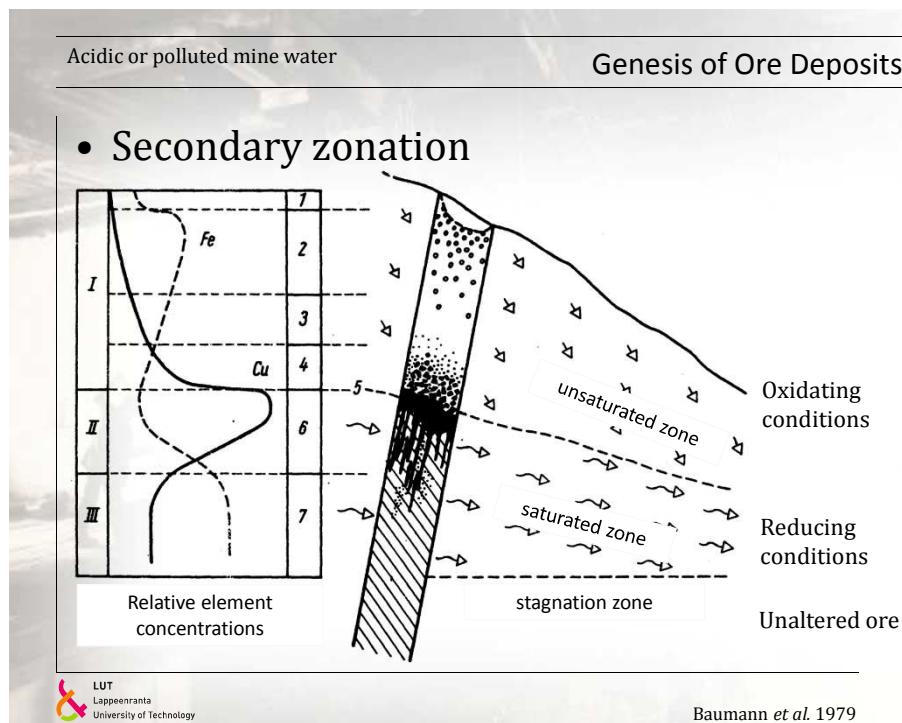
- Production of Energy
 - Water Resources Management with canals (ditches, water courses)
 - Return wheel (sprocket), Connecting rods
 - Hydro turbines (Ore-, Harz-Mountains)
- Acidic or polluted mine water
 - Ore processing
 - Mine water s.s.
 - Agricola
 - Genesis of ore deposits

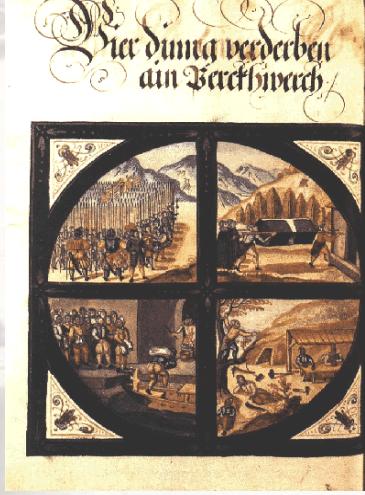
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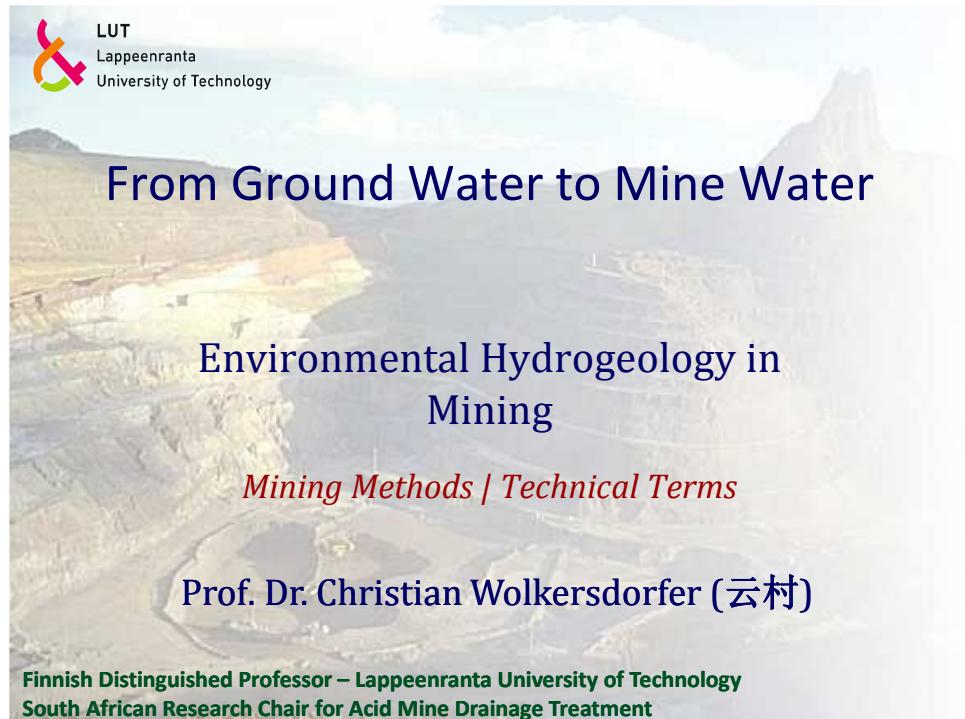
Acidic or polluted mine water	Reasons for Mine Closure
<ul style="list-style-type: none"> “Four things ruin a mine”  <p>The illustration consists of four circular panels. Top-left: "Krieg" (War) shows soldiers attacking miners. Top-right: "Sterben" (Diseases) shows miners with illness. Bottom-left: "Zerstörung" (Inflation) shows miners in a ruined environment. Bottom-right: "Völkern" (Listlessness) shows miners in a state of despair.</p>	<p>Reasons for Mine Closure</p> <ul style="list-style-type: none"> War Diseases Inflation Listlessness

from Schönberger 1556

History

Literature

- Agricola, G. (1556): *De re metallica libri XII.* – Basel.
- Kugler, J. & Schreiber, W. (1992): Das beste Ertz. – Haltern.
- Kunnert, H. (1974): Bergbauwissenschaft und technische Neuerungen im 18. Jahrhundert – Die „Anleitung zu der Bergbaukunst“ von Chr. Tr. Delius (1773). – München.
- Rebrik, B. M. (1987): Geologie und Bergbau in der Antike. – Leipzig.
- Sperges, J. v. (1765): Tyrolische Bergwerksgeschichte mit alten Urkunden, und einem Anhange, worin das Bergwerk zu Schwaz beschrieben wird. – Wien.
- Dictionary Applied Geology (English, German, French, Spanish): www.geo.tu-freiberg.de/fog/issues.html



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Mining Methods / Technical Terms

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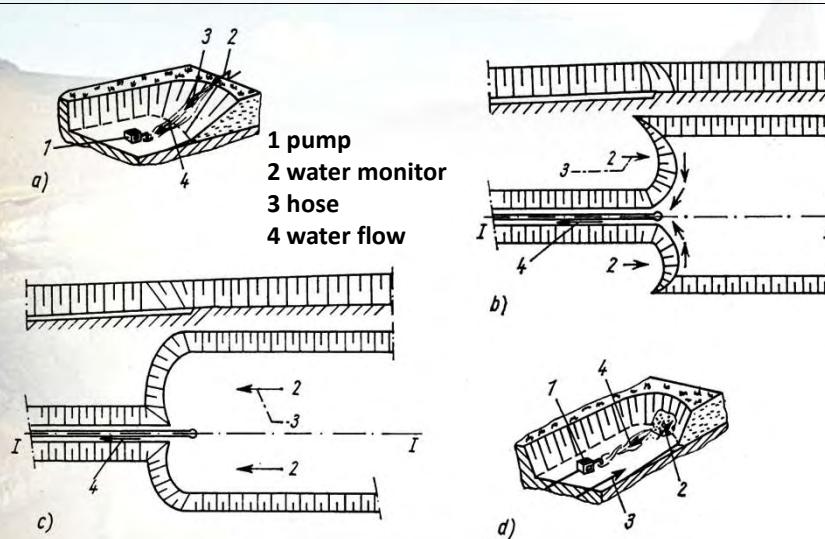
Mining Methods – Mine Types

- deep mine, underground mine
 - e.g. gold, iron, graphite, baryte
- open cast mine, surface mine
 - e.g. iron, hard coal, soft coal
- quarries
 - e.g. granite, basalte, sand, limestone
- sand, clay pit
- hydromining

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Mining Methods

Hydromining



a) 1 pump, 2 water monitor, 3 hose, 4 water flow

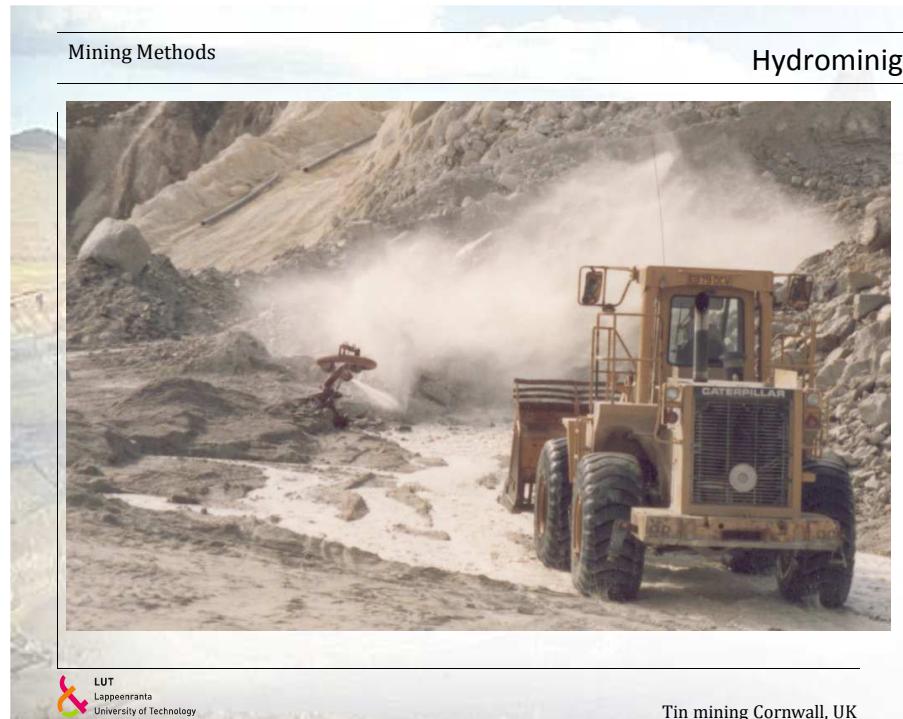
b)

c)

d)

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from Strzodka et al. 1979

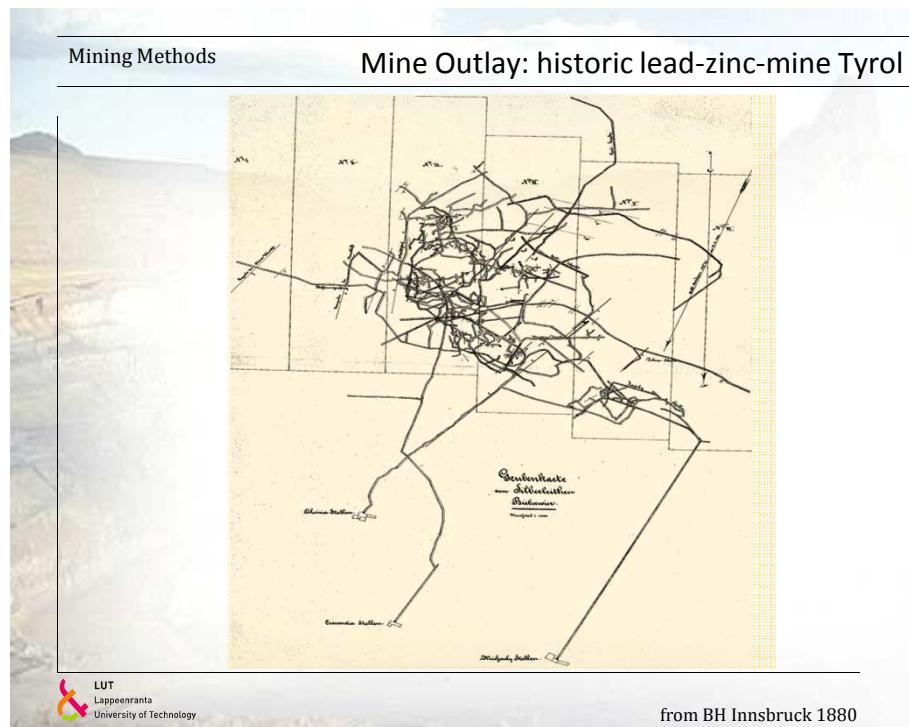
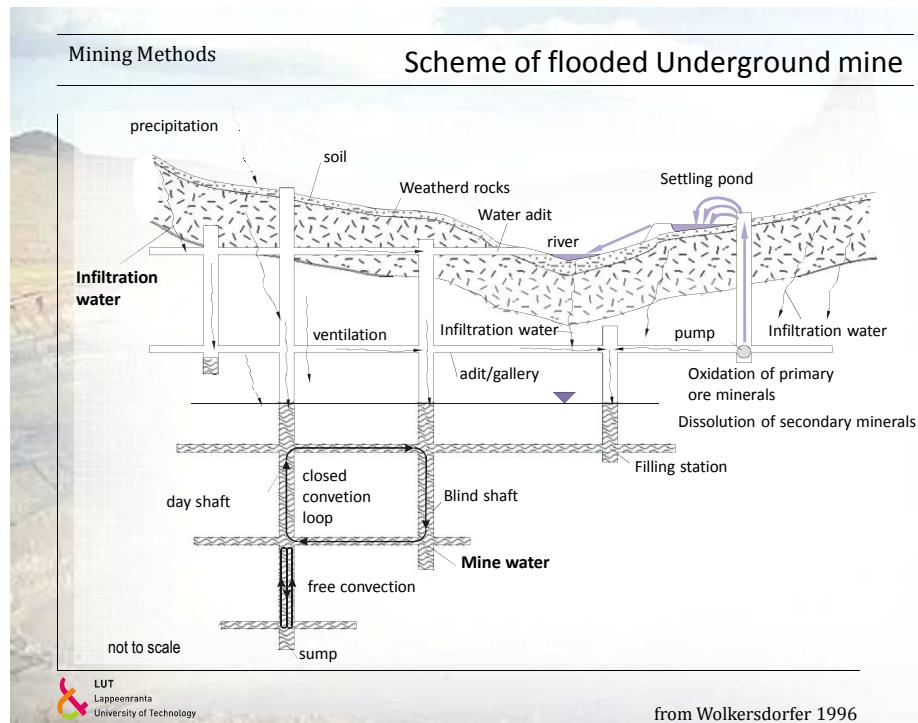


Mining Methods

Access to underground mines

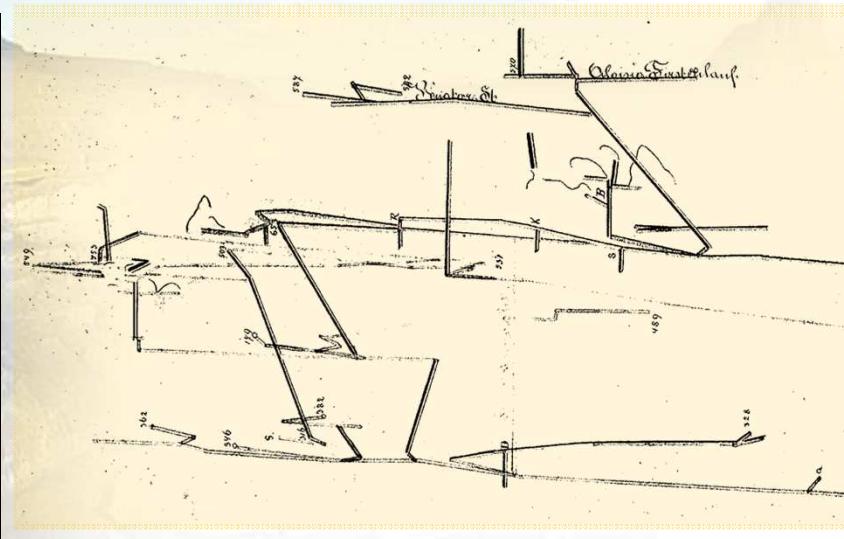
- shaft
 - Access to the mine by one or more vertical or sub-vertical shafts
 - Reiche Zeche, Freiberg; Schacht 371, Niederschlema
- drift, adit
 - Access by horizontal galleries
 - Pöhla/Ore Mts.; Wohlverwahrt Nammen
- slope, incline drift, dib
 - Access to the mine by spiral ramps
 - Wolkenhügel, Harz/Mts.; Mt. Lyell, Tasmania

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Mining Methods

Mine Outlay: historic lead-zinc-mine Tyrol

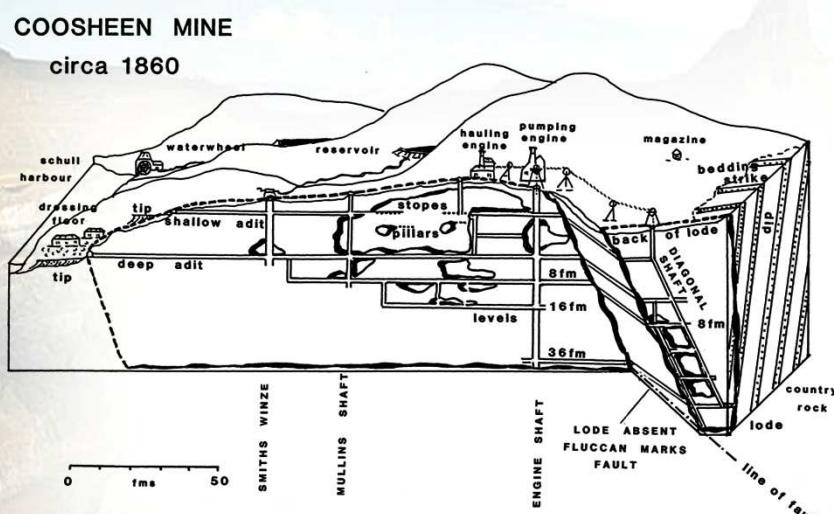



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from BH Innsbruck 1880

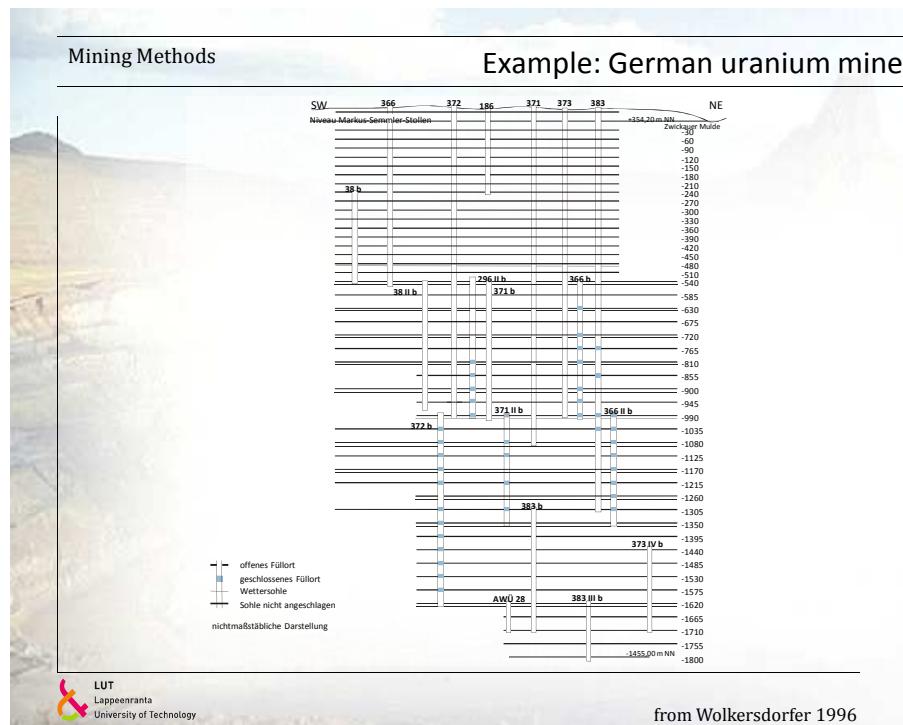
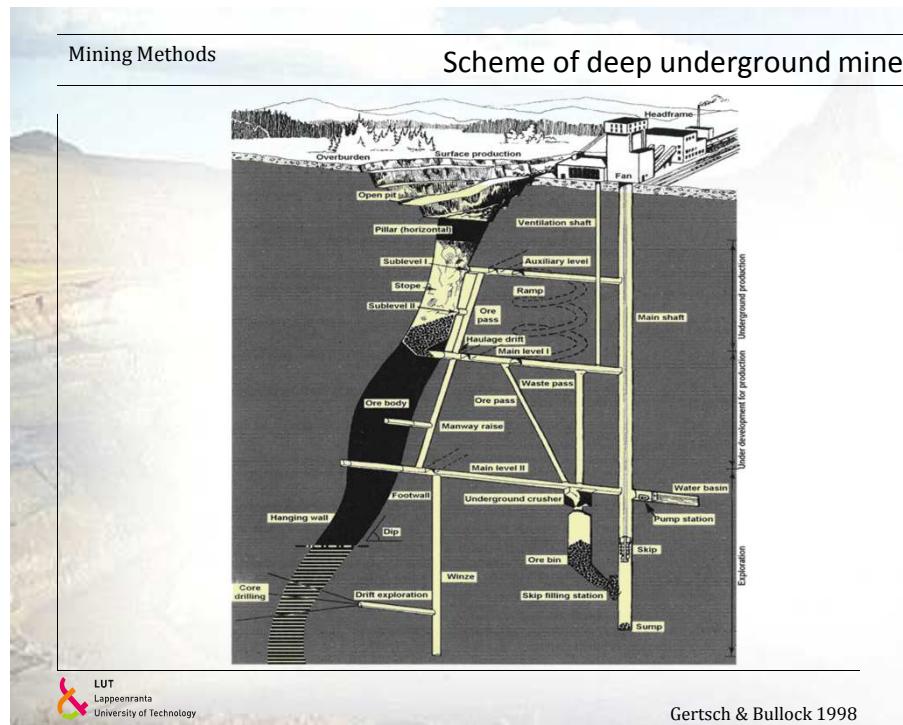
Mining Methods

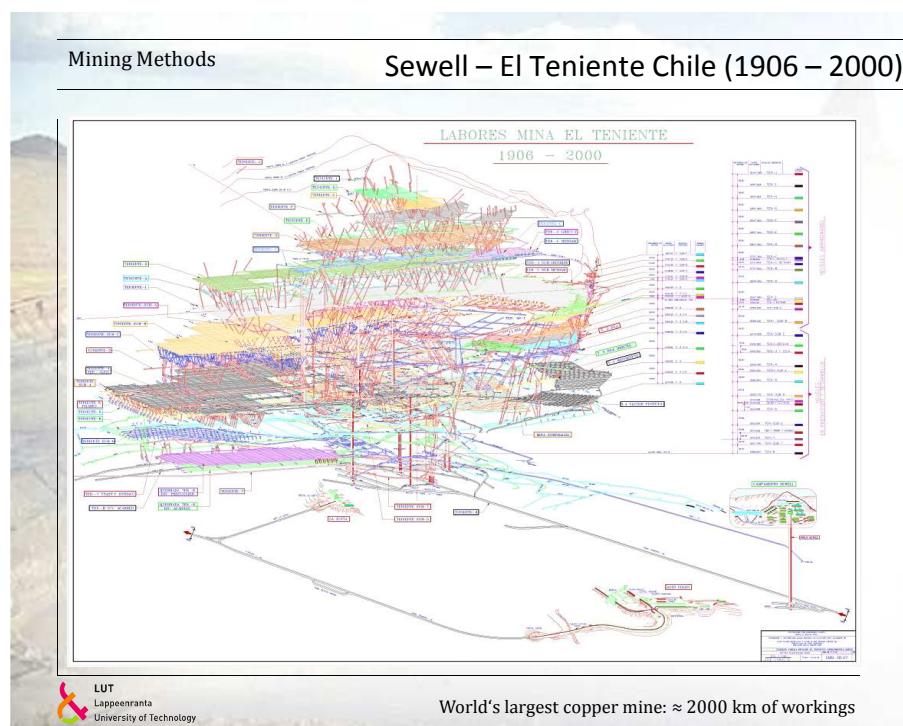
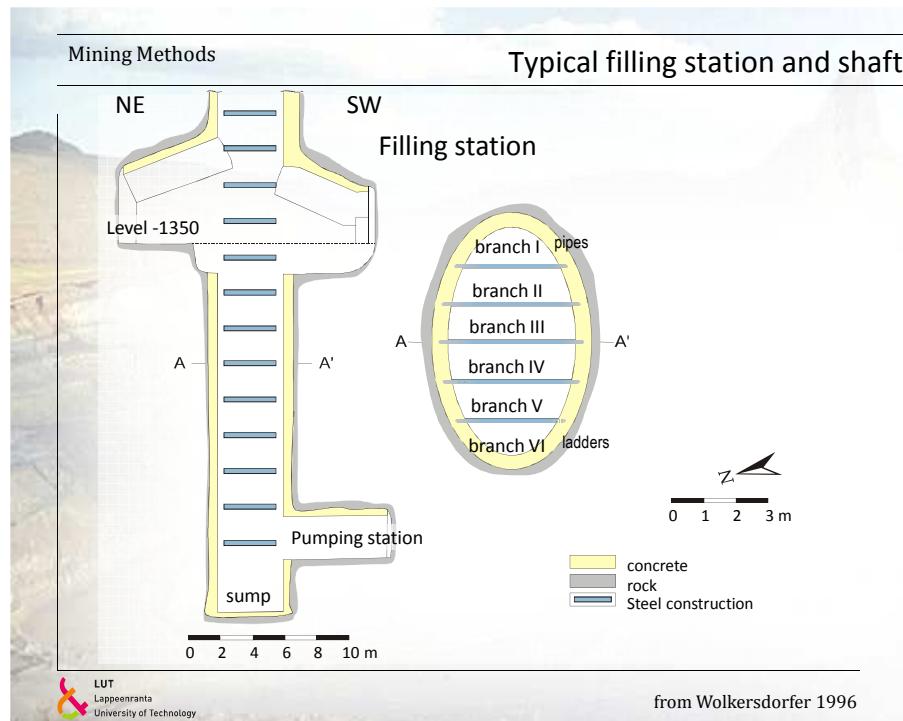
Scheme of deep underground mine

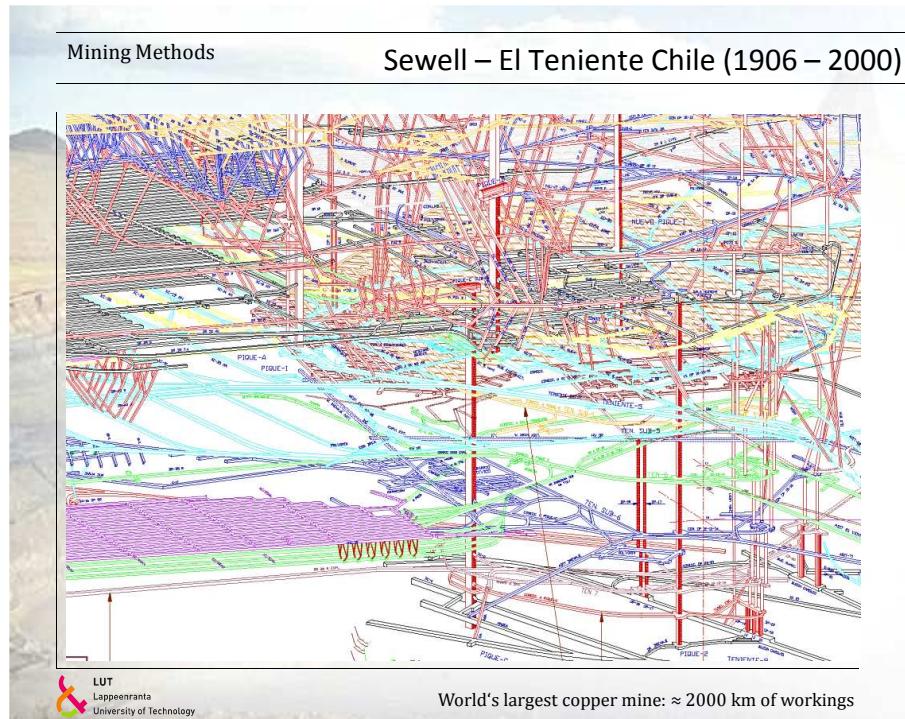



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Cowman & Reilly 1988





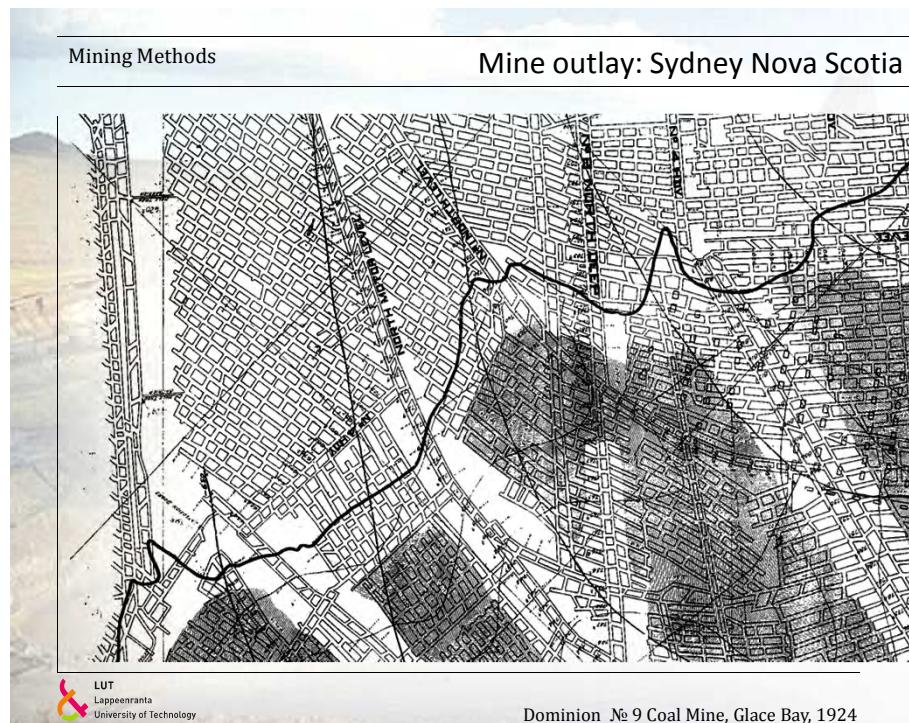
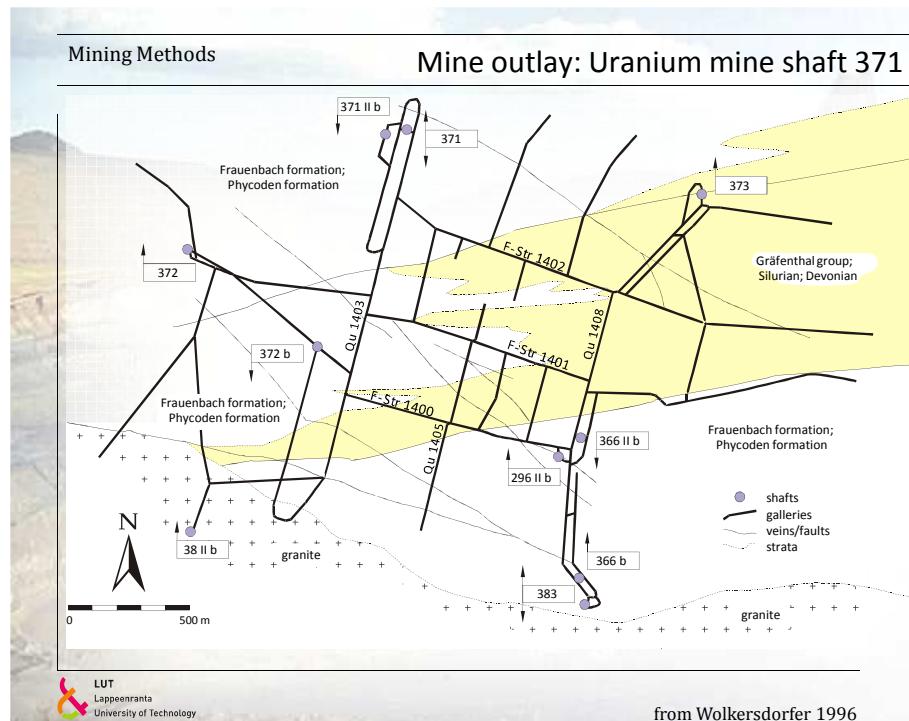


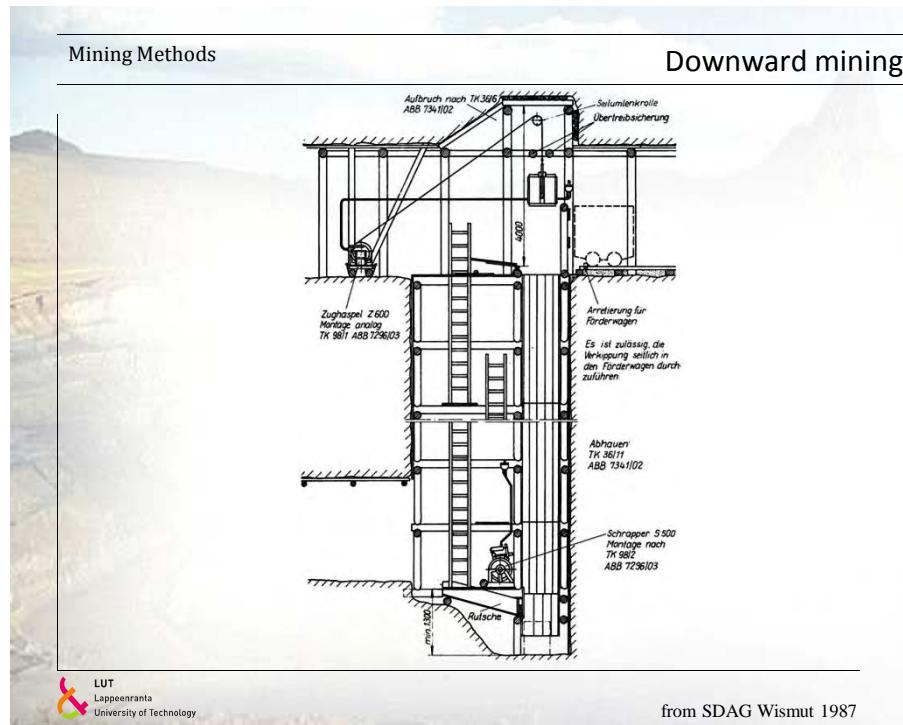
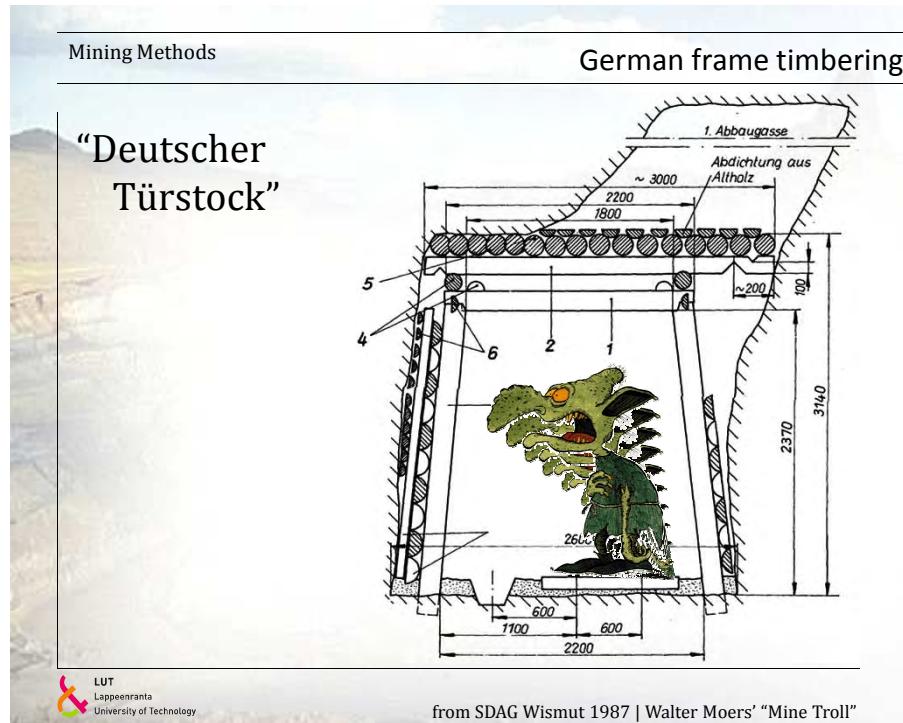
Mining Methods

Underground mining

- Shafts and galleries must guarantee:
 - Man haulage (Skips, trackless haulage, mine railway)
 - Material haulage
 - Raw material extraction (stopes)
 - Host rock, by-products
 - Mine ventilation (mine ventilators, ventilation shafts)
 - Mine dewatering (water drainage, mine pumps, sumps)
 - Mine power (electricity, water, pressurized air)

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Mining Methods

Cross/shaft timbering

“Bolzenschrot-zimmerung”

- SDAG Wismut
- Shaft Thies (Pluto Mine Wanne-Eickel)

from SDAG Wismut 1987

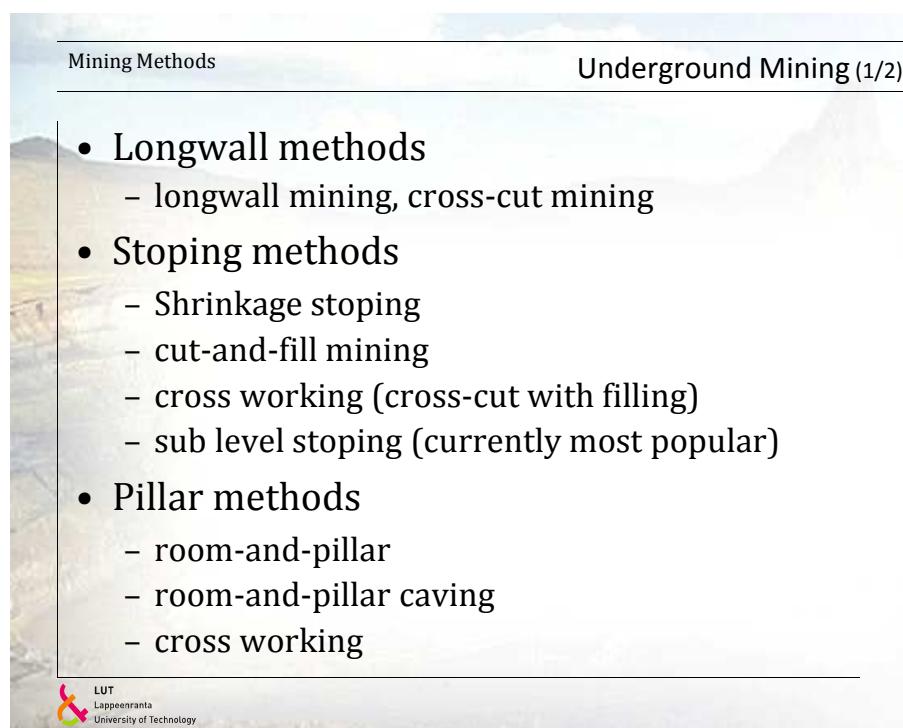
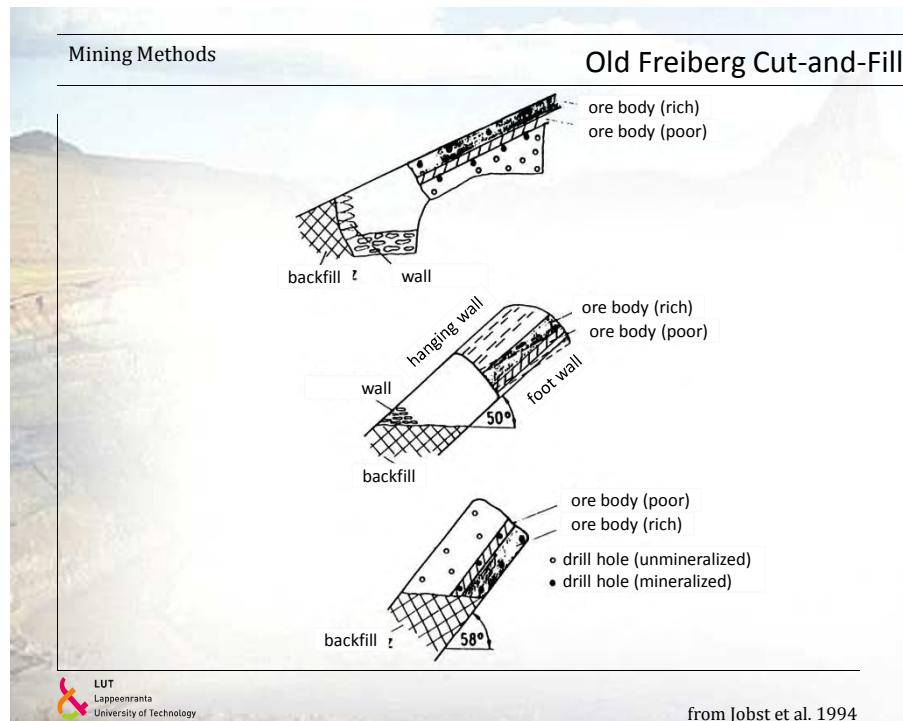
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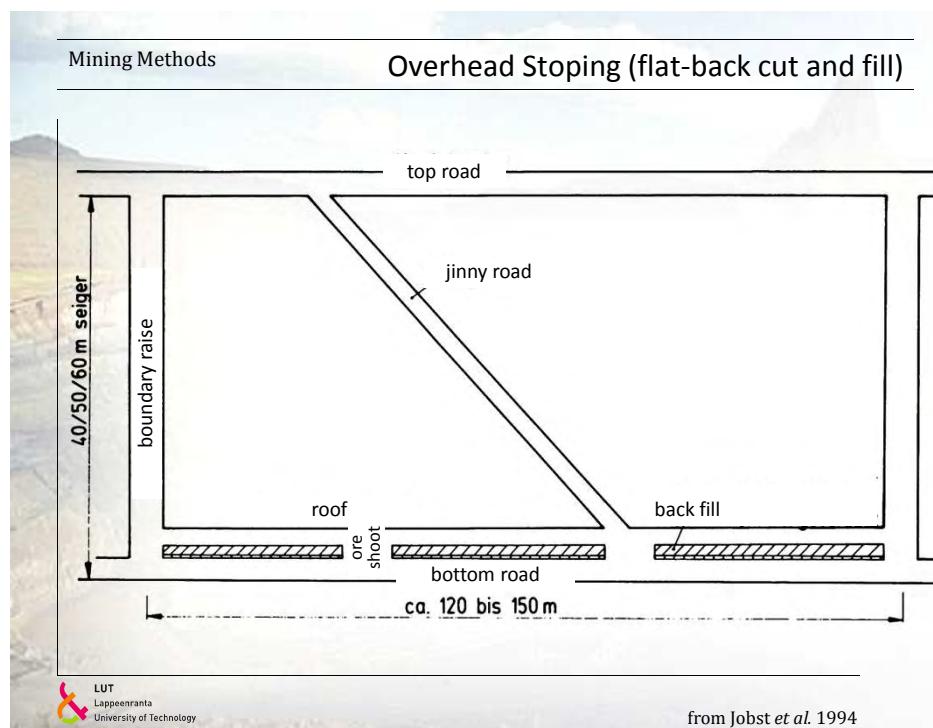
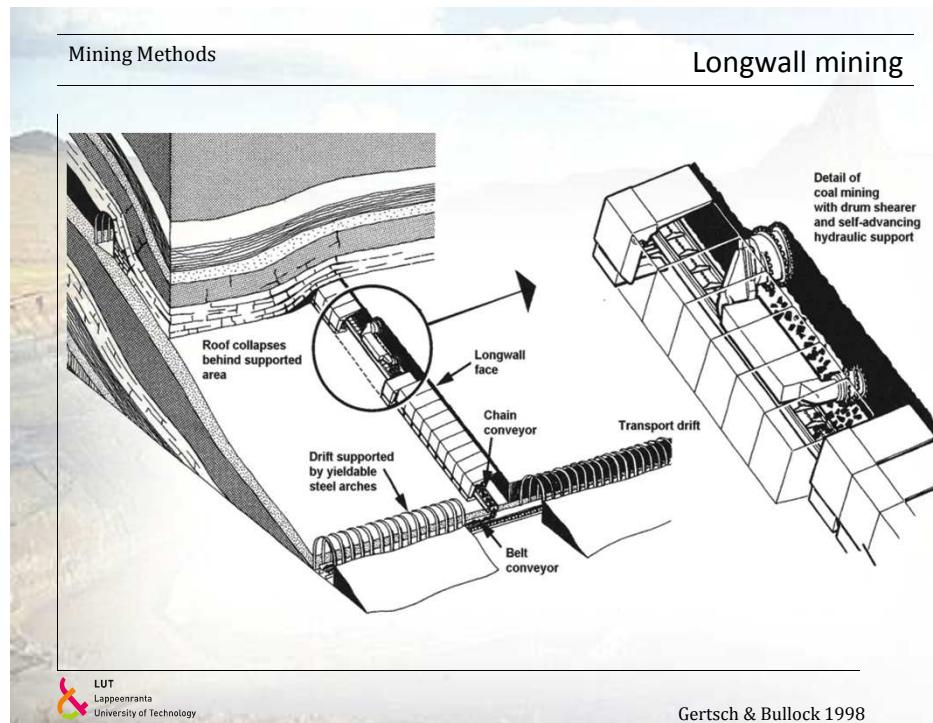
Mining Methods

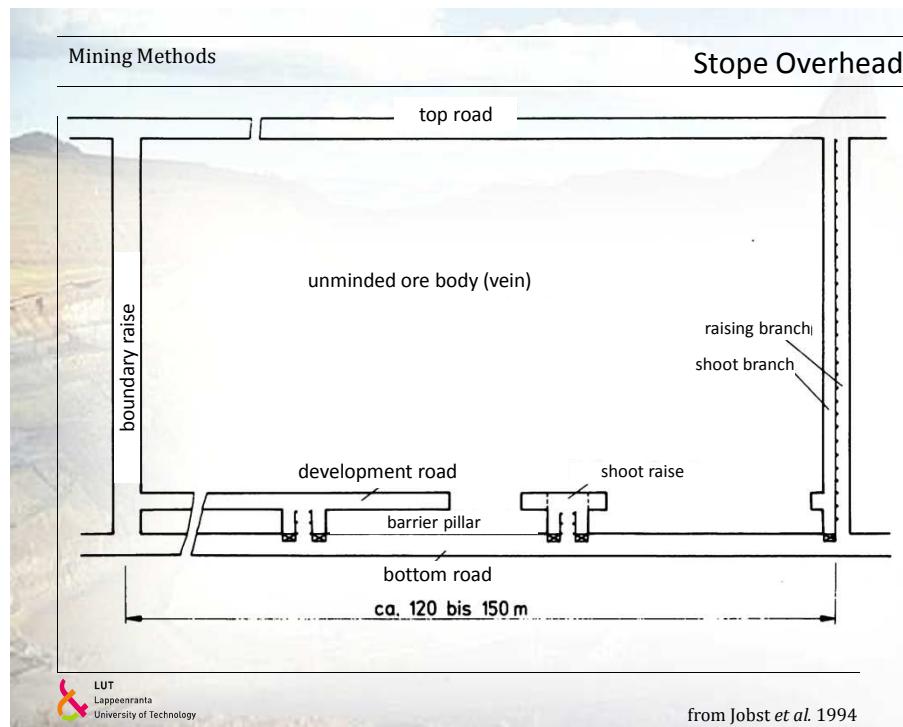
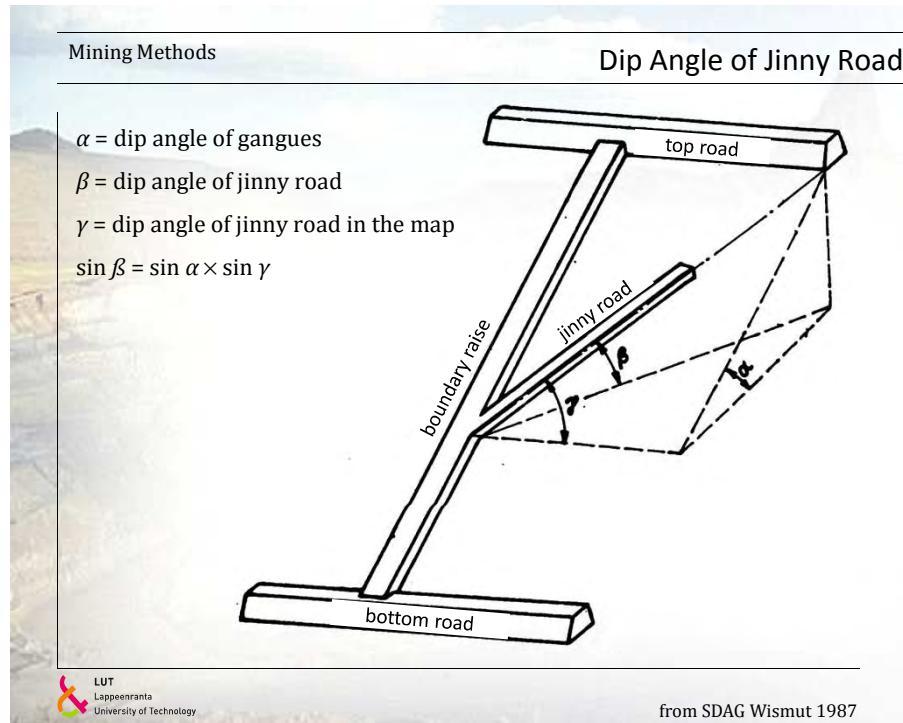
Auxillary Ventilation at Advancing Face

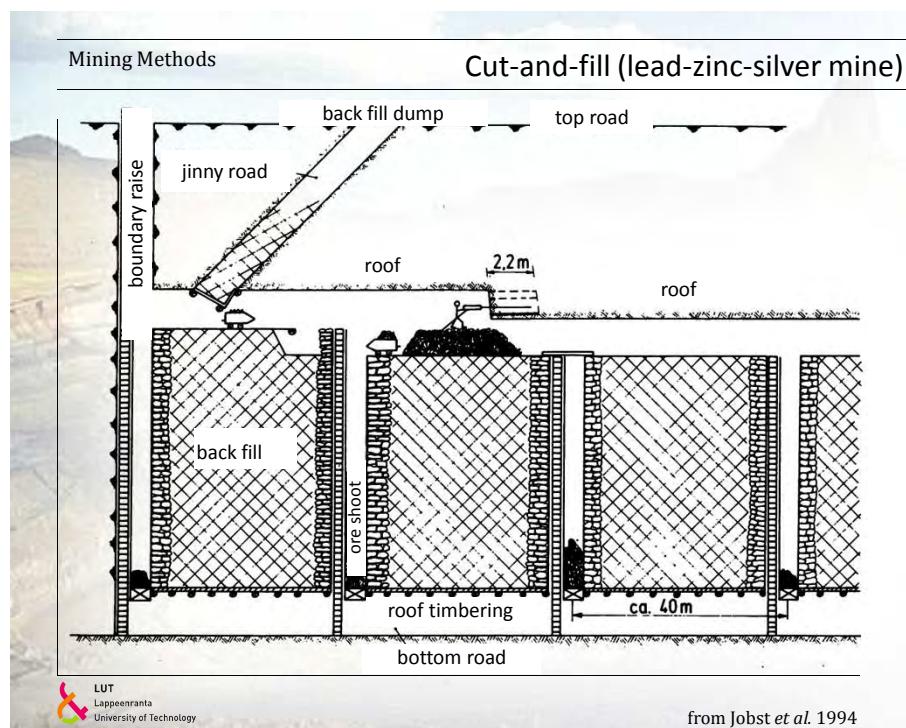
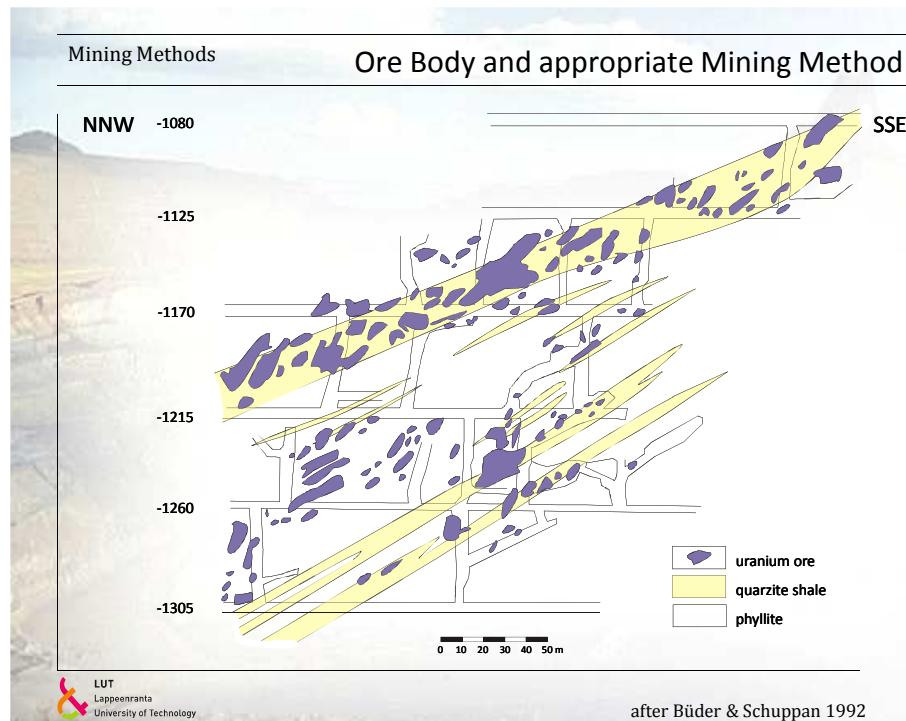
from Jobst et al. 1994

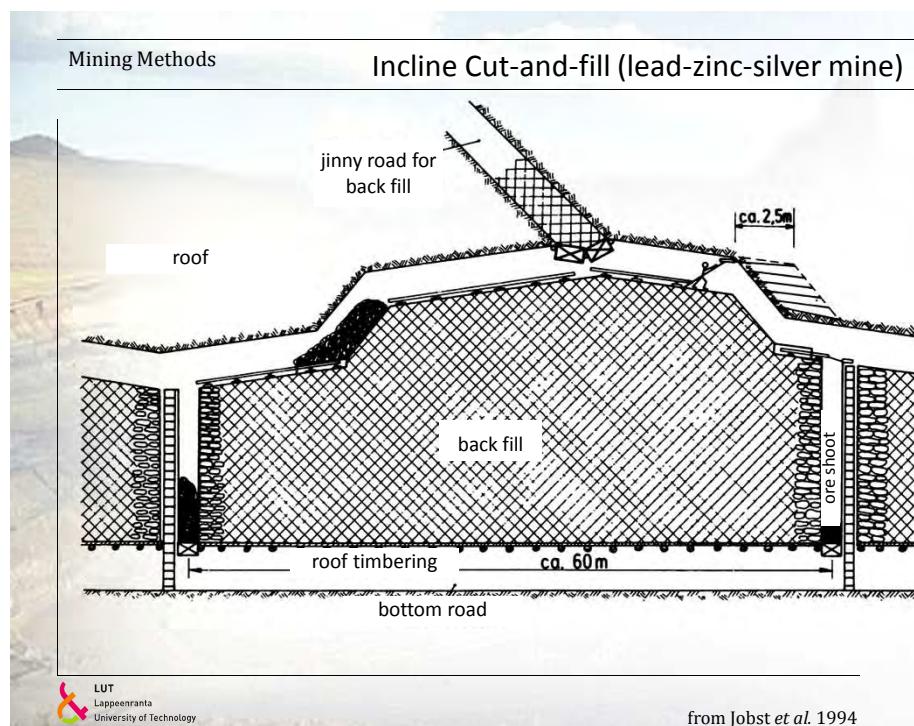
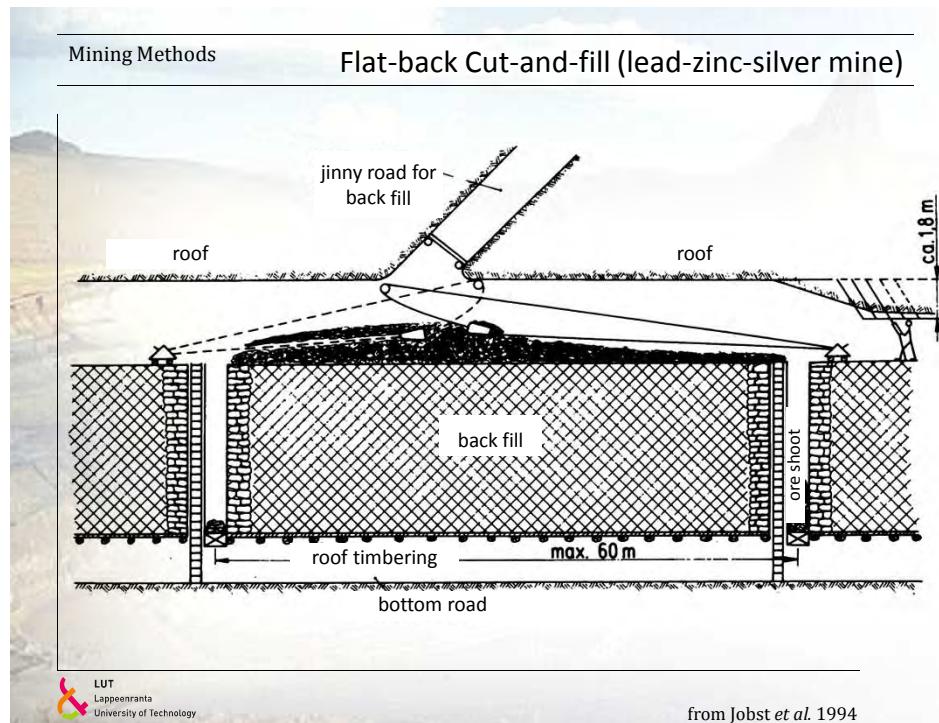
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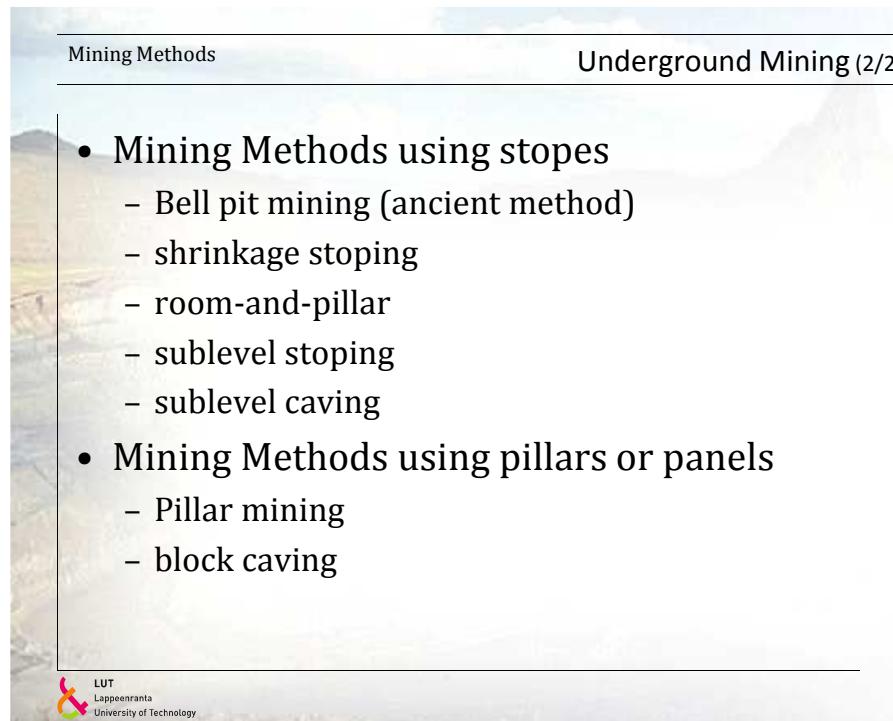
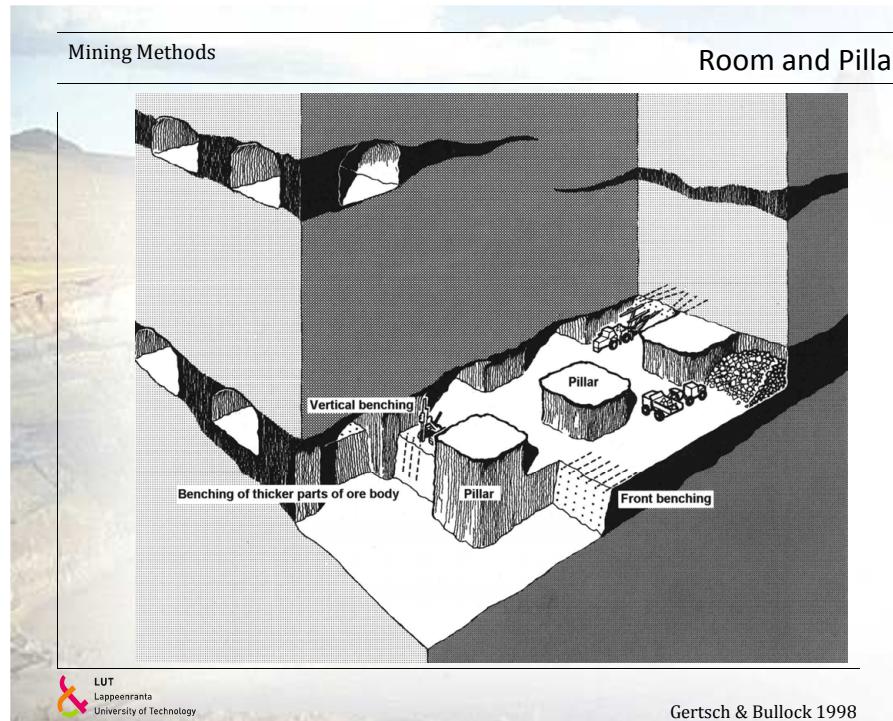


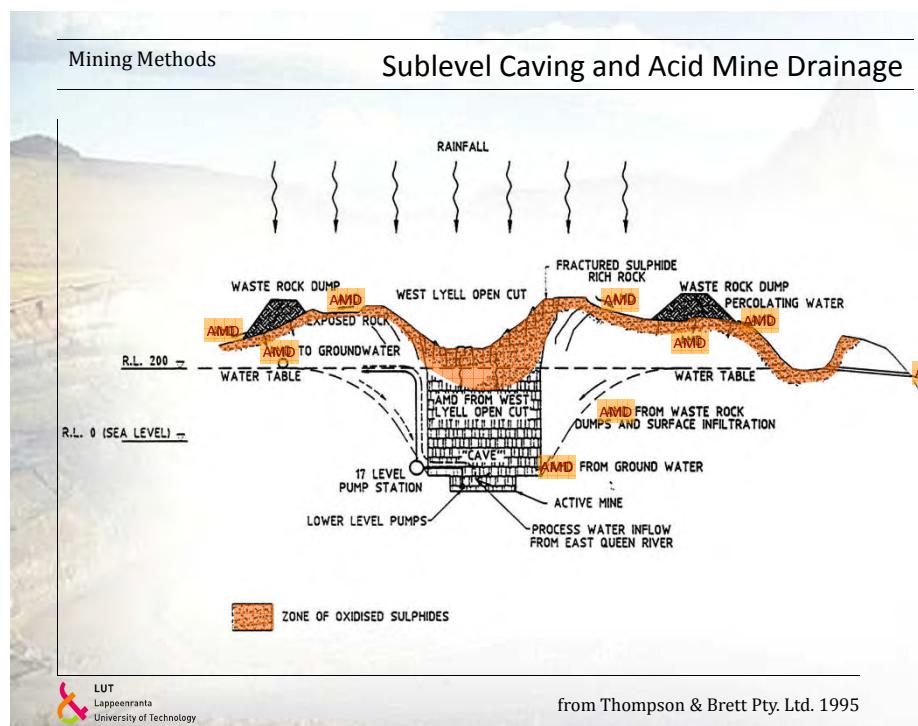
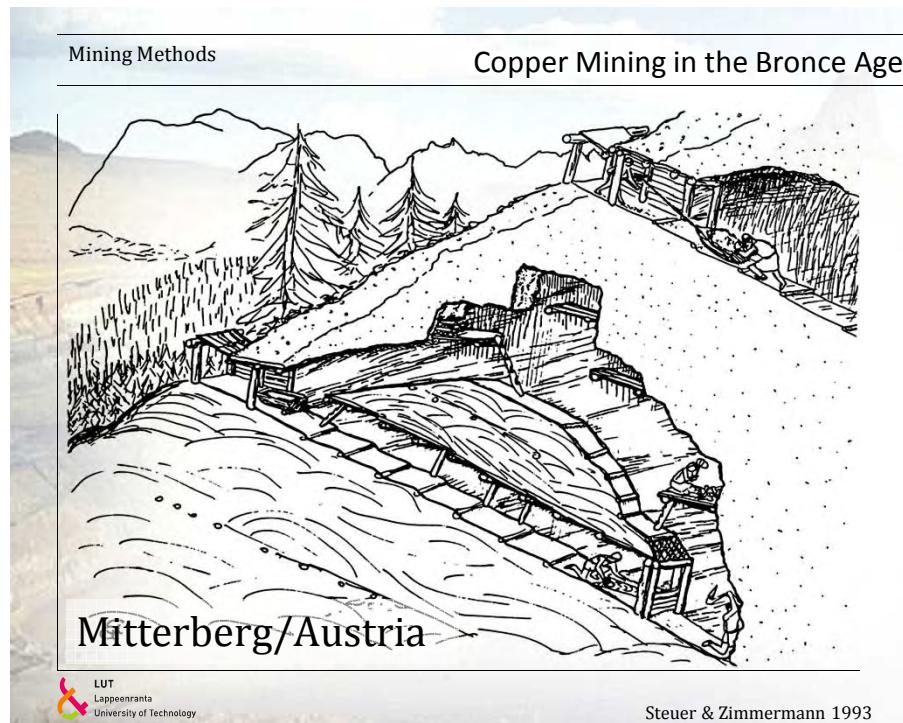


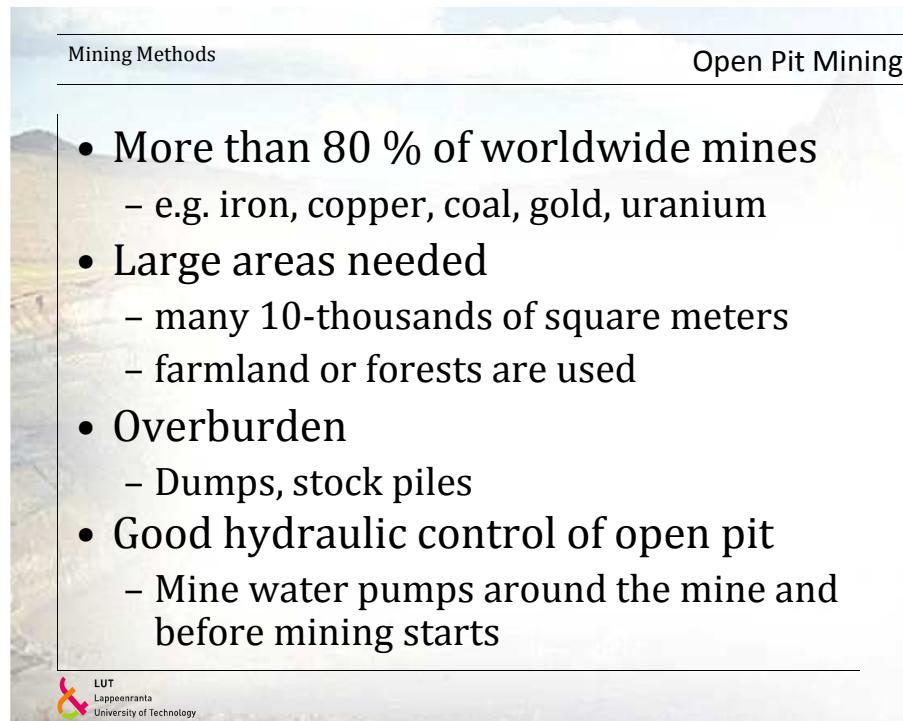
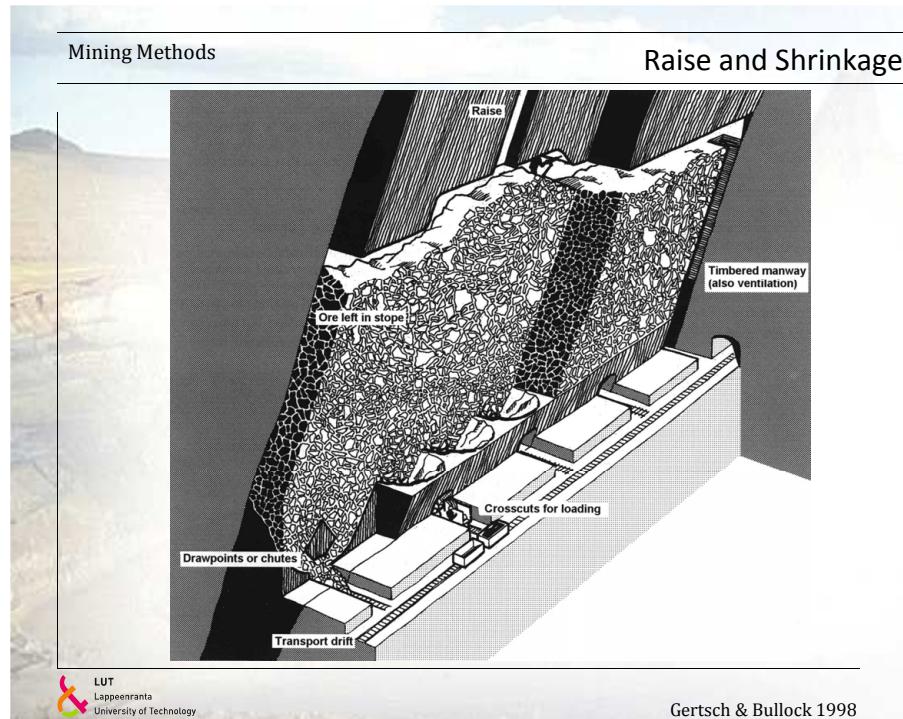


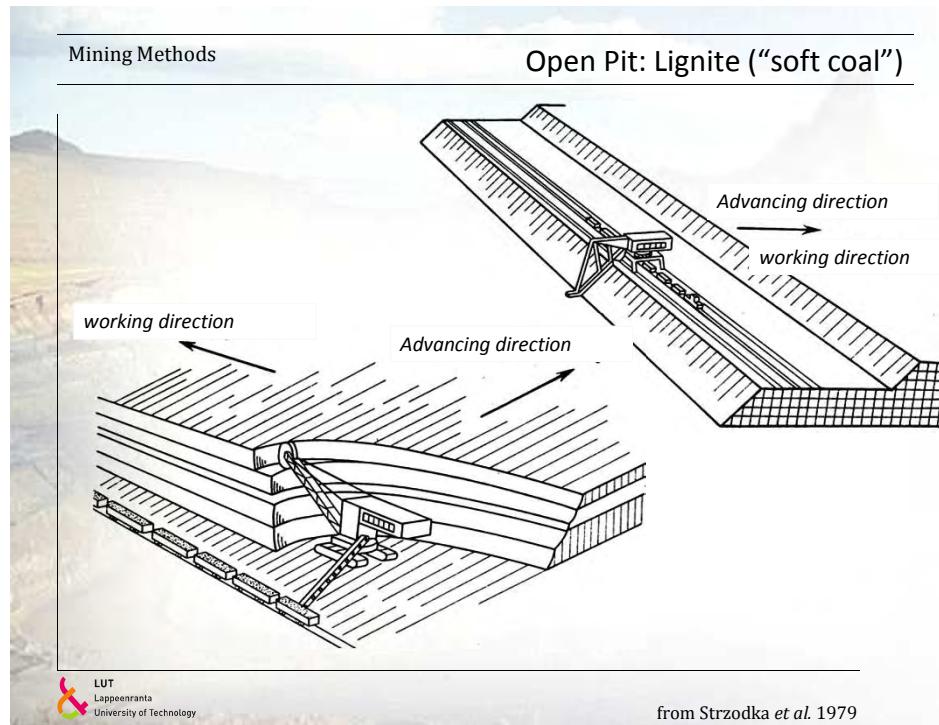
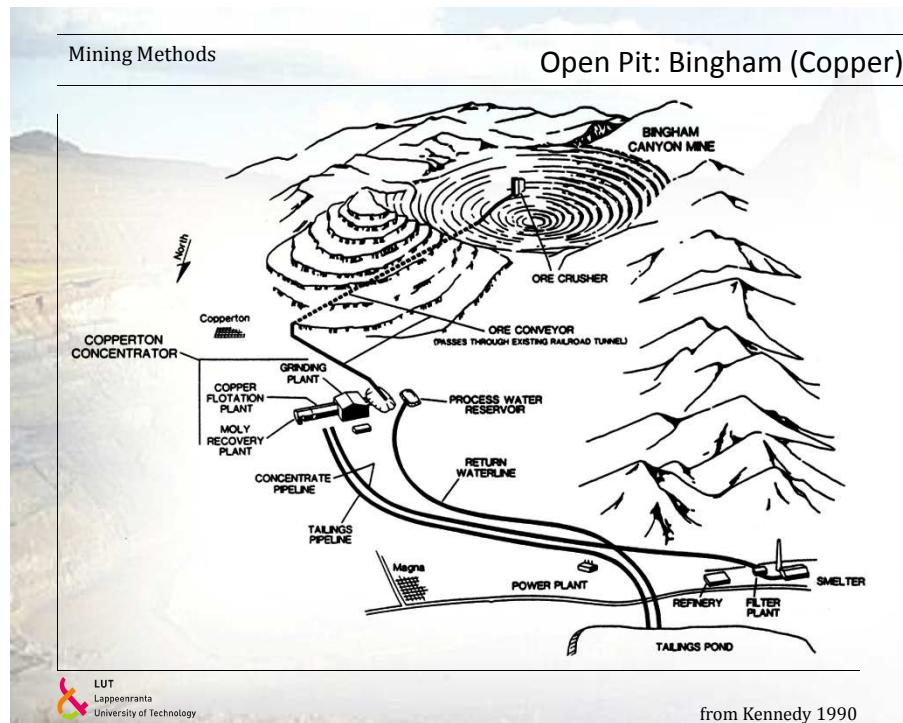






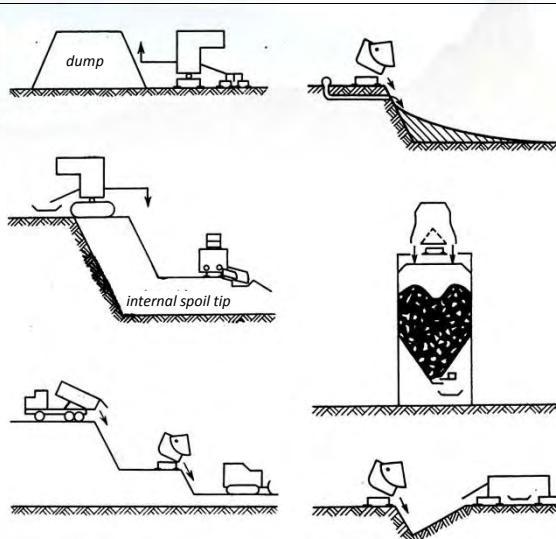






Mining Methods	Types of Backfill (“Goaf treatment”)
	<ul style="list-style-type: none"> • Rock filling <ul style="list-style-type: none"> – Manual packing, flow stowing • Pneumatic packing <ul style="list-style-type: none"> – 1924 Gewerkschaft “Deutschland” Oelsnitz • Slinger stowing (mechanical stowing) • Hydraulic filling <ul style="list-style-type: none"> – 1907 Bleicherode • Dummy road packing (hardly used nowadays) • Backfill ratio 0.4—0.7 (usually 0.55—0.6)

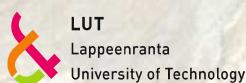
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Mining Methods	Types of Backfill
	<ul style="list-style-type: none"> • Stacker spoil dump: above track level • Stacker spoil dump: below track level • Plough dump • Truck dump • Bulldozer dump • Hydraulic dump • Dump in bunker • Dump in sub-level bunker 

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from Strzodka *et al.* 1979

Mining Methods	Literature
	<ul style="list-style-type: none">• Büder, W. & Schuppan, W. (1992): Zum Uranerzbergbau im Lagerstättenfeld Schneeberg-Schlema-Alberoda im Westerzgebirge. – Schriftenreihe Gesellschaft Deutscher Metallhütten- und Bergleute, 64: 203—221.• Fritzsche, C. F. (1982 [1962]): Lehrbuch der Bergbaukunde mit besonderer Berücksichtigung des Steinkohlenbergbaus II. – 759 S.• Gertsch, R. E. & Bullock, R. L. (1998): Techniques in Underground Mining. – 823 S.• Jobst, W., Rentzsch, W., Schubert, W. & Trachbrod, K. (1994): Bergwerke im Freiberger Land. –227 S.• Strzodka, K., Sajkiewicz, J. & Dunikowski, A. (1979): Tagebautechnik I. – 425 S.



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Water and Water Inrushes

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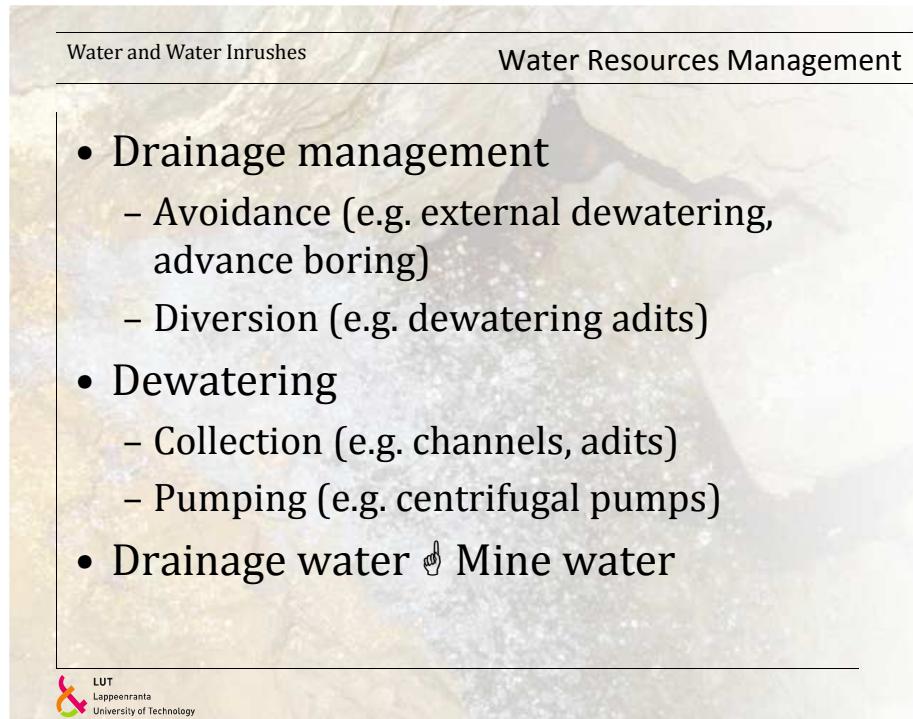
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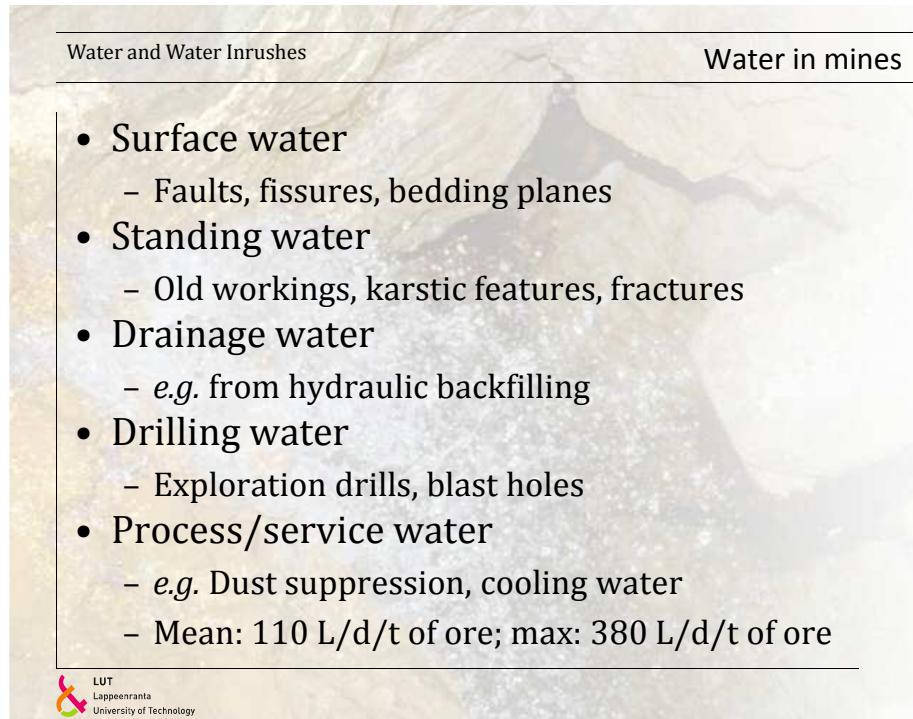




Water and Water Inrushes Water Resources Management

- Drainage management
 - Avoidance (e.g. external dewatering, advance boring)
 - Diversion (e.g. dewatering adits)
- Dewatering
 - Collection (e.g. channels, adits)
 - Pumping (e.g. centrifugal pumps)
- Drainage water ↳ Mine water

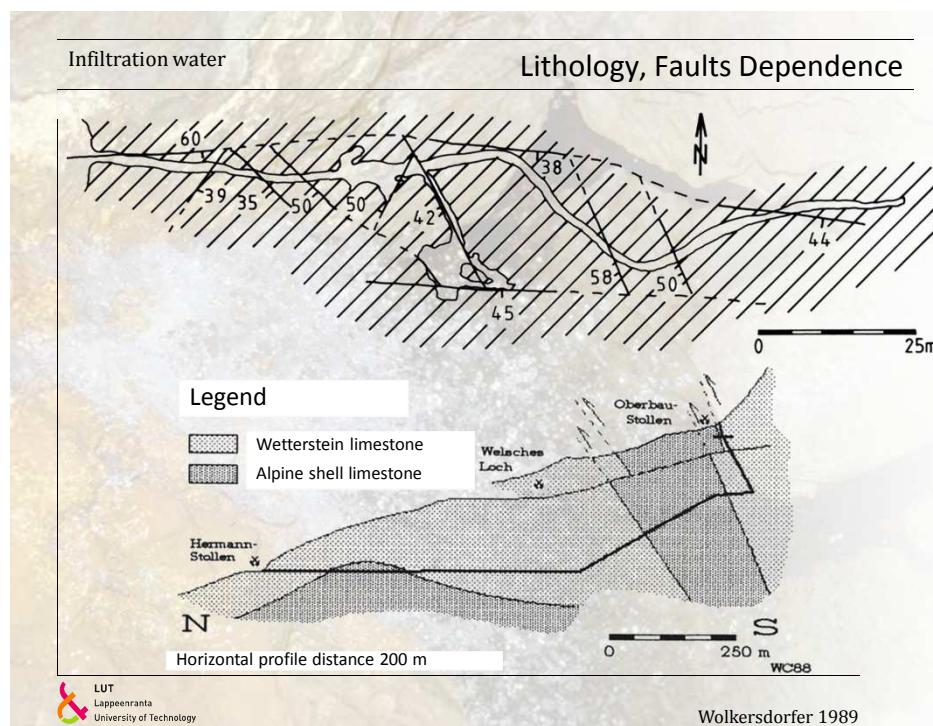
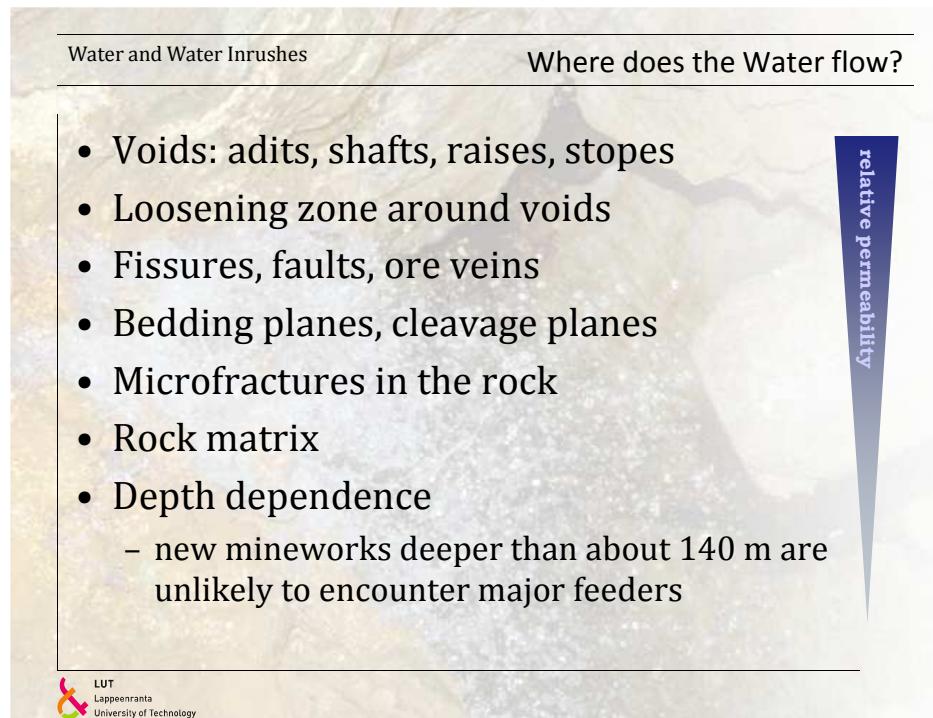
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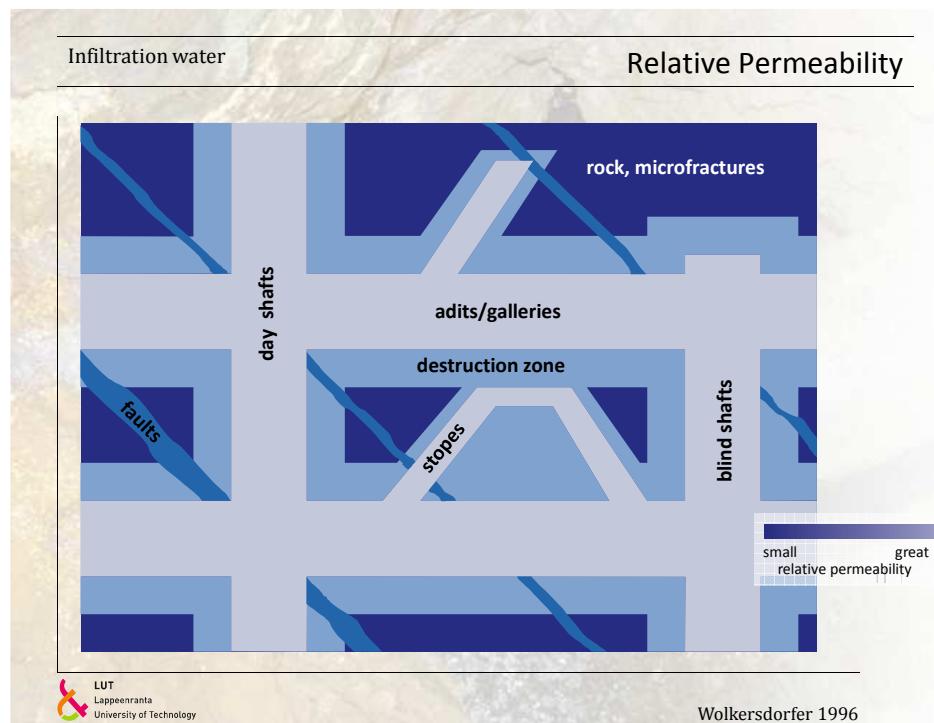
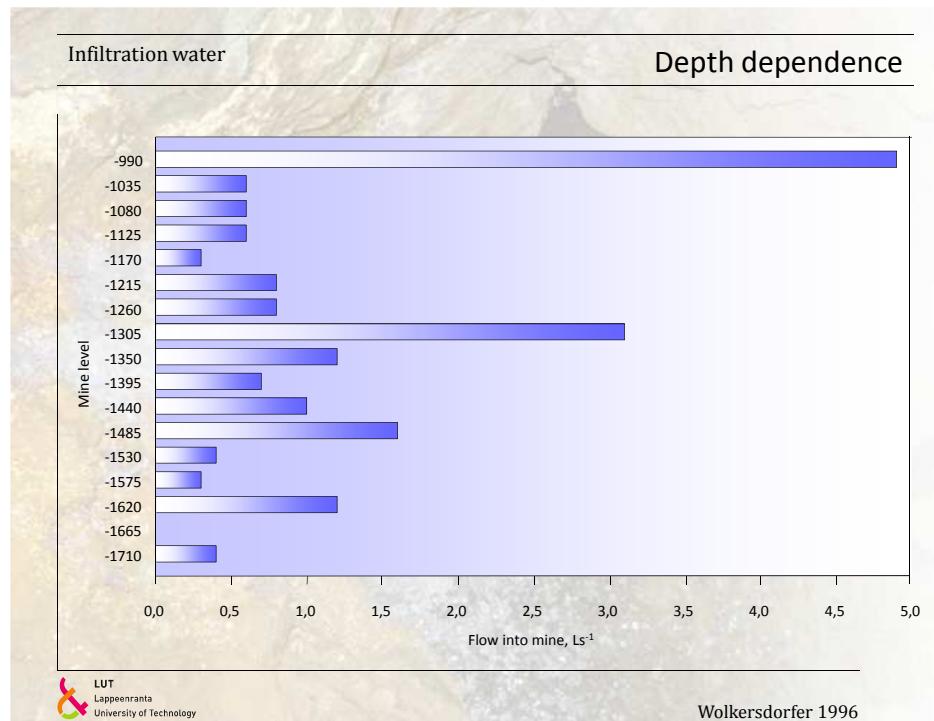


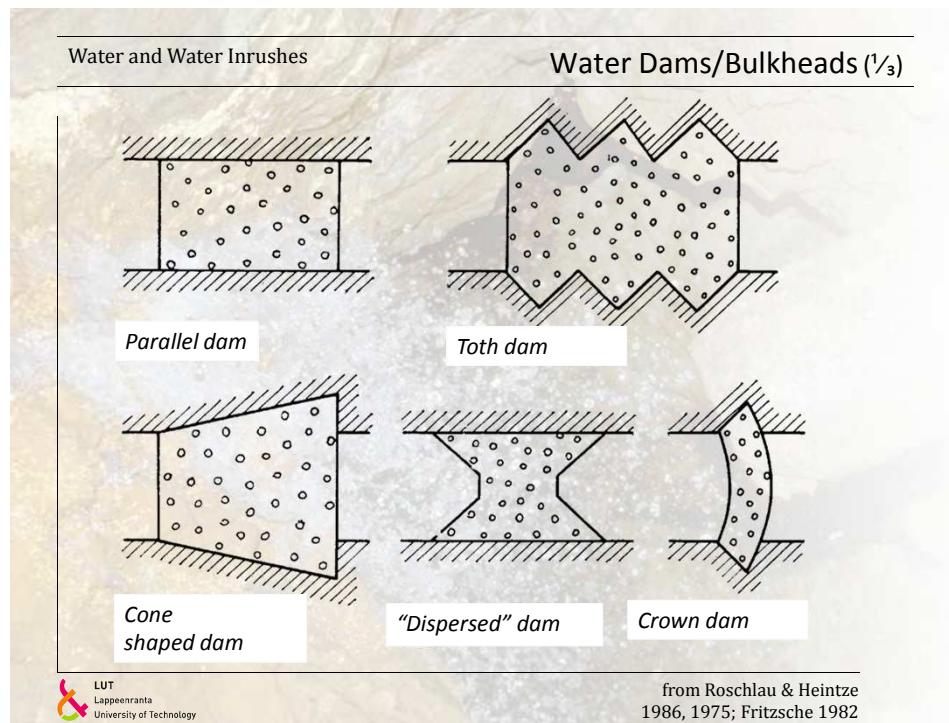
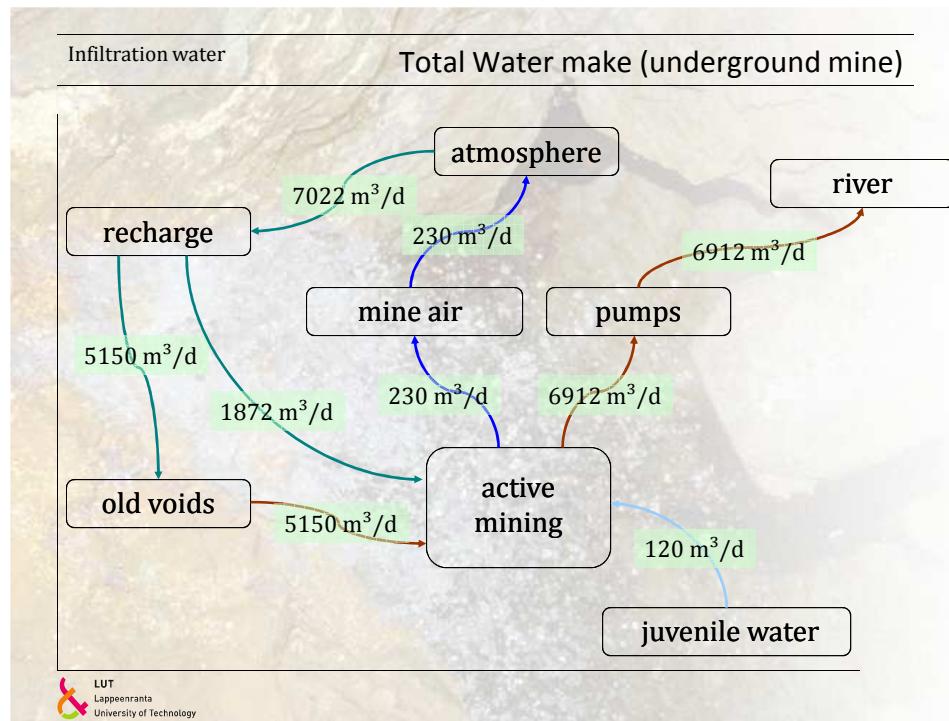
Water and Water Inrushes Water in mines

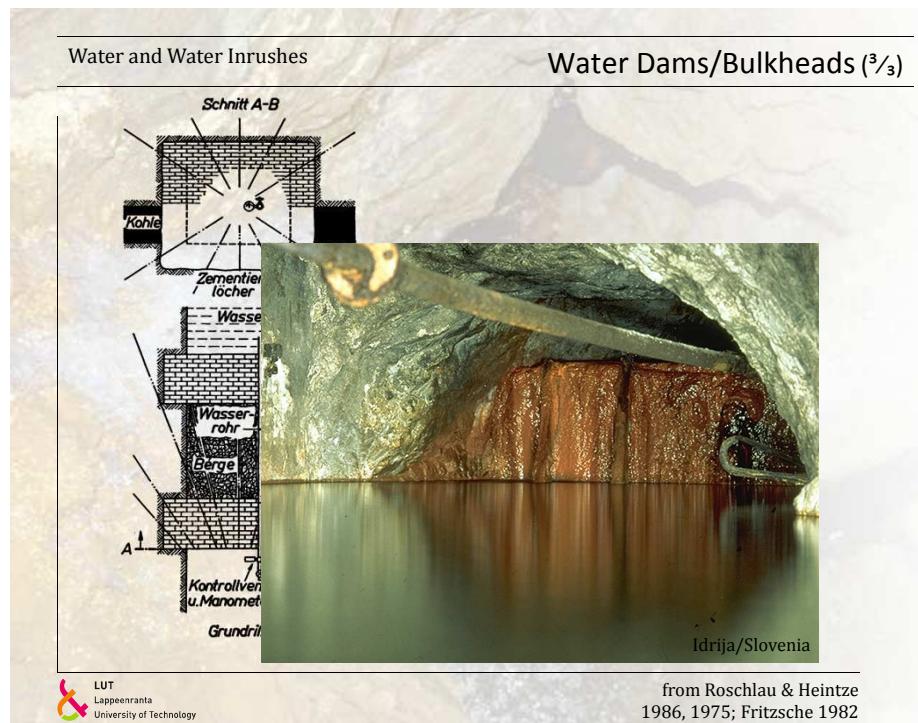
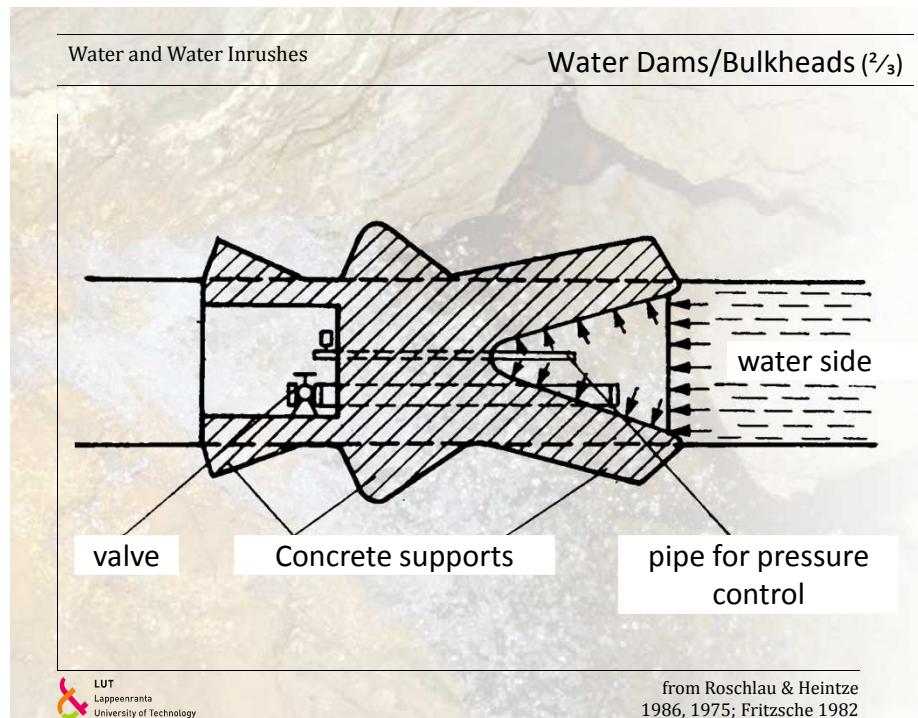
- Surface water
 - Faults, fissures, bedding planes
- Standing water
 - Old workings, karstic features, fractures
- Drainage water
 - e.g. from hydraulic backfilling
- Drilling water
 - Exploration drills, blast holes
- Process/service water
 - e.g. Dust suppression, cooling water
 - Mean: 110 L/d/t of ore; max: 380 L/d/t of ore

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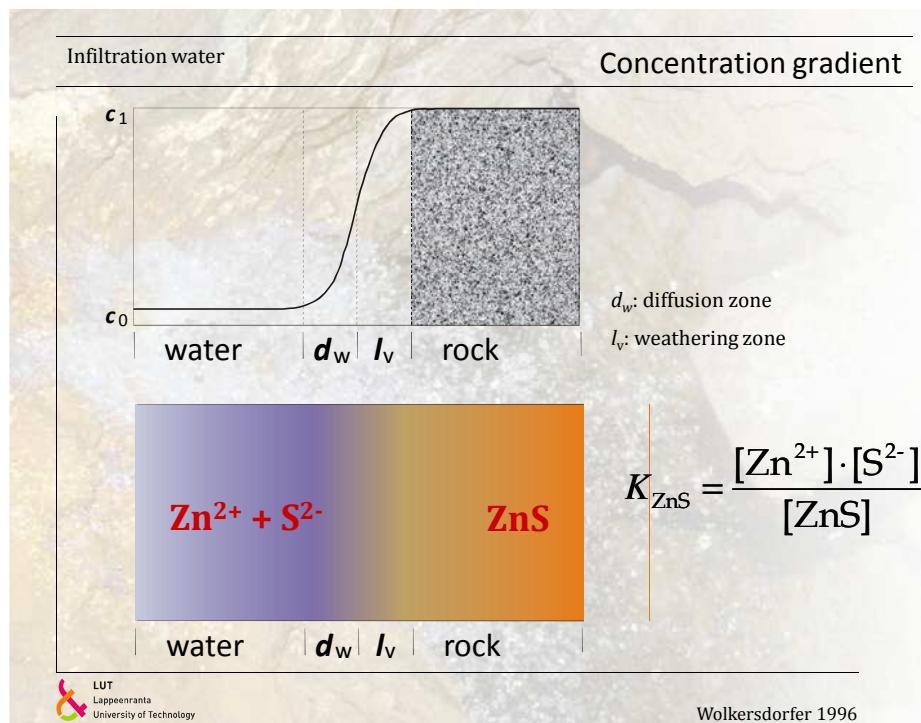


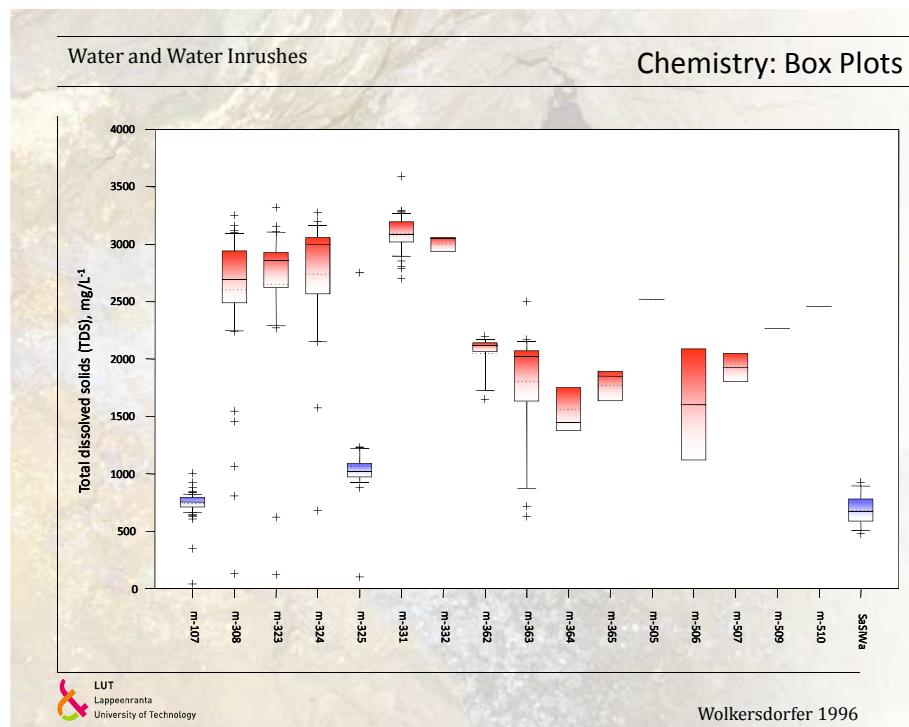
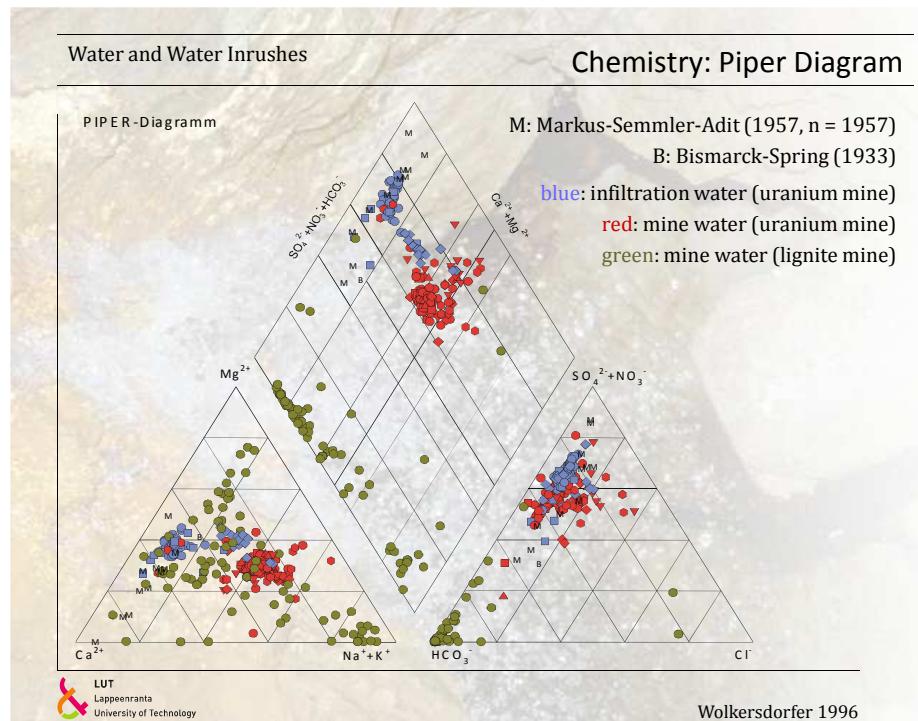


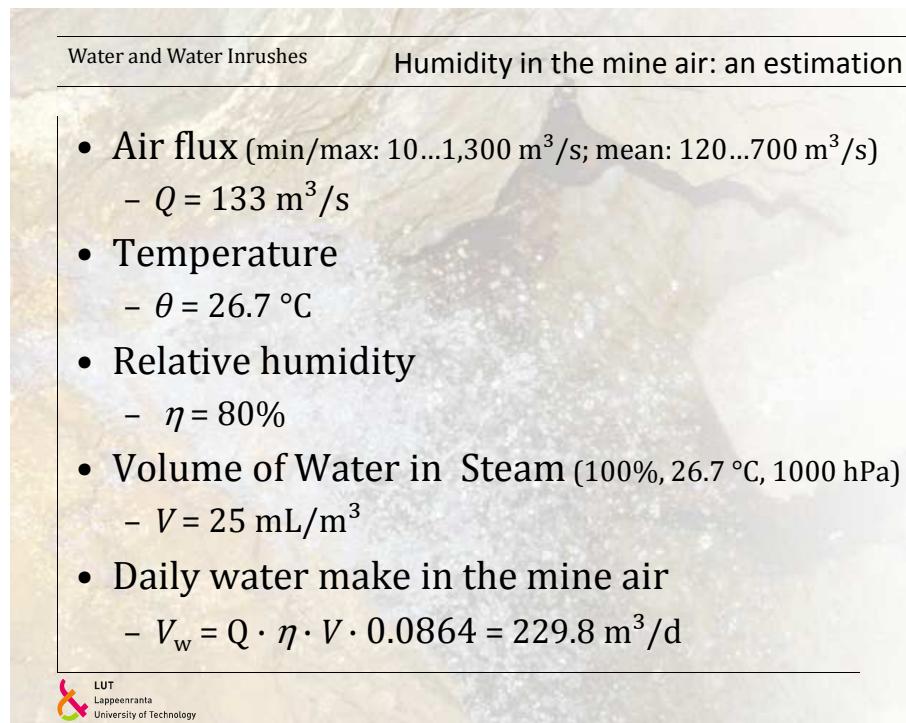
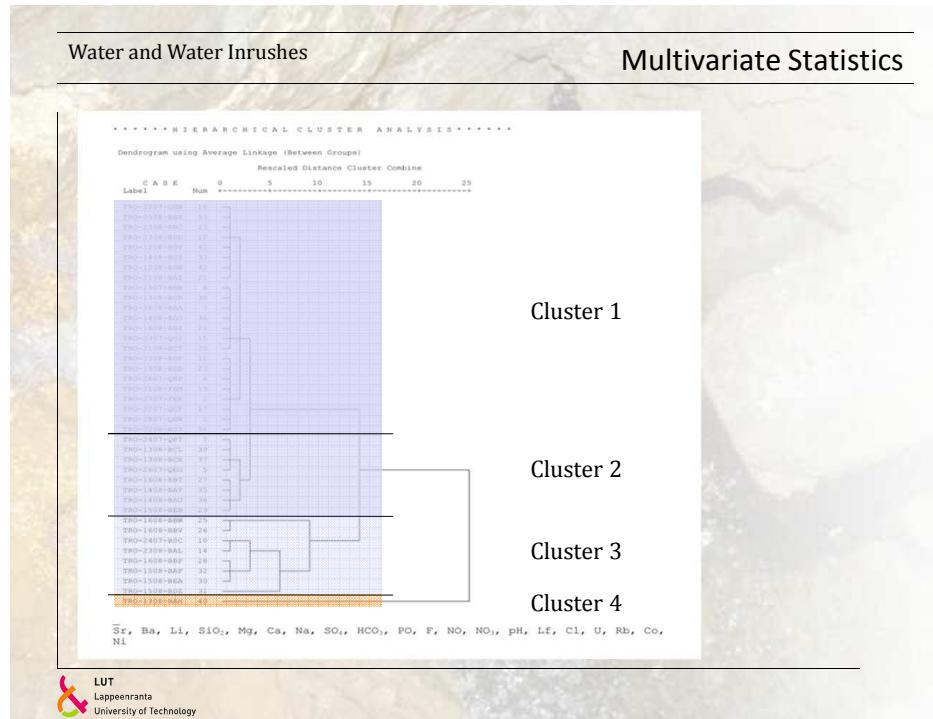
Infiltration water Chemistry of mine waters (overview)

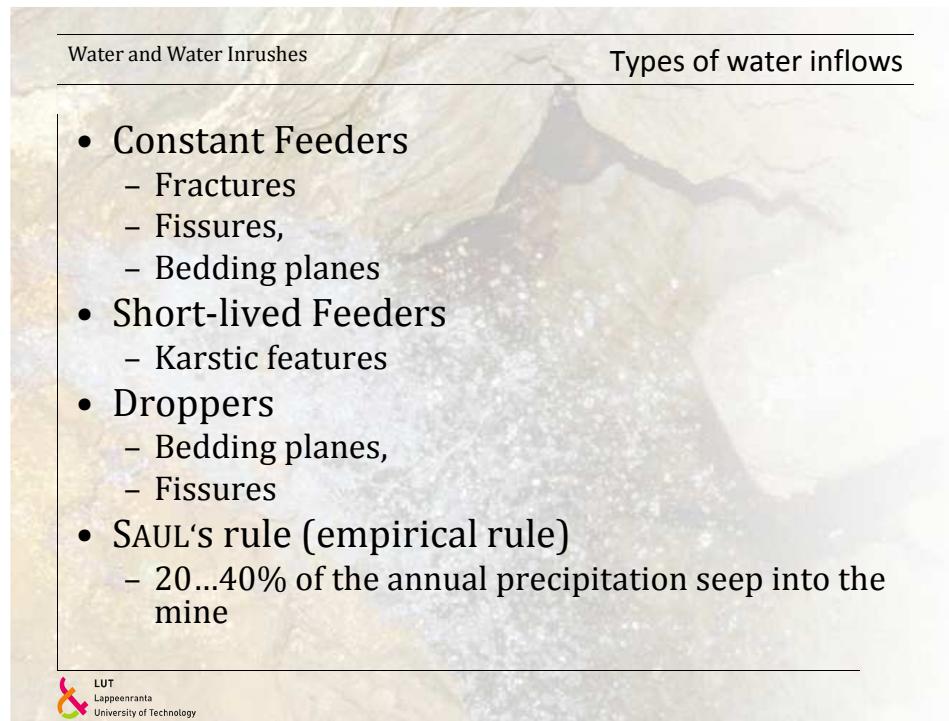
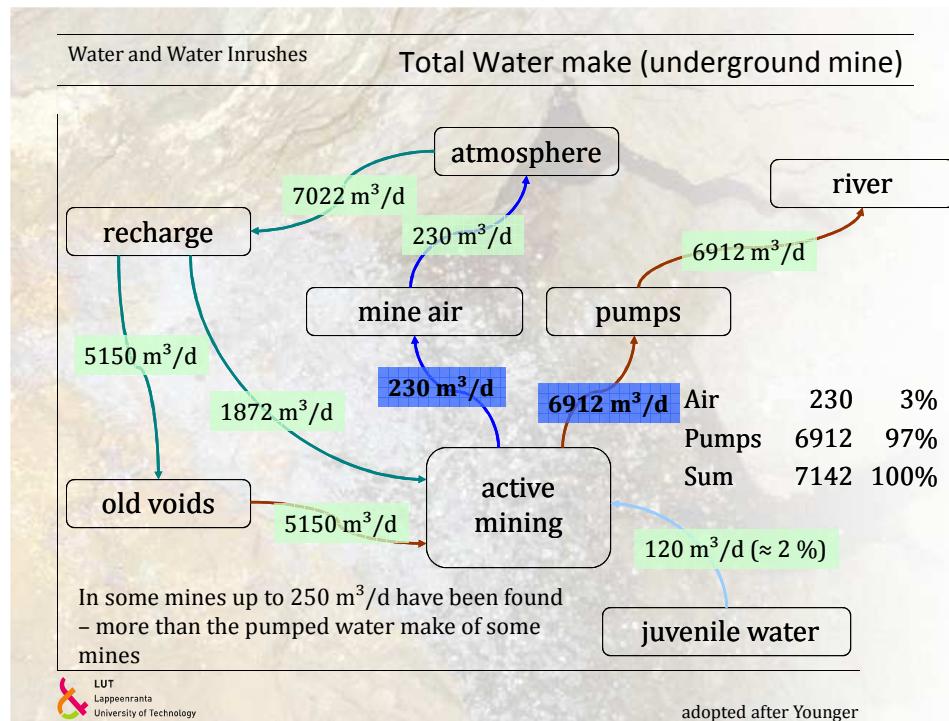
- Drainage water
 - Low mineralization, low temperature
- Mine water
 - High mineralization, warm temperature
 - Mineralization increases with depth
- Brine
 - Extremely high mineralization, especially in salt mines
 - Mississippi Valley Area (Lead-Zinc-brines)

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Water and Water Inrushes Temporary development of water make

- GAUSS distribution
 - Driefontain, South Africa
- Increasing
 - Aliveri Mine, Greek
- Constant
 - Konkola, Zambia
- Decreasing
 - Castilla/Guadalajara, Spain
- Mixed conditions
 - Vasante Zinc Mine, Brazil

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from Fernández-Rubio
& Fernández-Lorca 1993

Water and Water Inrushes Measuring of water flows

- Bucket-and-stopwatch (up to 400 L min^{-1})
- Impeller current meter
- Channels
- H-flumes, V-weirs
- Pump run-times and ratings
- Water meters
- Pressure meter measurements of boreholes
- Venturi tube
- Foil sheets

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Water and Water Inrushes

Weir Equations

$$Q = \Phi(L, B, P, \textcolor{red}{h}, \gamma, \rho, \mu, \sigma)$$

Q	flow rate
L	width of the notch
B	width of approach channel
P	crest height of weir above mean bed level
$\textcolor{red}{h}$	gauged head related to weir crest
γ	specific weight of fluid
ρ	density of fluid
μ	dynamic viscosity of fluid
σ	surface tension of fluid

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Kindsvater & Carter 1959

Water and Water Inrushes

Weir Types

a) Rectangular or PONCELET weir without end contractions

$$Q = 1.773 \times \left(1 + 0.148 \times \frac{h}{P}\right) b \times h^{1.5}$$

b) Rectangular or PONCELET weir with end contractions

$$Q = 1.758 \times b \times h^{1.5}$$

c) V-notch, triangular or THOMSON weir
typical angles of α : 90° ; $53^\circ 8'$; $28^\circ 4'$
equations on next slide

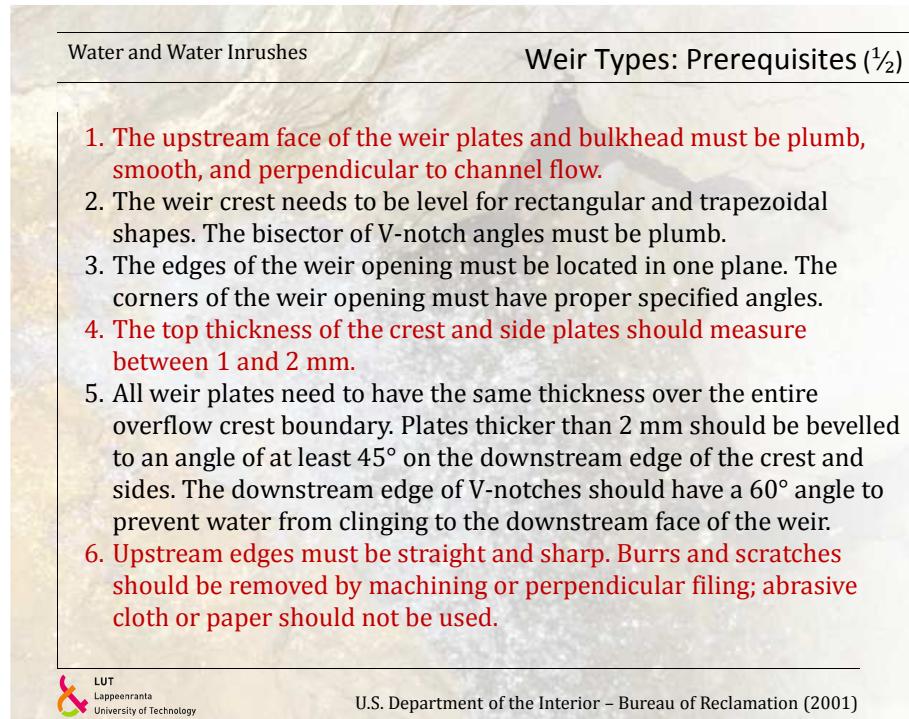
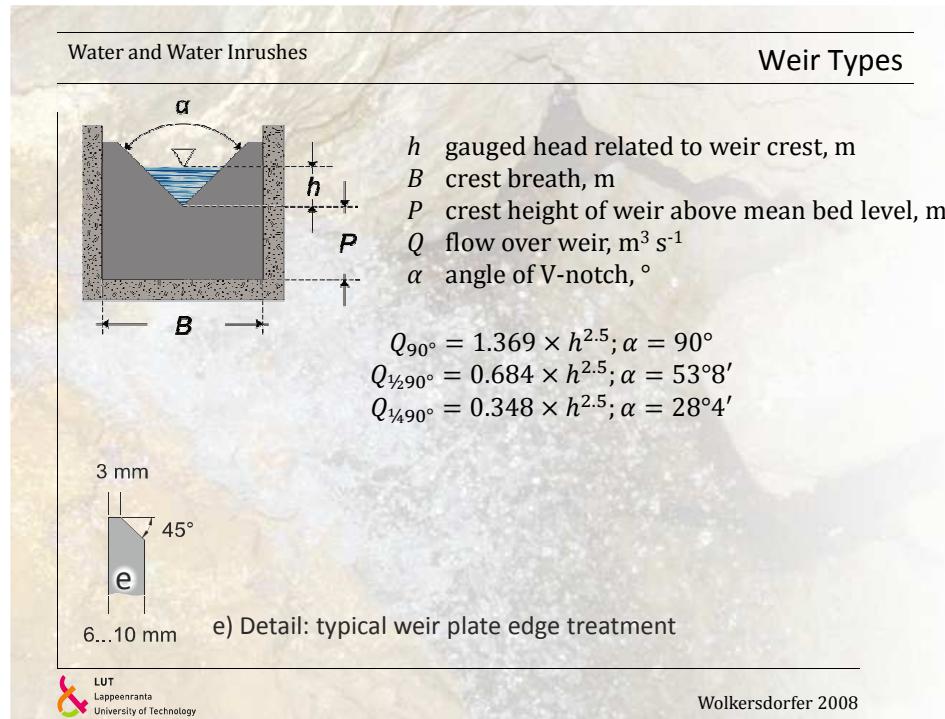
d) Trapezoidal or CIPOLLETTI weir

$$Q = 1.869 \times b \times h^{1.5}$$

Equations for metric units only; errors: -10...4%

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Wolkersdorfer 2008



Water and Water Inrushes

Weir Types: Prerequisites ($\frac{7}{2}$)

7. The bottom edge plates and upstream fastener projection should be located at least the distance of two measuring heads from the crest. All upstream faces must be free of oil and grease.
8. **The overflow sheet or nappe touches only the upstream faces of the crest and side plates.**
9. The weir head measurement is the difference in elevation between the crest and the water surface at a point located upstream. **The upstream point is at a distance of four to five times the maximum expected head on the weir.**
10. The maximum downstream water surface level should be at least 2–6 cm below the crest elevation.
11. **The weir head measurement, depending on the weir type, should be at least 2–6 cm to prevent the overflow sheet from clinging to the downstream weir face.**
12. The weir approach should be kept clear of sediment deposits and other debris.

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U.S. Department of the Interior – Bureau of Reclamation (2001)

Water and Water Inrushes

Weir Types: Errors

Wrongly constructed weirs can cause errors up to 64 % compared to correct reading.

Normal errors due to wrong constructions in the range of 5 to 20 %

Most common errors:

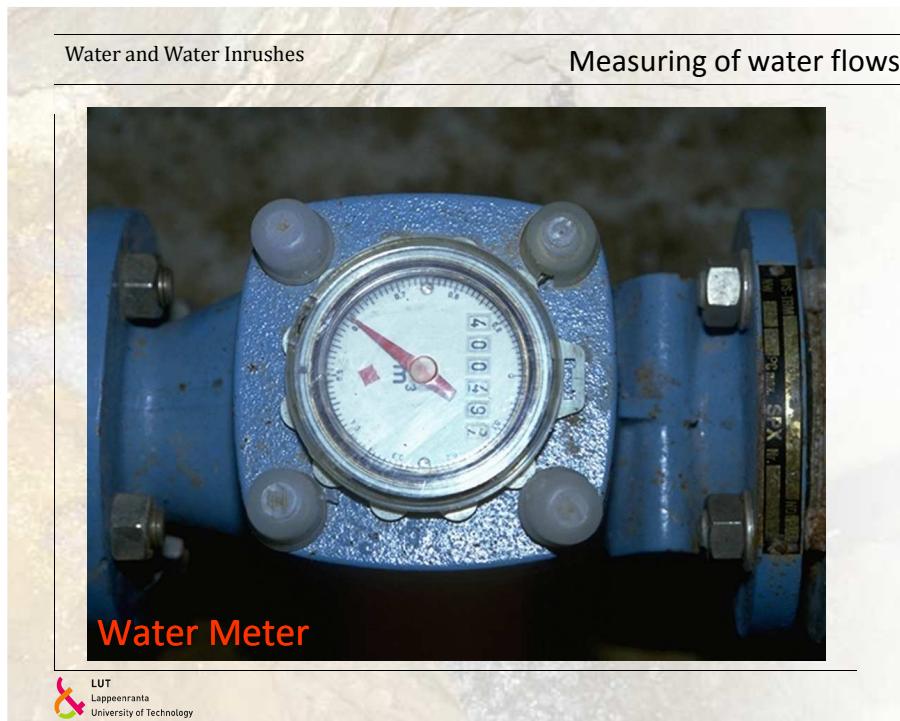
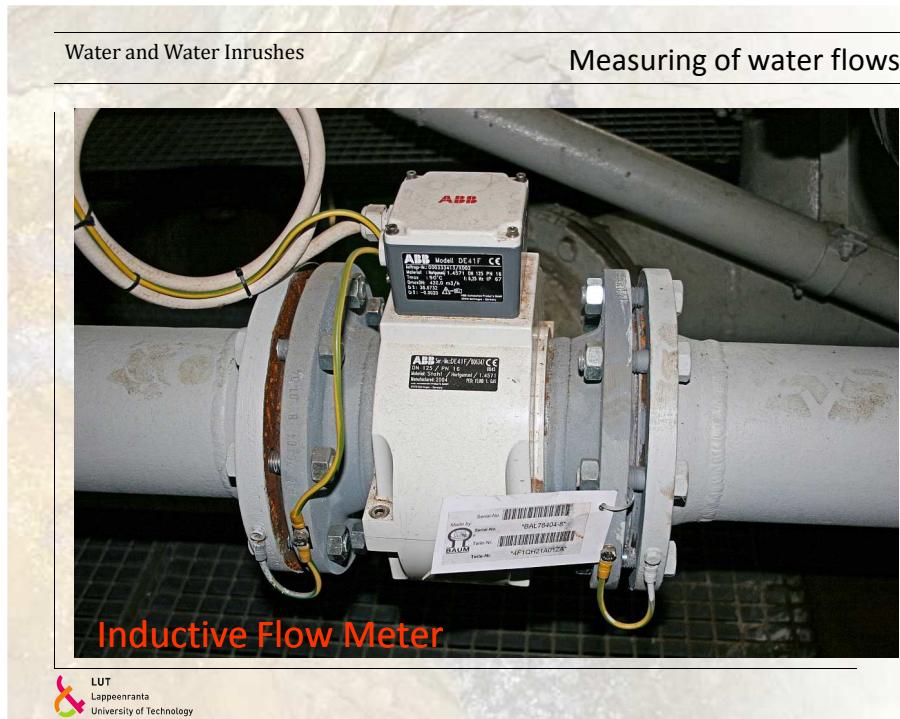
- Wrong head readings
- Nappe not aerated
- Sharp crest on air side
- Wrong construction material

Potential Solution:

- All weirs should be calibrated or double checked for each individual location (e.g. Bucket-and-Stopwatch)

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Thomas 1959 and personal experience



Water and Water Inrushes

Measuring of water flows



V-weir

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Water and Water Inrushes

Calculation of water inflows ($\frac{V}{3}$)

- Mining area: $A = 30 \text{ km}^2$
- Precipitation 1950—1990: $N = 825 \text{ mm/a}$
- Mean surface flow: $a_o = 38.7\%$
- Mean evaporation: $V_E = 630 \text{ mm/a}$
- Mean temperature: $\theta = 8.5 \text{ }^\circ\text{C}$
- Evapotranspiration ET :

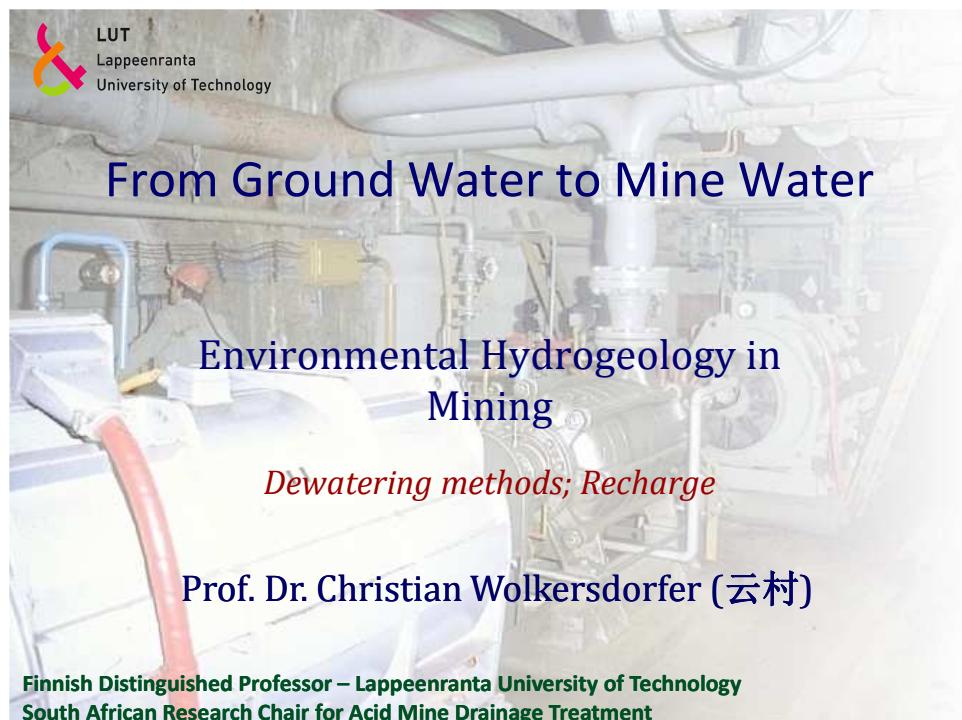
$$ET_{\text{real}} = \frac{N}{\sqrt{0.9 + \left(\frac{N}{300 + 25 \cdot \theta + 0.05 \cdot \theta^3} \right)^2}}$$

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Water and Water Inrushes	Calculation of water inflows (2/3)
• $V_N = A \cdot N =$	$\cdot 10^6 \text{ m}^3/\text{a}$
• $V_A = V_N \cdot a_o =$	$\cdot 10^6 \text{ m}^3/\text{a}$
• $ET_{reel} =$	mm/a
• $V_{ETreel} =$	$\cdot 10^6 \text{ m}^3/\text{a}$
• $V_{sick} = V_N - V_A - V_{ETreel} =$	$\cdot 10^6 \text{ m}^3/\text{a}$
• Total water make: $V_{pump} = 7 \dots 10$	$\cdot 10^6 \text{ m}^3/\text{a}$
• From droppers: $V_{drops} = 0.6$	$\cdot 10^6 \text{ m}^3/\text{a}$
• SAUL's rule:	$\cdot 10^6 \text{ m}^3/\text{a}$

Water and Water Inrushes	Calculation of water inflows (3/3)
• $V_N = A \cdot N =$	24.75 $\cdot 10^6 \text{ m}^3/\text{a}$
• $V_A = V_N \cdot a_o =$	9.58 $\cdot 10^6 \text{ m}^3/\text{a}$
• $ET_{reel} =$	461 mm/a
• $V_{ETreel} =$	13.8 $\cdot 10^6 \text{ m}^3/\text{a}$
• $V_{sick} = V_N - V_A - V_{ETreel} =$	1.37 $\cdot 10^6 \text{ m}^3/\text{a}$
• V_{pump} (measured) =	7 ... 10 $\cdot 10^6 \text{ m}^3/\text{a}$
• V_{drops} (measured) =	0.6 $\cdot 10^6 \text{ m}^3/\text{a}$
• SAUL's rule:	5 ... 10 $\cdot 10^6 \text{ m}^3/\text{a}$

Water and Water Inrushes	Literature
	<ul style="list-style-type: none">• Fritzsche, C. F. (1982 [1962]): Lehrbuch der Bergbaukunde mit besonderer Berücksichtigung des Steinkohlenbergbaus II. – 10th ed., 759 p., 599 fig.; Berlin u.a. (Springer).• Roschlau, H. & Heintze, W. (1975): Bergbautechnologie. – 1st ed., 349 p., 344 fig., 35 tab.; Leipzig (VEB Deutscher Verlag für Grundstoffindustrie).• Roschlau, H. & Heintze, W. (1986): Wissensspeicher Bergbau - Erzbergbau und Kalibergbau. – 3rd ed., 288 p., 314 fid., 85 tab.; Leipzig (VEB Deutscher Verlag für Grundstoffindustrie).



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From Ground Water to Mine Water

Environmental Hydrogeology in Mining

Dewatering methods; Recharge

Prof. Dr. Christian Wolkersdorfer (云村)

Finnish Distinguished Professor – Lappeenranta University of Technology
South African Research Chair for Acid Mine Drainage Treatment

From Ground Water to Mine Water

Contents

- Introduction, Historical Background
- Mining Methods, Technical Terms
- Water and Water Inrushes
- **Dewatering methods; Recharge**
- Mine Flooding
- Mine Water Geochemistry
- Prediction of Mine Flooding
- Mine Water Treatment

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Dewatering methods

Underground Mining

- Mine water can be contaminated!
- Pumps must prevent:
 - Water inundation
 - flooding of mines
- Shafts
- Voids
 - Sump, sump galleries, drainage level
 - Escape ways
 - Stemmings; grouting
 - Grout injections

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Dewatering methods

Underground Mining

- Water table differences in different shafts
- Density of water

$$\frac{h_1}{h_2} = \frac{\rho_2}{\rho_1}$$

$$\Delta h = \rho_1 h_1 \left(1 - \frac{\rho_2}{\rho_1}\right) \frac{1}{\rho_2}$$

$$h_1 = 100 \text{ m}$$

$$\rho_1 = 1.002 \text{ g cm}^{-3}$$

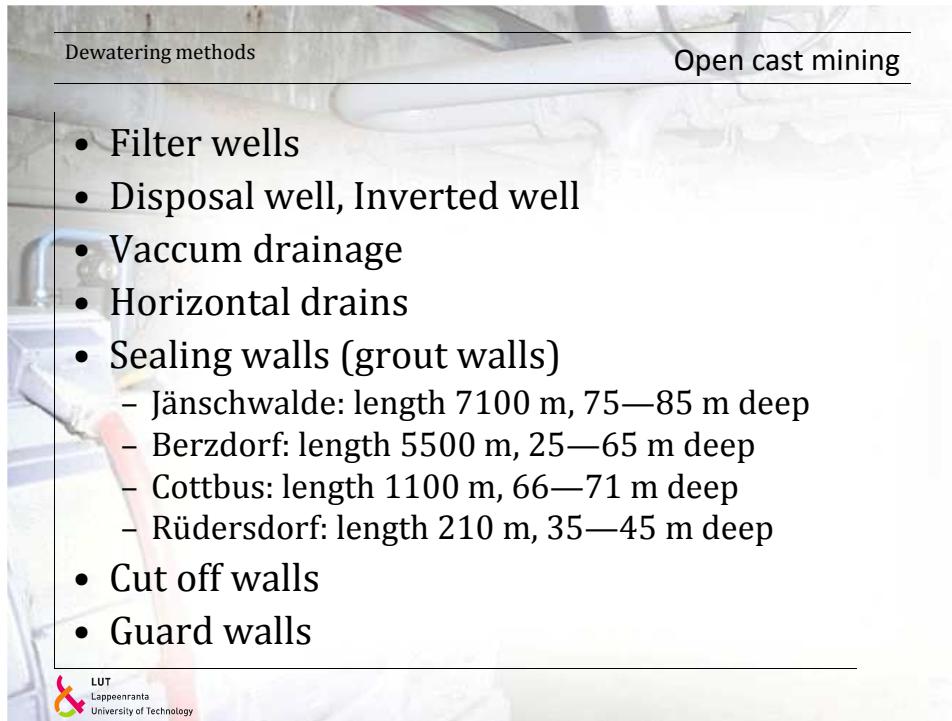
$$\rho_2 = 1.223 \text{ g cm}^{-3}$$

$$\Delta h = \cancel{-18.07031889 \text{ m}}$$

$$-18 \text{ m}$$

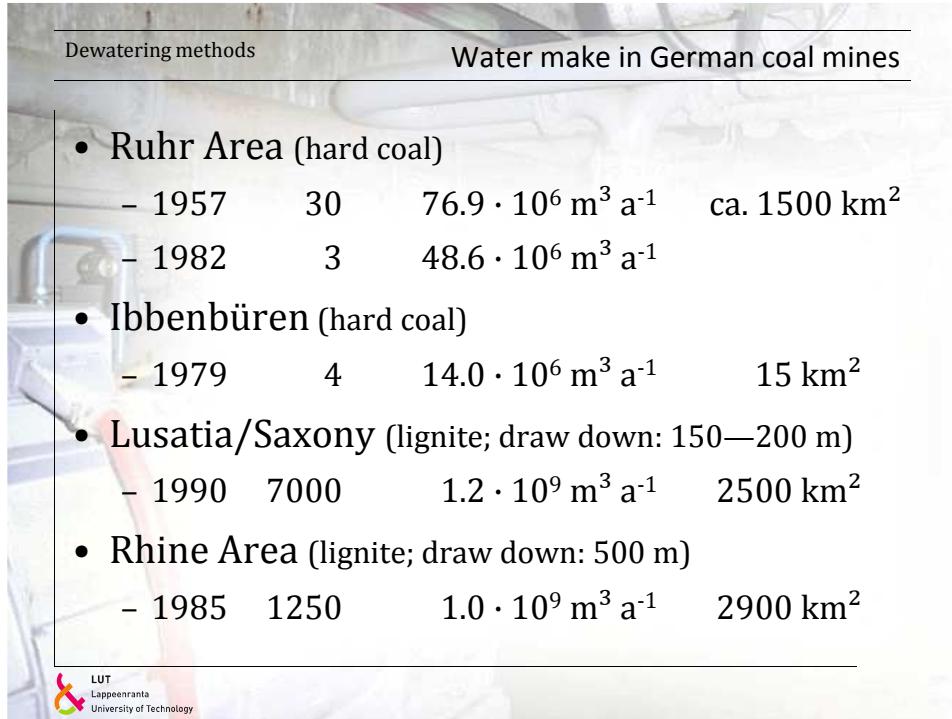
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Dewatering methods	Open cast mining
<ul style="list-style-type: none"> • Filter wells • Disposal well, Inverted well • Vacuum drainage • Horizontal drains • Sealing walls (grout walls) <ul style="list-style-type: none"> – Jänschwalde: length 7100 m, 75—85 m deep – Berzdorf: length 5500 m, 25—65 m deep – Cottbus: length 1100 m, 66—71 m deep – Rüdersdorf: length 210 m, 35—45 m deep • Cut off walls • Guard walls 	

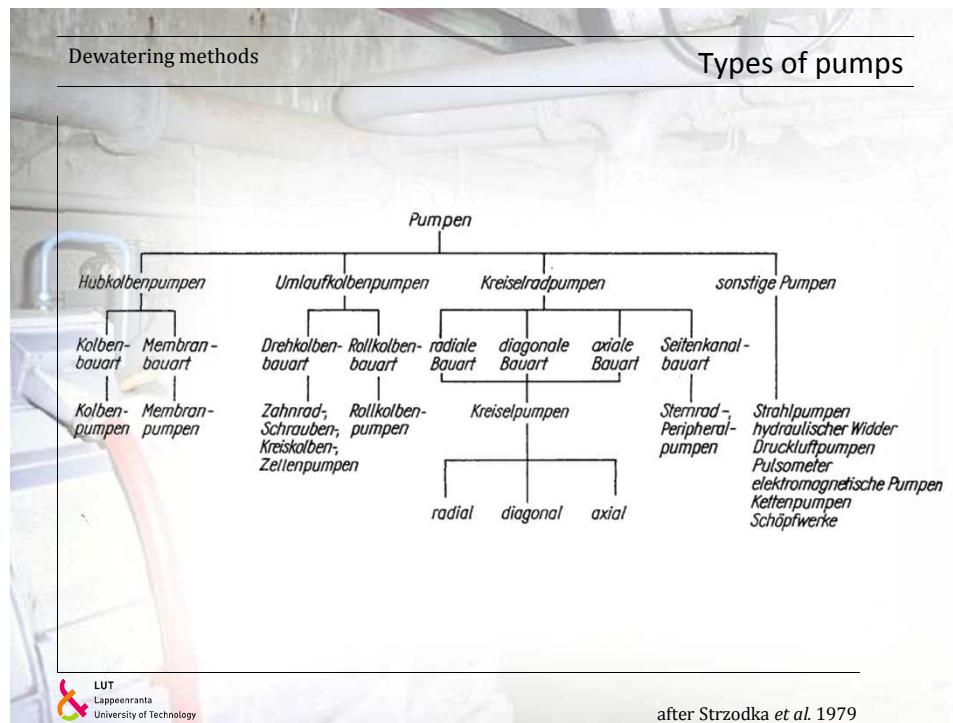
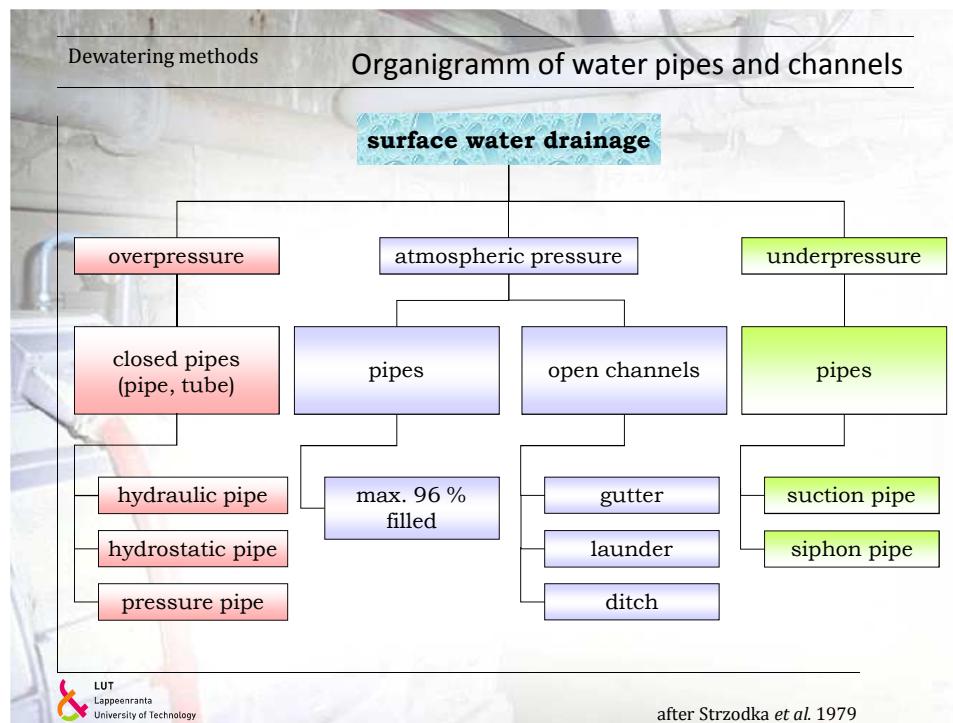


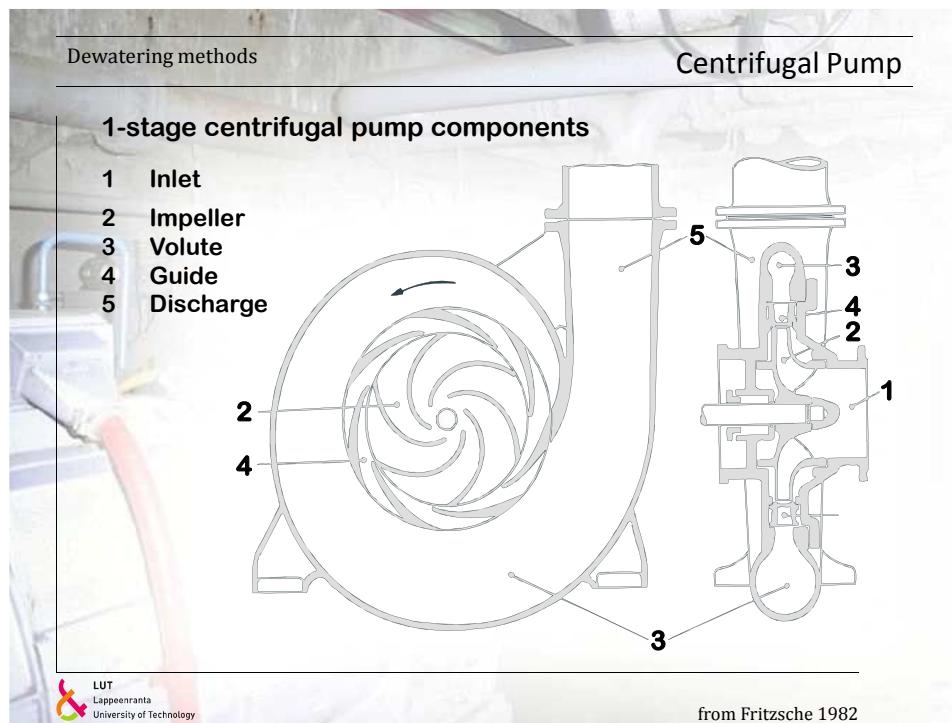
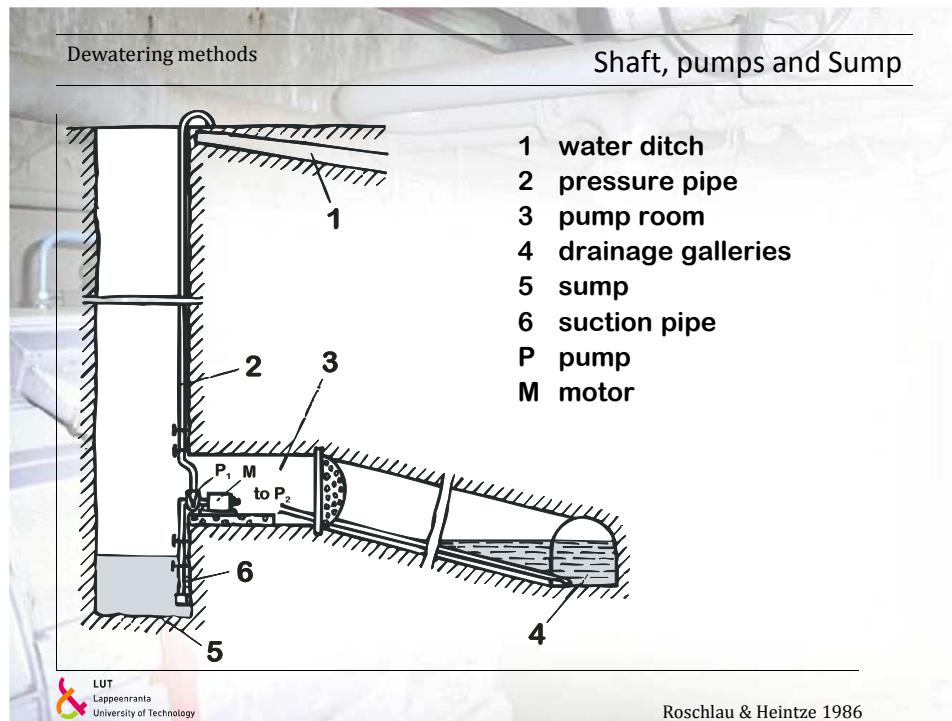
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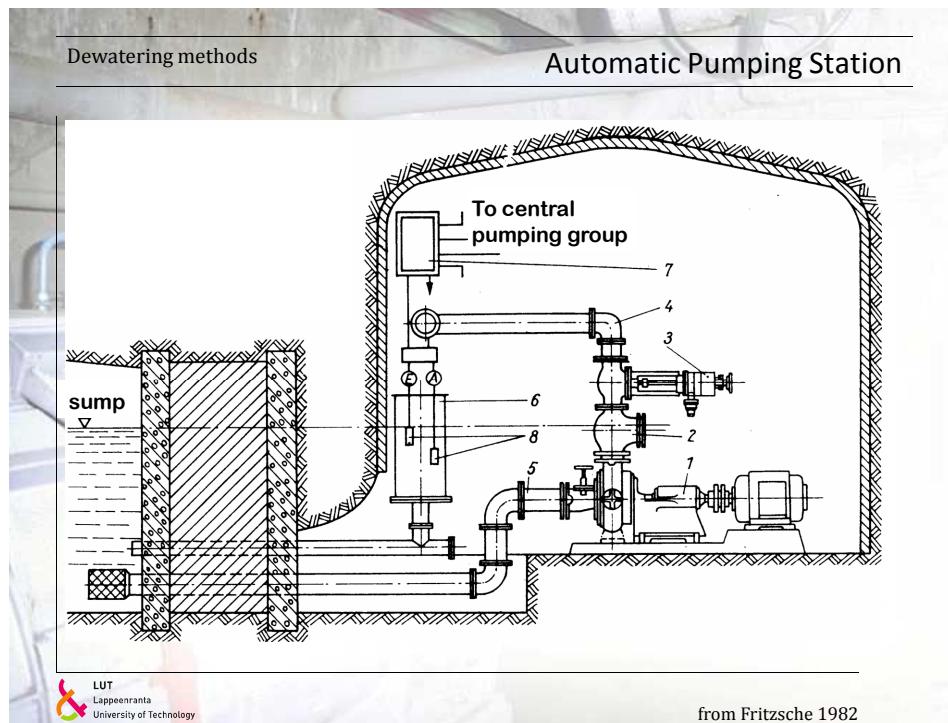
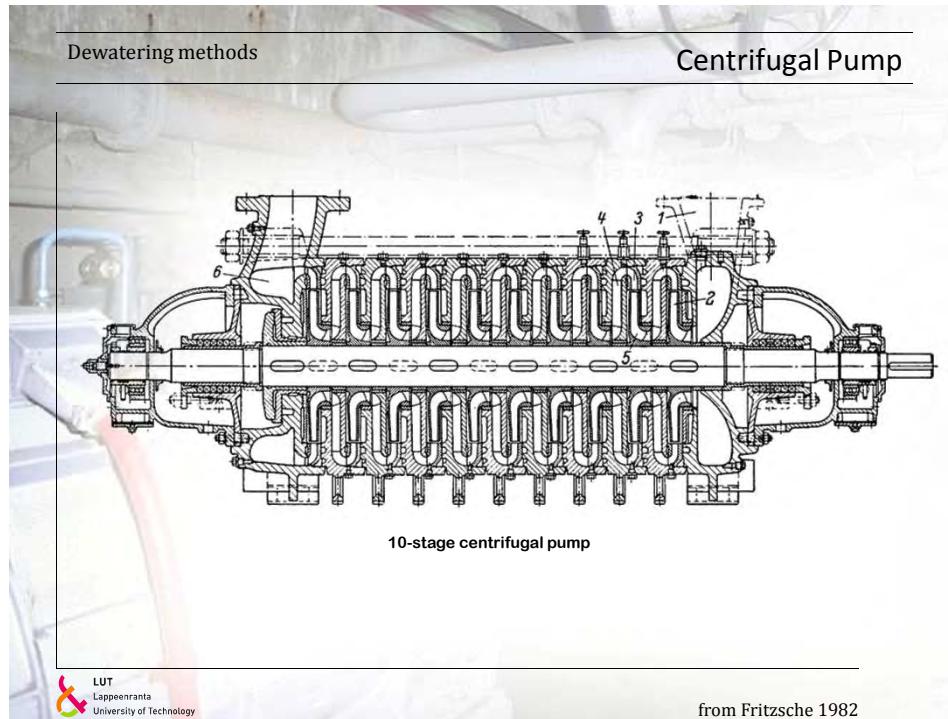
Dewatering methods	Water make in German coal mines
<ul style="list-style-type: none"> • Ruhr Area (hard coal) <ul style="list-style-type: none"> – 1957 30 $76.9 \cdot 10^6 \text{ m}^3 \text{ a}^{-1}$ ca. 1500 km² – 1982 3 $48.6 \cdot 10^6 \text{ m}^3 \text{ a}^{-1}$ • Ibbenbüren (hard coal) <ul style="list-style-type: none"> – 1979 4 $14.0 \cdot 10^6 \text{ m}^3 \text{ a}^{-1}$ 15 km² • Lusatia/Saxony (lignite; draw down: 150—200 m) <ul style="list-style-type: none"> – 1990 7000 $1.2 \cdot 10^9 \text{ m}^3 \text{ a}^{-1}$ 2500 km² • Rhine Area (lignite; draw down: 500 m) <ul style="list-style-type: none"> – 1985 1250 $1.0 \cdot 10^9 \text{ m}^3 \text{ a}^{-1}$ 2900 km² 	



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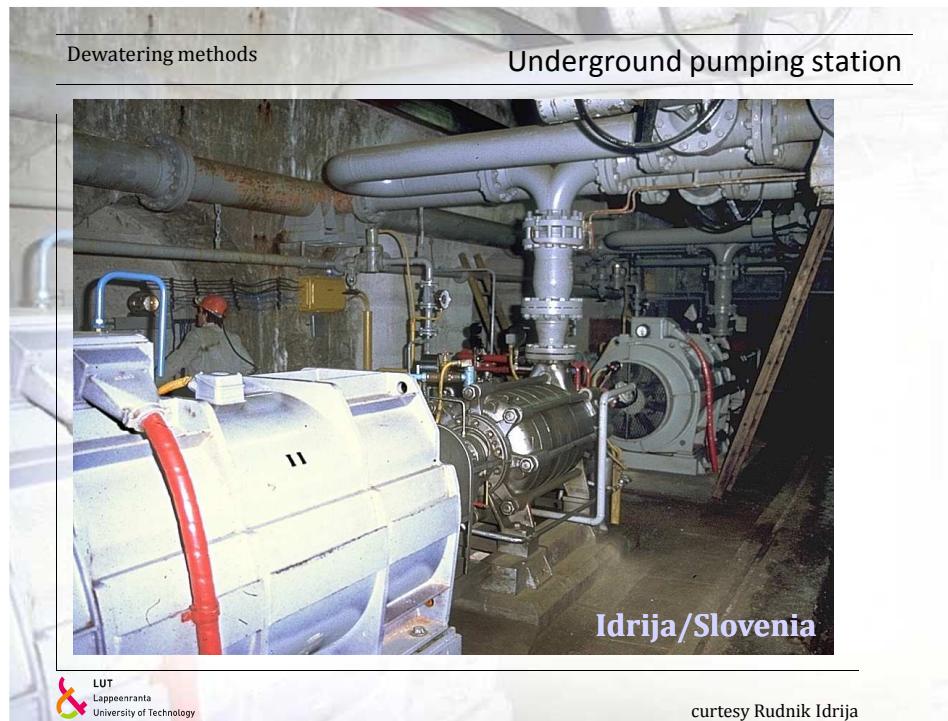






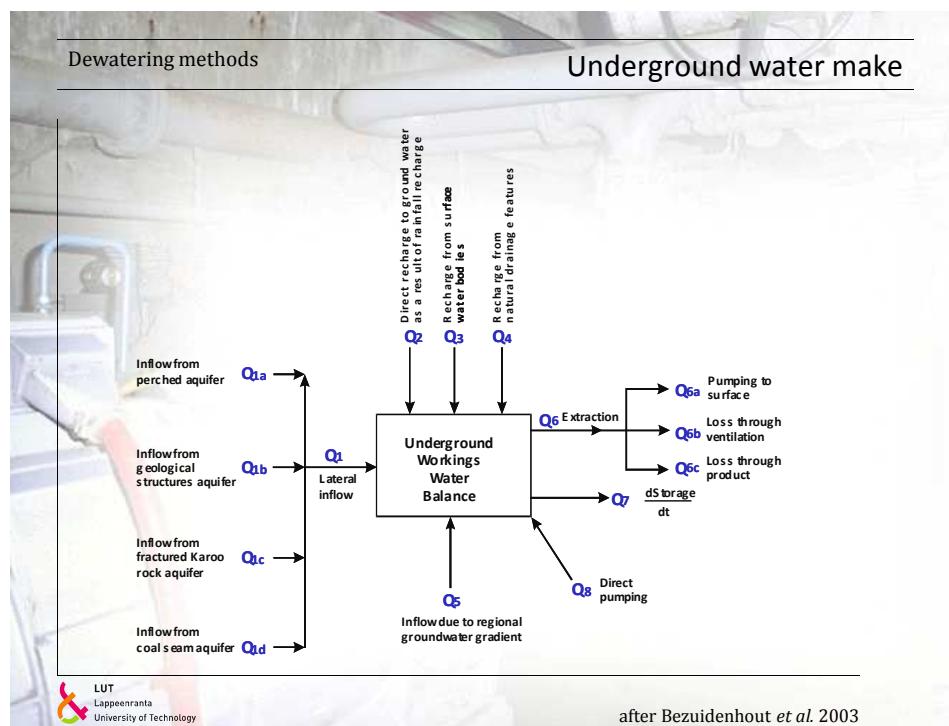
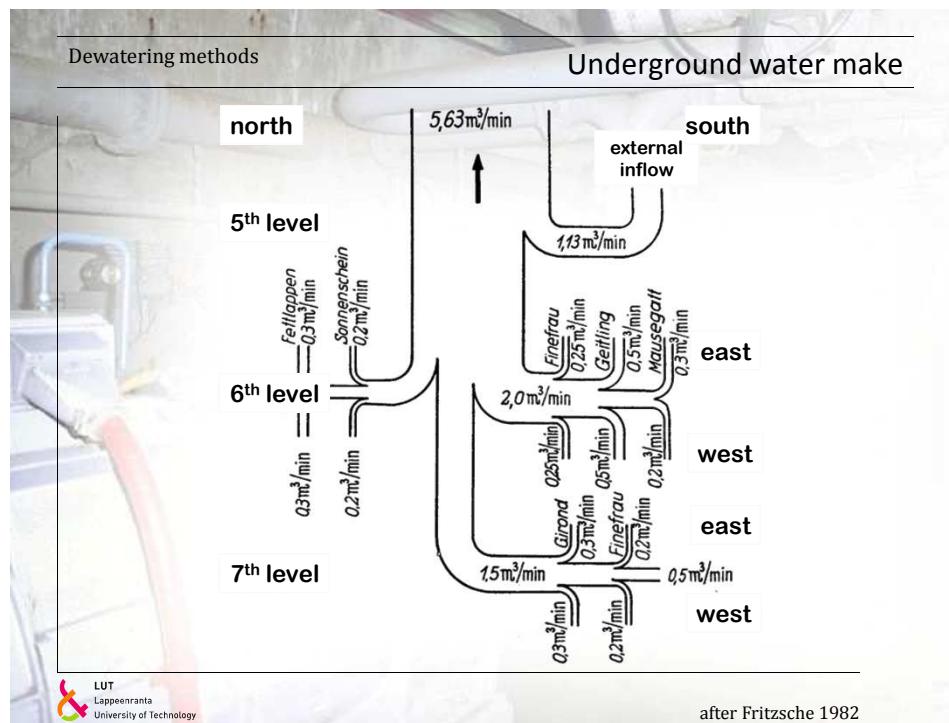
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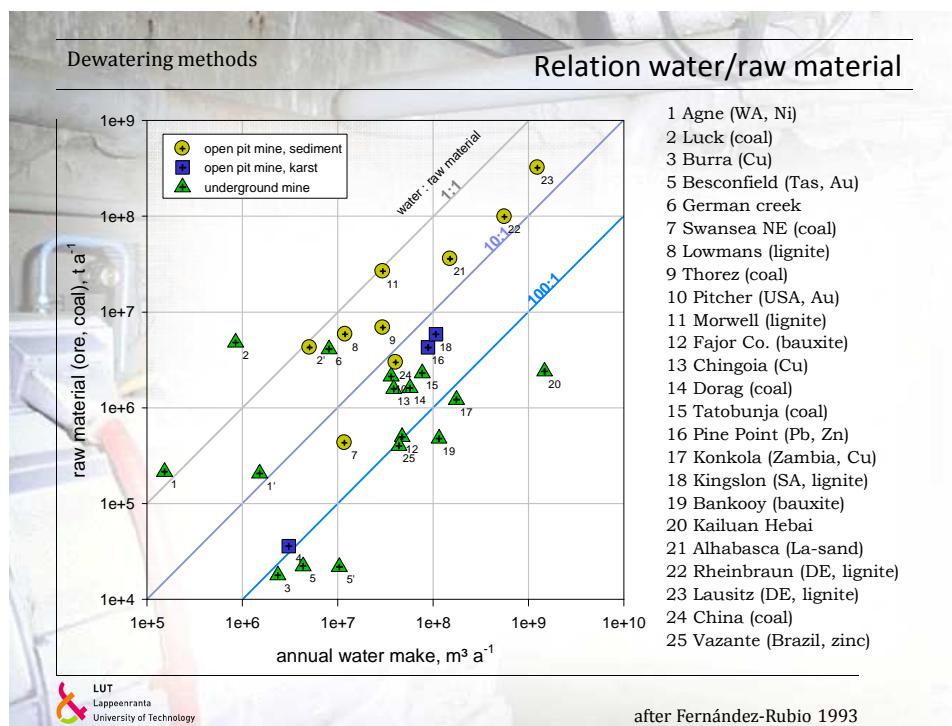
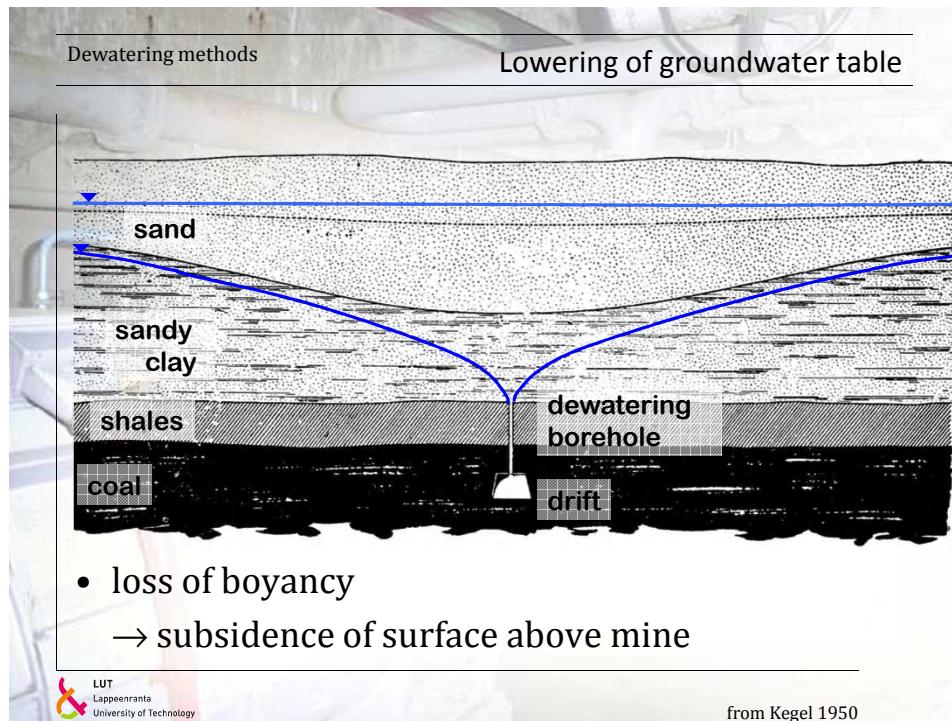
from Böttcher *et al.* 1991

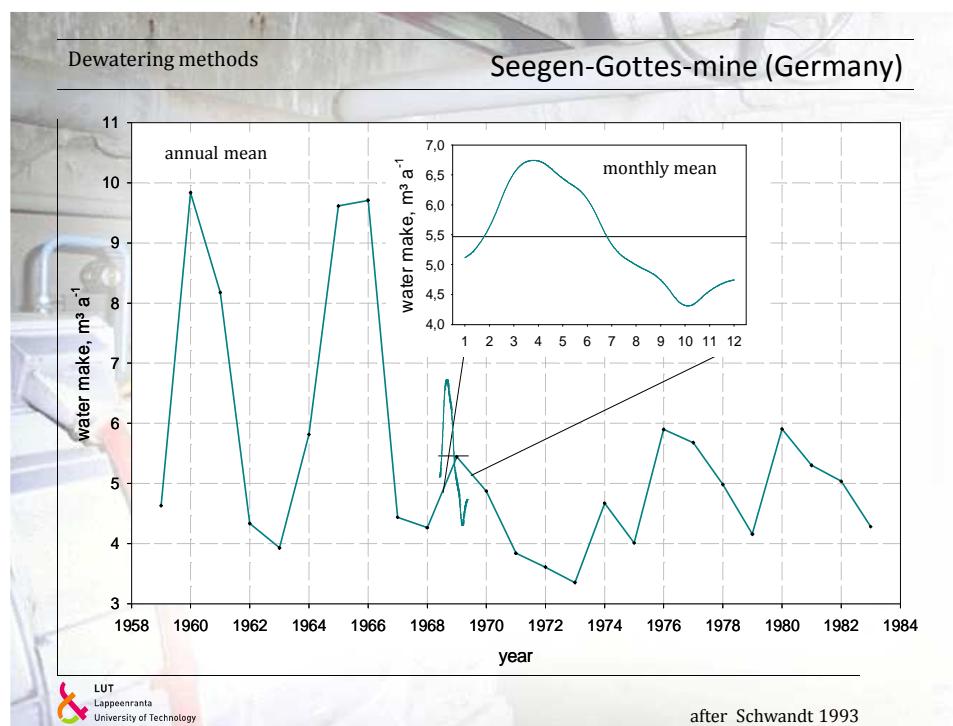
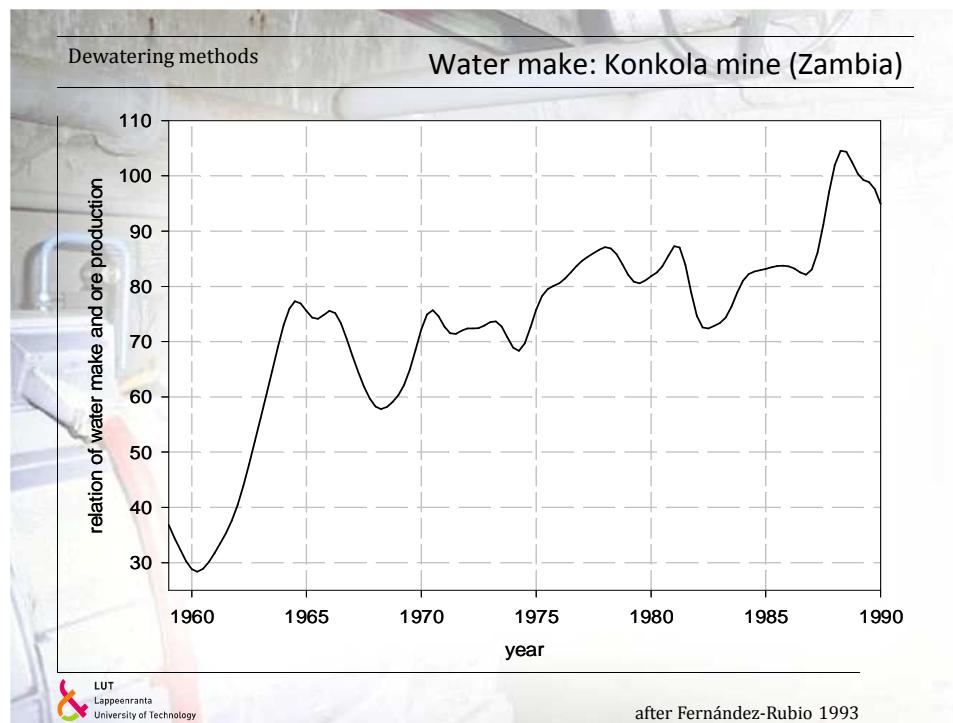


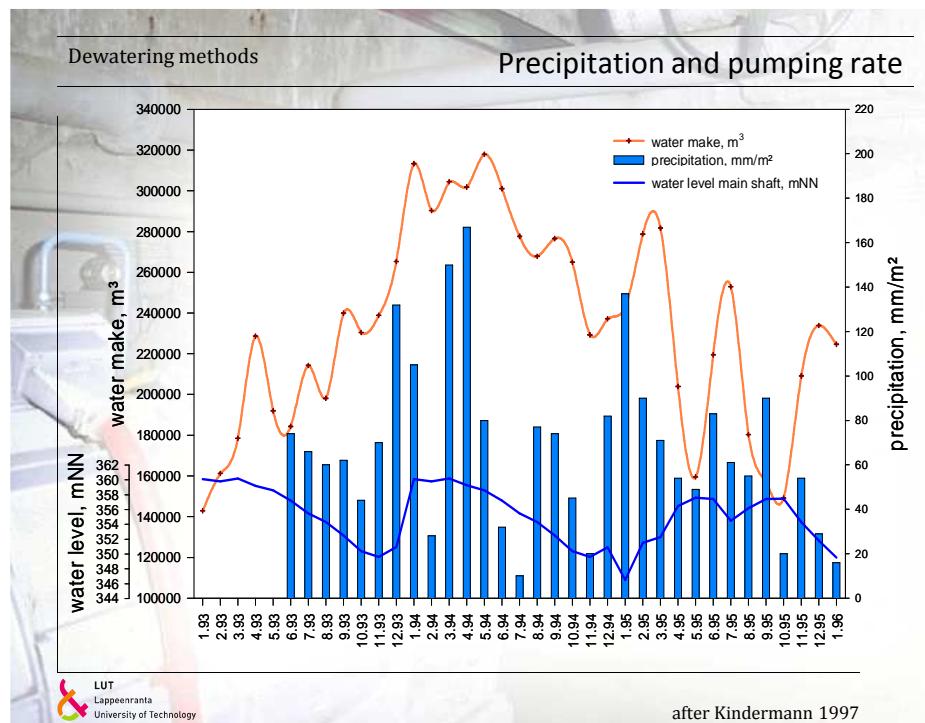
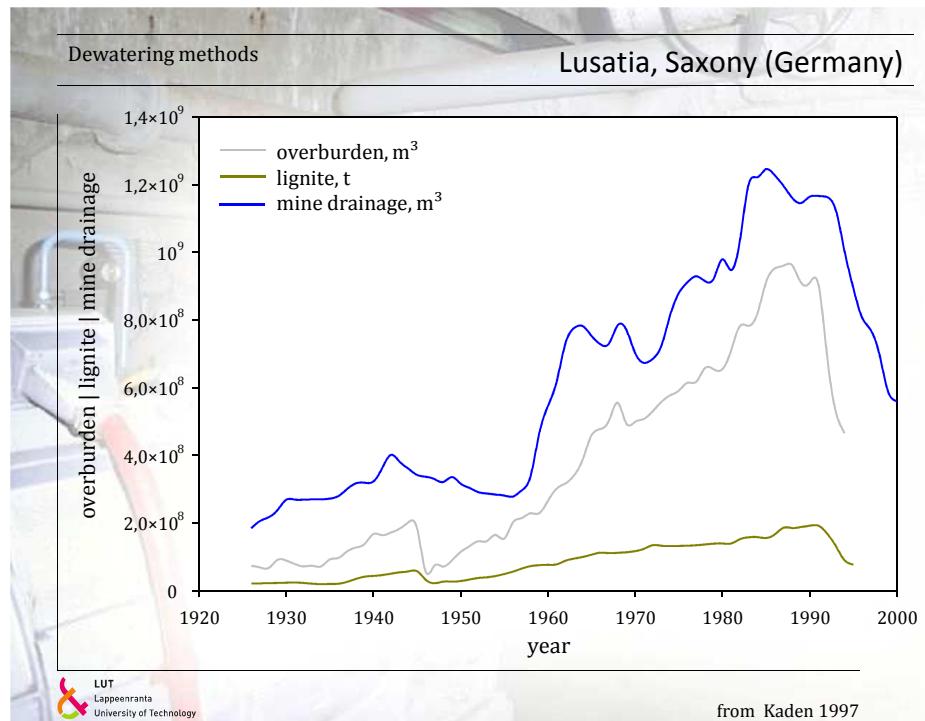
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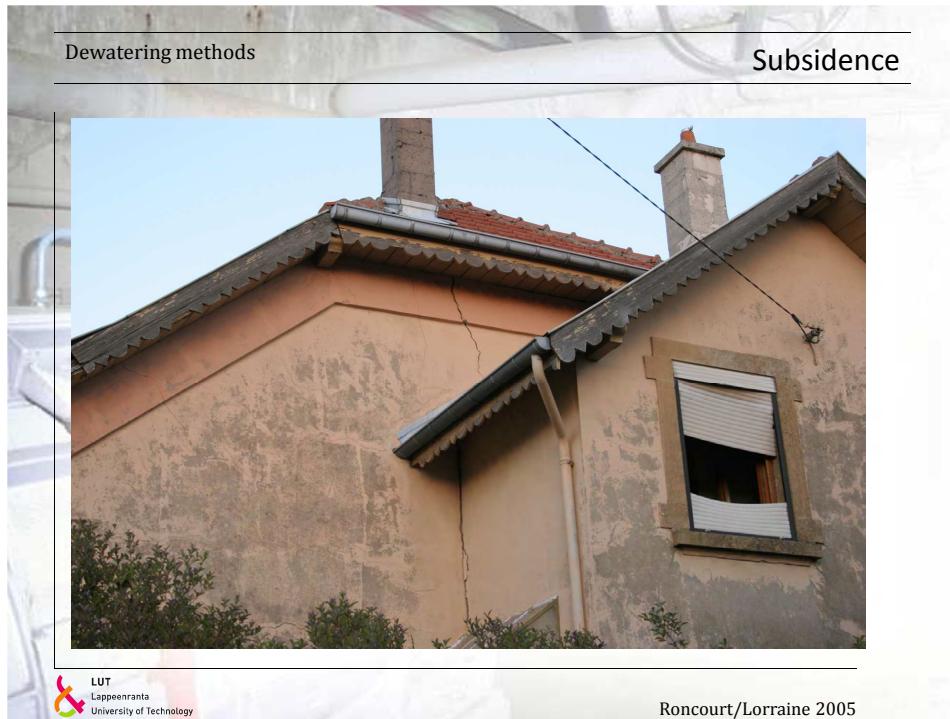
curtesy Rudnik Idrija

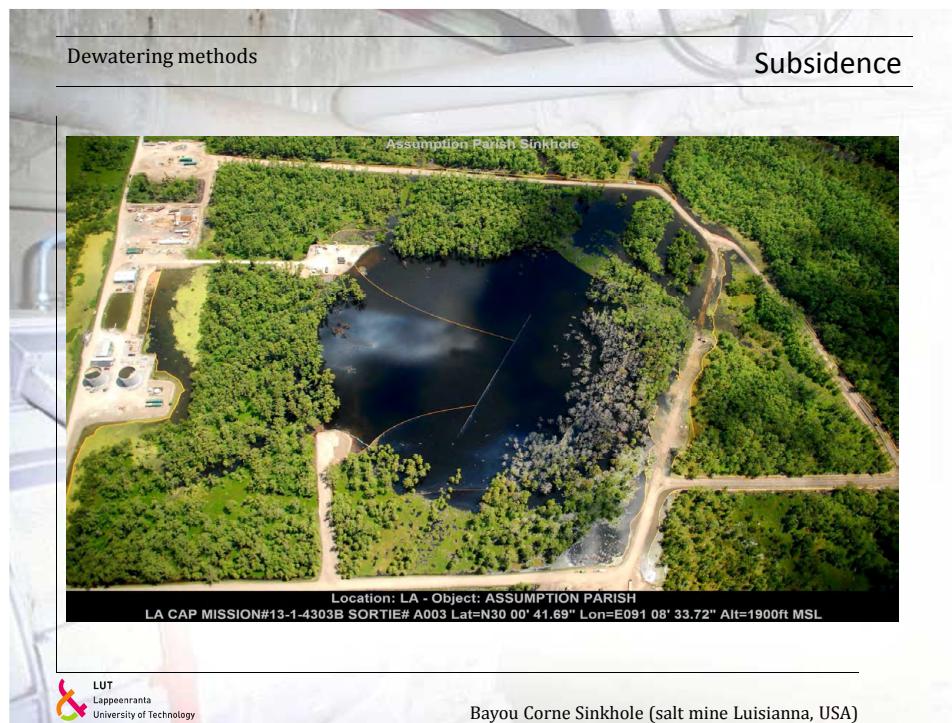
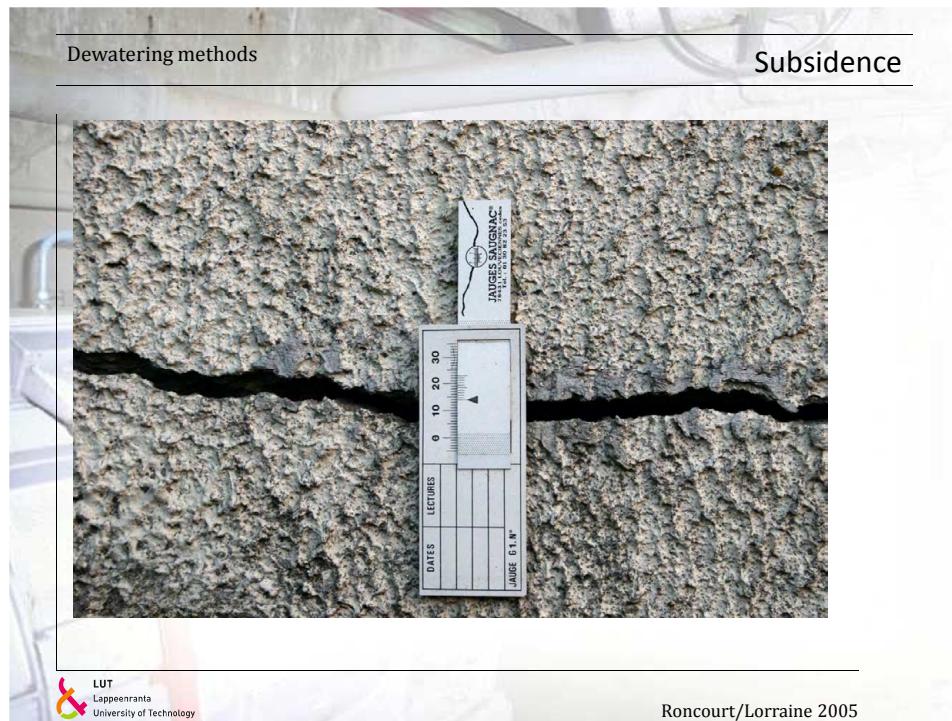


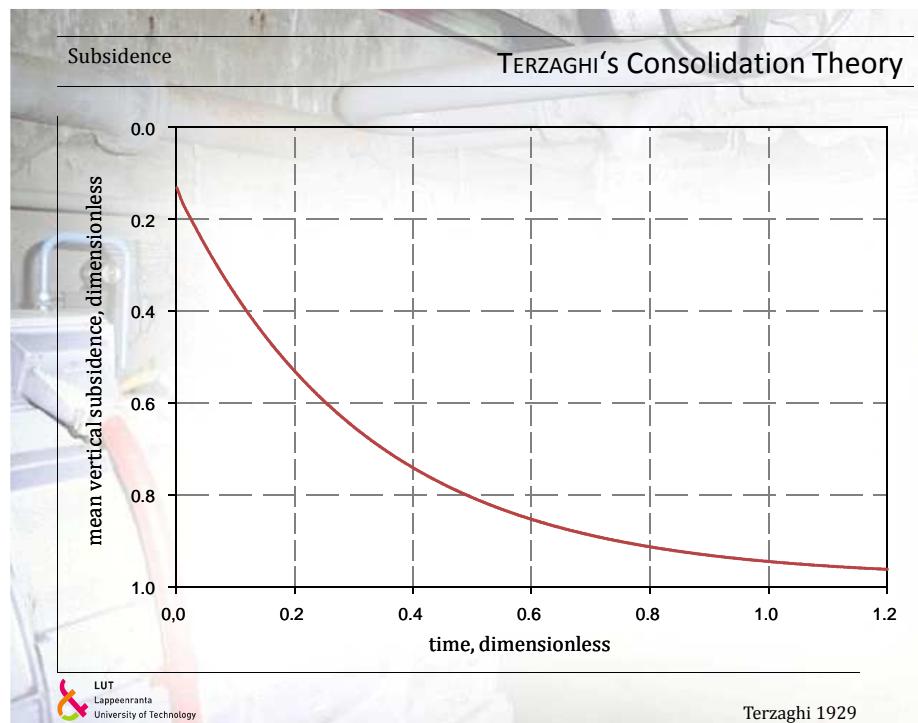
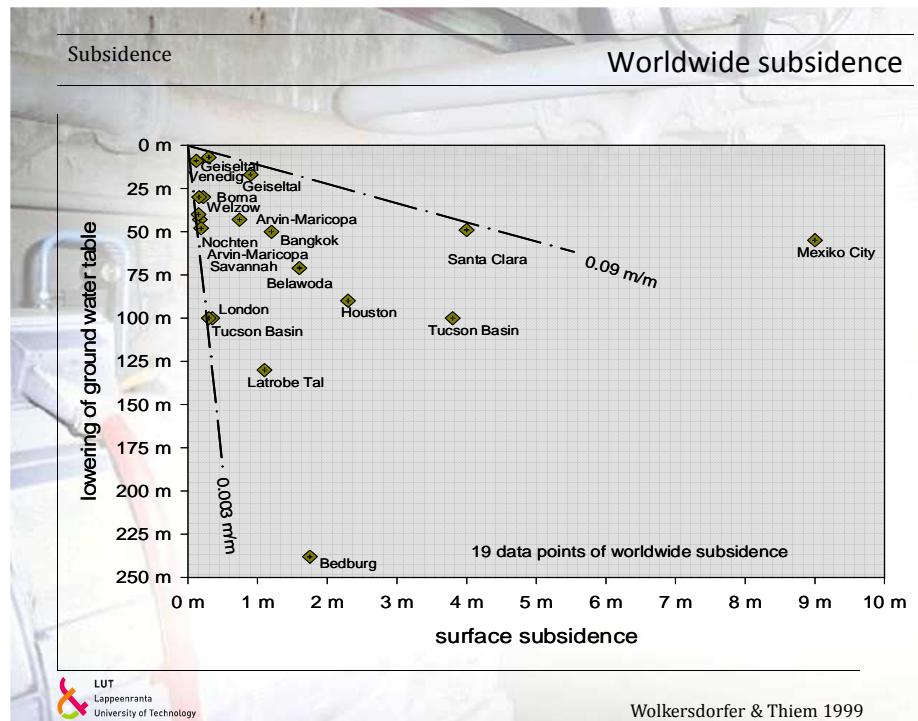


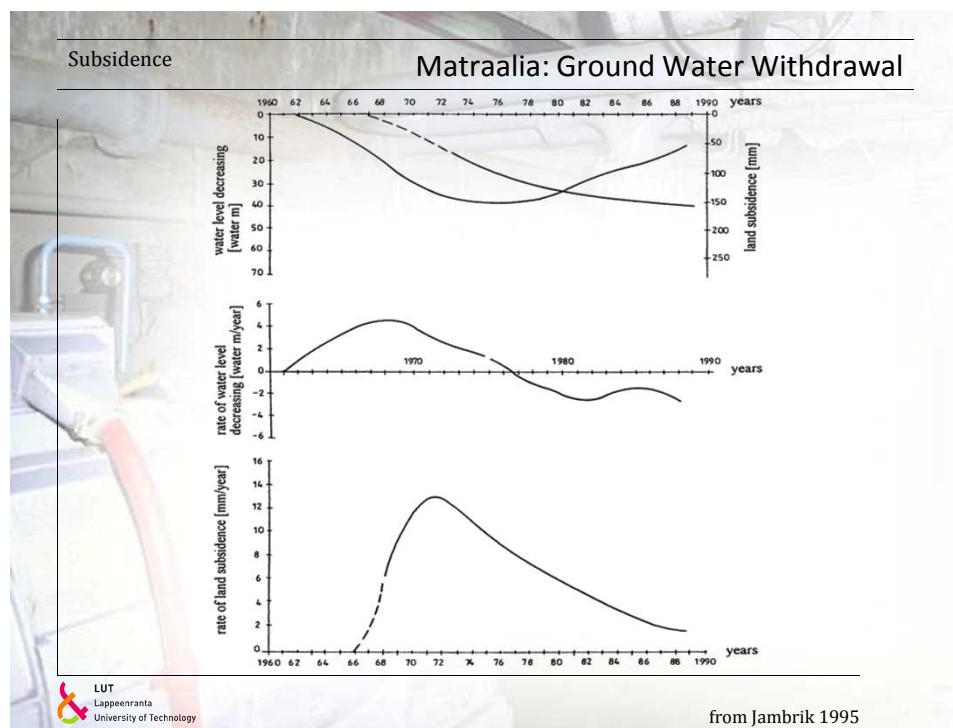
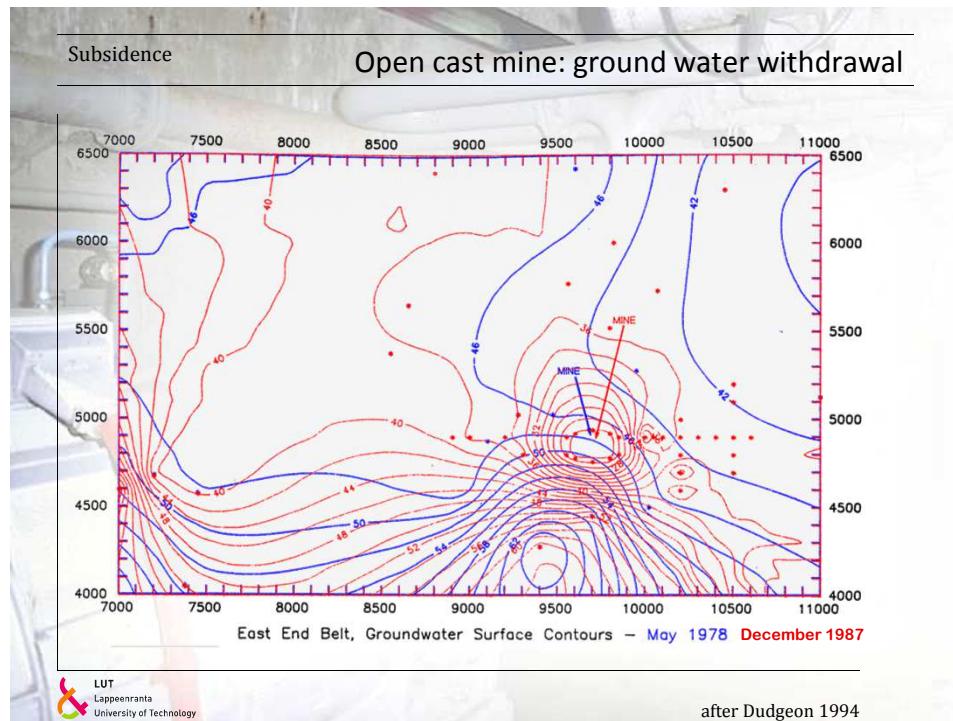






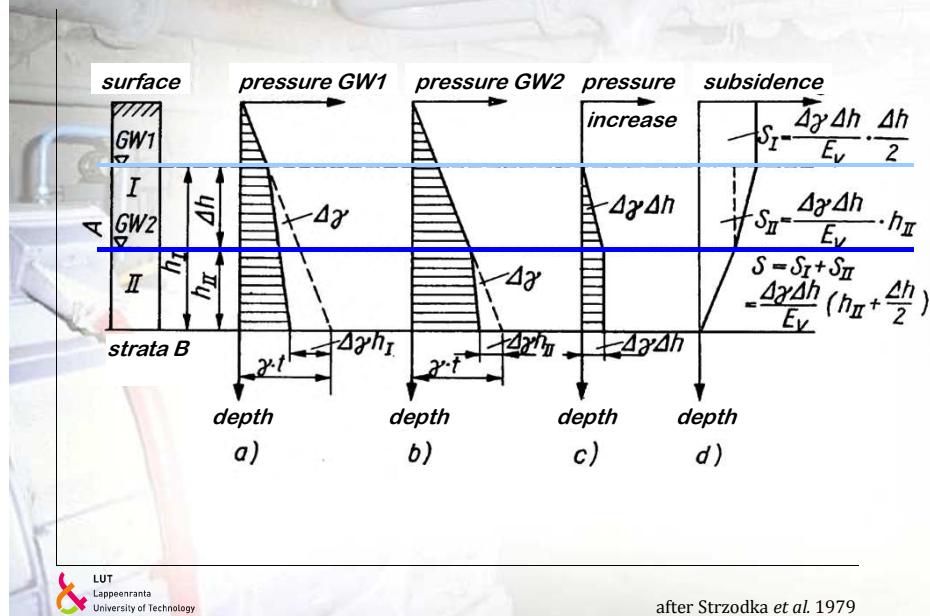






Subsidence

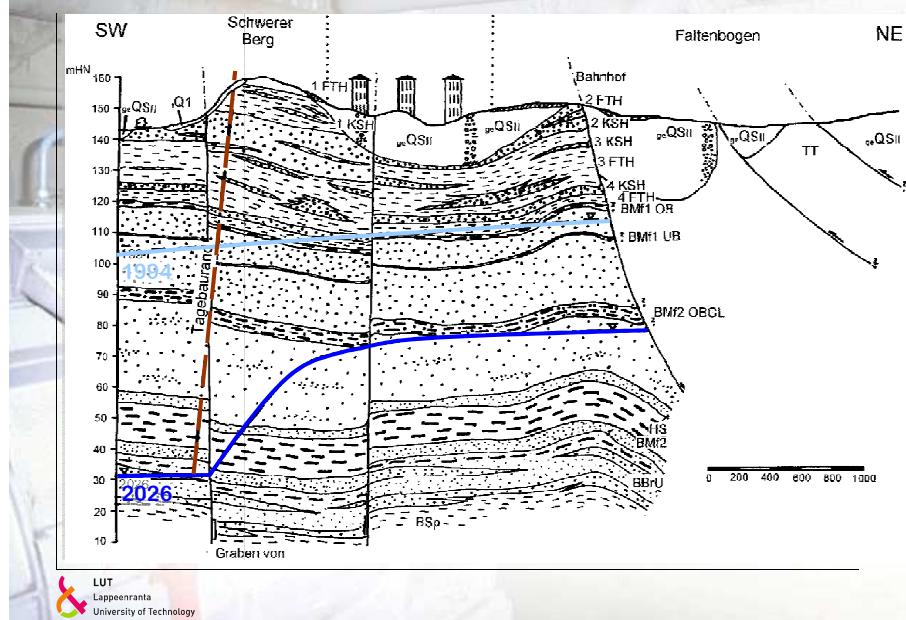
Ground Water Withdrawal: Subsidence



after Strzodka *et al.* 1979

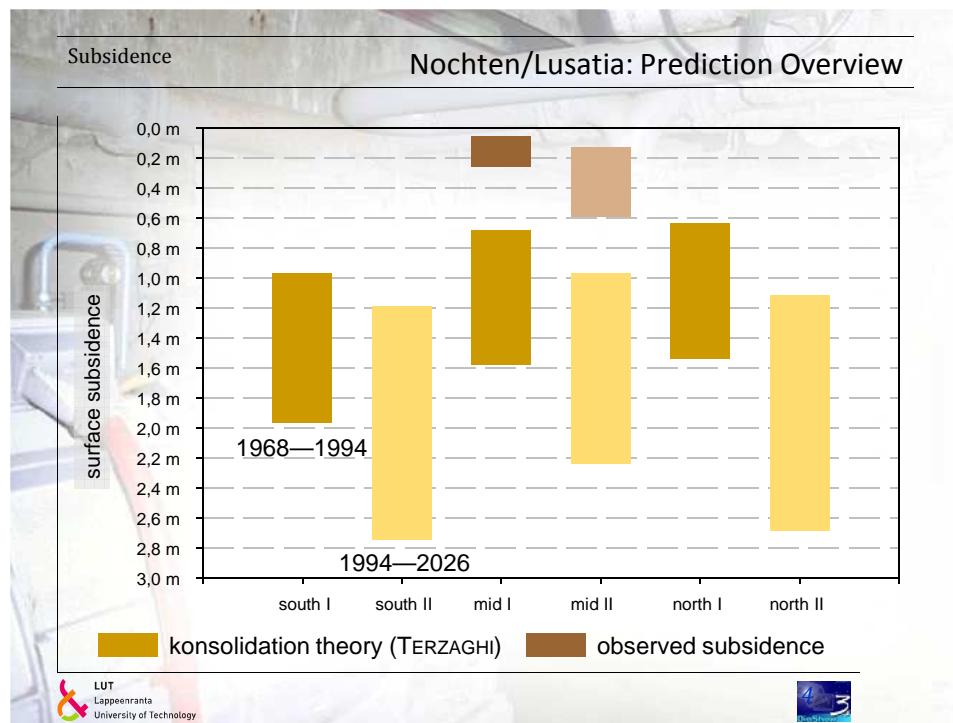
Subsidence

Nochten/Lusatia: Geological Cross Section



Subsidence		Nachten/Lusatia: Soil Parameters		
stratum	soil type	thickness M	compressibility E_v	porosity n
		m	MN/m ²	1
1	sand/gravel	15	80...200	0.32
2	sand/gravel	1	80...200	0.32
3	clay	5	4...10	0.53
4	sand/gravel	2	80...200	0.32
5	clay	6	4...10	0.53
6	sand/gravel	1	80...200	0.32
7	clay	2	4...10	0.53
8	sand/gravel	2	80...200	0.32
9	clay	3	4...10	0.53
10	soft coal	2	20...20	0.6
11	sand	9	60...150	0.35
12	soft coal	1	20...30	0.6
13	sand, silt	16	40...100	0.35
14	soft coal	4	20...30	0.6
15	sand, silt	22	40...100	0.35
16	silt	3	5...15	0.4
17	soft coal	11	20...30	0.6
18	fine sand	4	40...80	0.35
19	soft coal	3	20...30	0.6
20	fine sand	4	40...80	0.35
21	silt	5	5...15	0.4
22	fine sand	4	40...80	0.35

Subsidence		Nachten/Lusatia: Calculation (2026)		
stratum	soil type	subsidence (min)	subsidence (max)	mean
		cm	cm	cm
1	sand/gravel	0.4	1.0	0.7
2	sand/gravel	0.1	0.1	0.1
3	clay	6.0	15.1	10.5
4	sand/gravel	0.1	0.3	0.2
5	clay	9.6	24.0	16.8
6	sand/gravel	0.1	0.2	0.2
7	clay	3.7	9.3	6.5
8	sand/gravel	0.2	0.5	0.3
9	clay	6.3	15.8	11.1
10	soft coal	1.5	2.2	1.9
11	sand	1.5	3.8	2.7
12	soft coal	1.0	1.4	1.2
13	sand, silt	5.4	13.6	9.5
14	soft coal	5.3	8.0	6.7
15	sand, silt	9.0	22.5	15.7
16	silt	8.2	24.5	16.3
17	soft coal	15.0	22.5	18.7
18	fine sand	2.0	4.1	3.1
19	soft coal	4.1	6.1	5.1
20	fine sand	2.0	4.1	3.1
21	silt	13.6	40.9	27.2
22	fine sand	2.0	4.1	3.1
sum	–	97	224	161





From Ground Water to Mine Water

Environmental Hydrogeology in Mining

Mine Flooding

Prof. Dr. Christian Wolkersdorfer (云村)

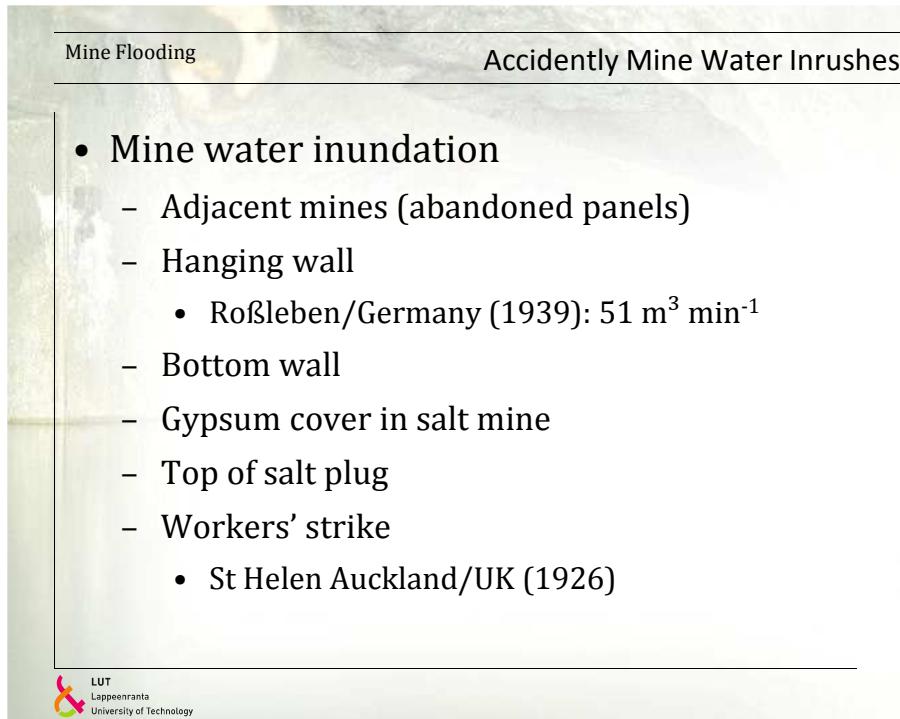
Finnish Distinguished Professor – Lappeenranta University of Technology
South African Research Chair for Acid Mine Drainage Treatment

From Ground Water to Mine Water

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- Introduction, Historical Background
- Mining Methods, Technical Terms
- Water and Water Inrushes
- Dewatering methods; Recharge
- **Mine Flooding**
- Mine Water Geochemistry
- Prediction of Mine Flooding
- Mine Water Treatment



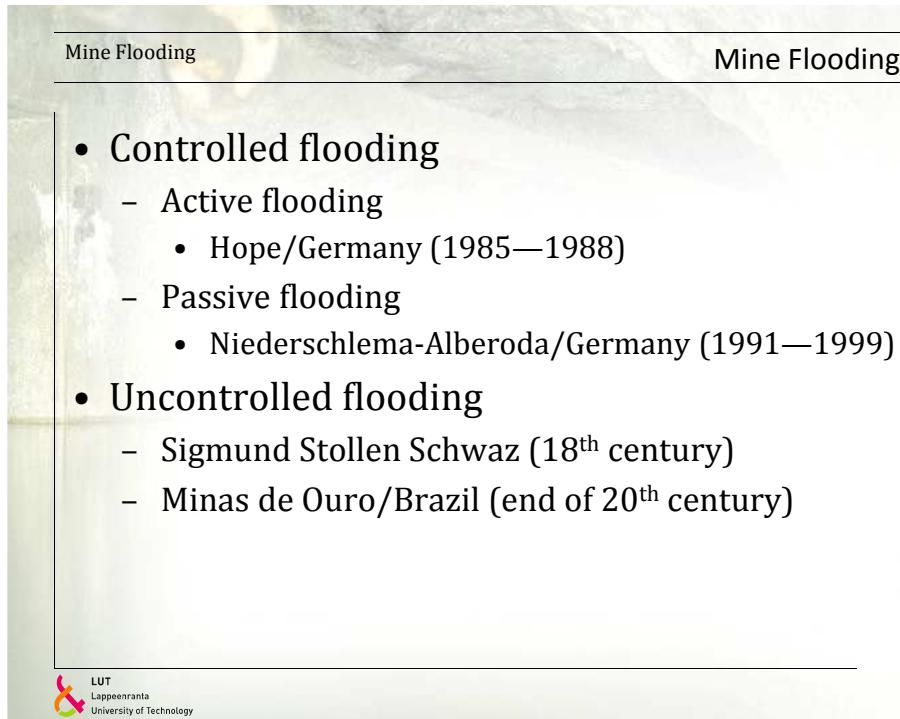


Mine Flooding

Accidently Mine Water Inrushes

- Mine water inundation
 - Adjacent mines (abandoned panels)
 - Hanging wall
 - Roßleben/Germany (1939): $51 \text{ m}^3 \text{ min}^{-1}$
 - Bottom wall
 - Gypsum cover in salt mine
 - Top of salt plug
 - Workers' strike
 - St Helen Auckland/UK (1926)

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Mine Flooding

Mine Flooding

- Controlled flooding
 - Active flooding
 - Hope/Germany (1985—1988)
 - Passive flooding
 - Niederschlema-Alberoda/Germany (1991—1999)
- Uncontrolled flooding
 - Sigmund Stollen Schwaz (18th century)
 - Minas de Ouro/Brazil (end of 20th century)

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Mine Flooding	Controlled Flooding
<ul style="list-style-type: none">• Monitoring system• Controlled raise of mine water table• Interference with raise of mine water table possible• Active flooding (<i>e.g.</i> Hope/Germany)• Passive flooding (Niederschlema/Germany)	

Mine Flooding	Uncontrolled Flooding
<ul style="list-style-type: none">• Stop of mine water pumps• No geotechnical monitoring system• No chemical control• Usually without monitoring system• If mine budget is unclear• No risk for people or buildings• During war times or crisis	

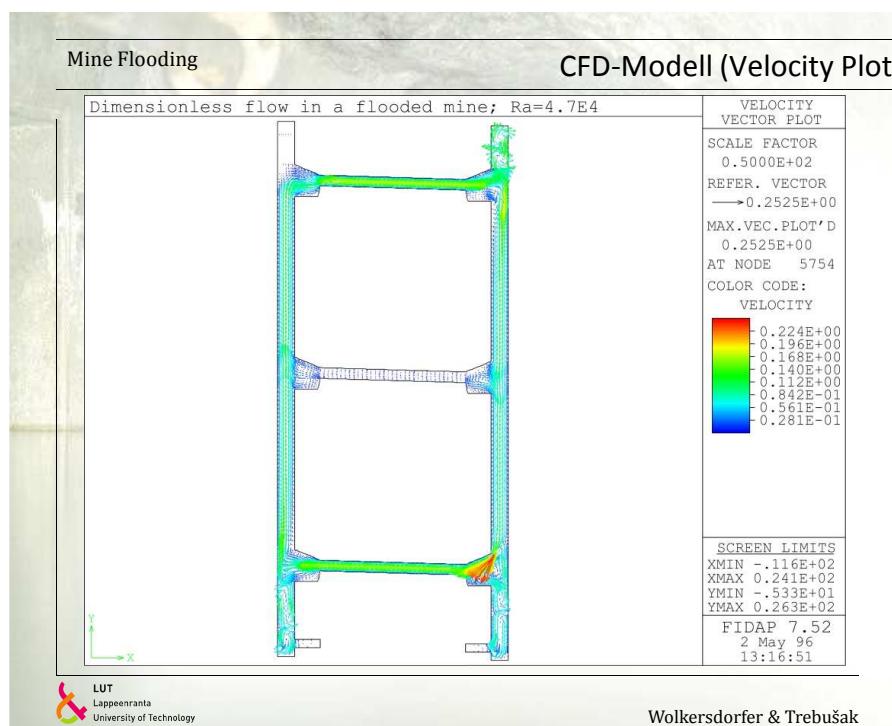
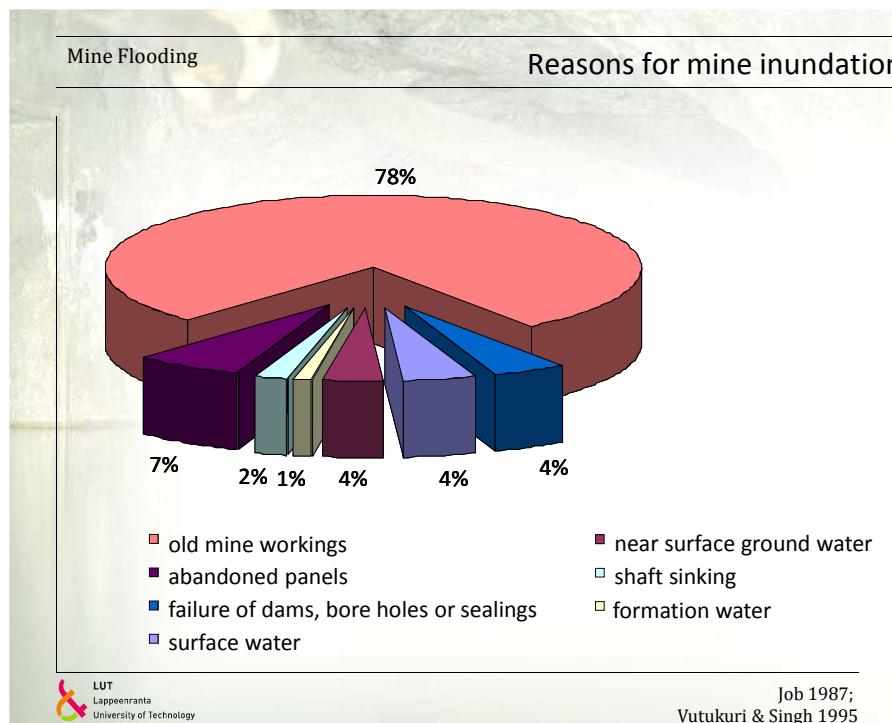
Mine Flooding	Calculations
<ul style="list-style-type: none"> • Empirical <ul style="list-style-type: none"> - SAUL's rule • Analytical <ul style="list-style-type: none"> - Turbulent flow - Laminar flow • Numerical (partly geochemical) <ul style="list-style-type: none"> - GRAM - SHETRAN - Monte Carlo - CFD - FEFLOW - MODFLOW - EPA NET - CE-QUAL-W2 - GOLDSIM - VULCAN 	

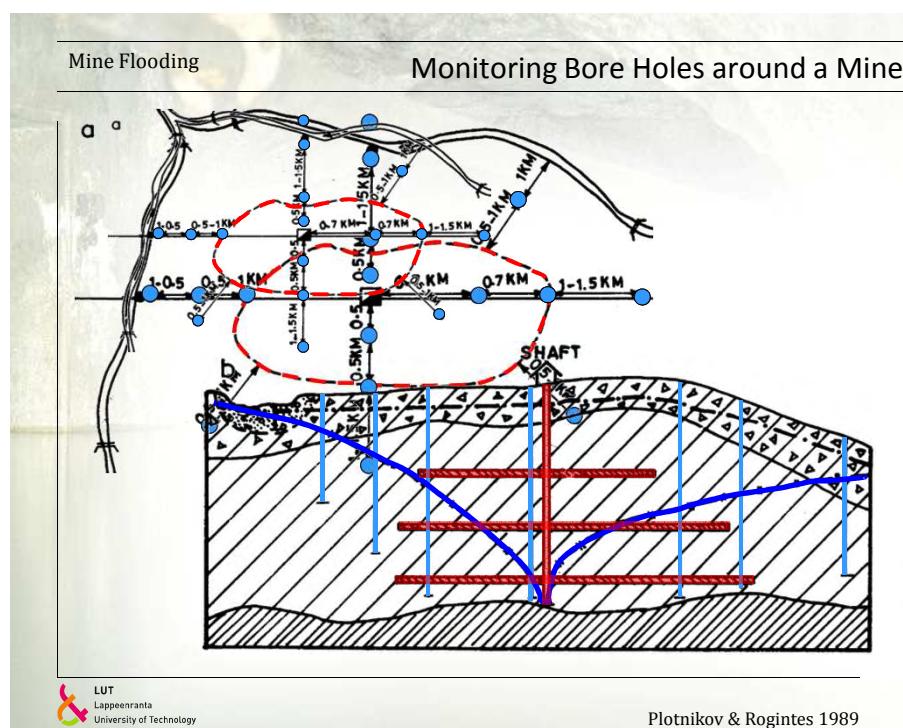
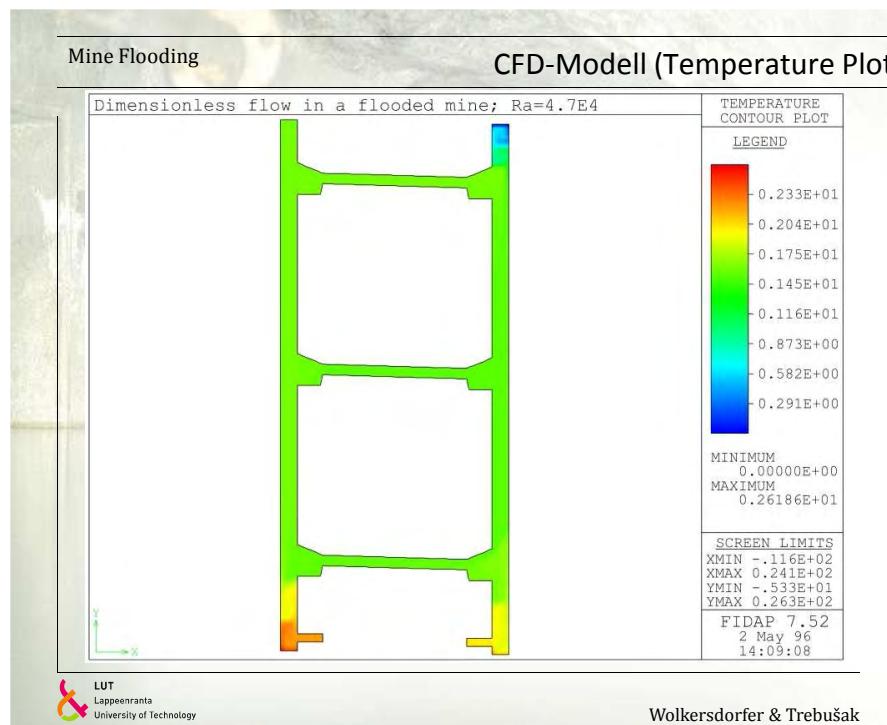
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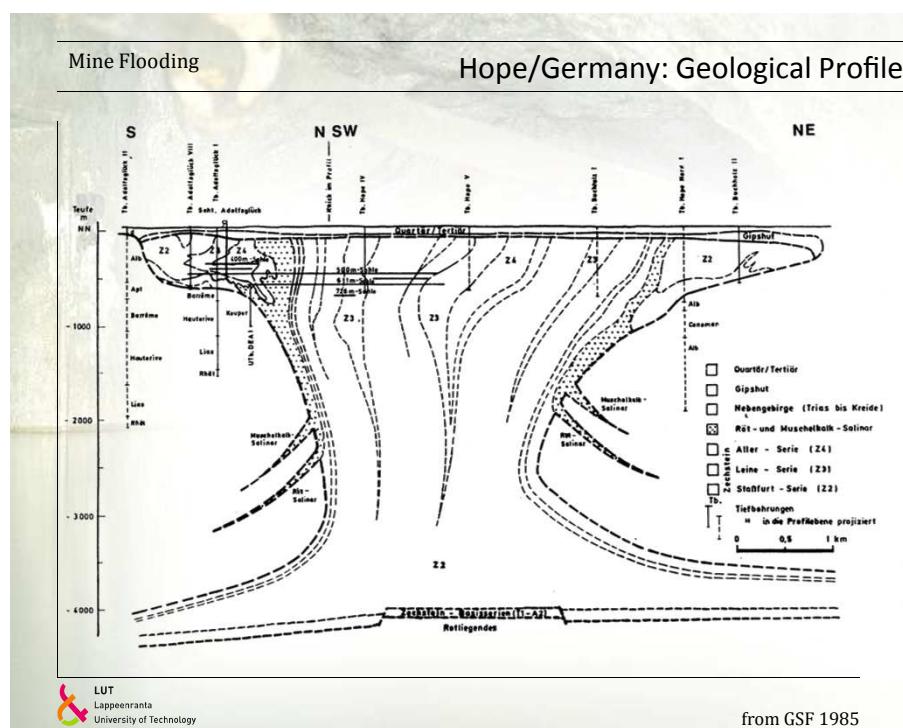
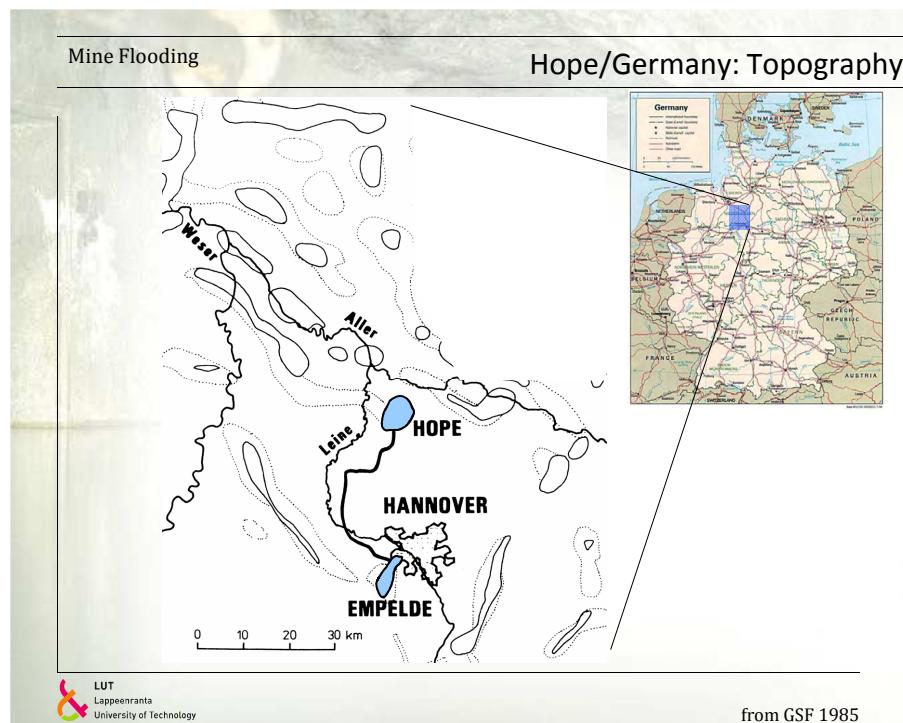
Mine Flooding	Catastrophical mine water inundations	
1815	1927 Carbonado Mine. Carbonado. Col	7
1837	1950 Knockshinnoch Colliery, Ayrshire. Scot	13
1883	1952 Holmes Slope, Forrestville, Pa. A	5
1885	1954 Newton Chickli Colliery, M.P, India	62
1895	1958 Central Bowrah, Jharia, India	23
1889	1959 River Slope. Port Griffith. Pa. A	12
1891	1960 Dhamua main , M.P., India	16
1892	1970 Karanpura Colliery, Bihar, India	3
1898	1973 Lofthouse Colliery. Northumberland, England.	7
1901	1975 Silvewara Colliery, Nagpur, M.P., India	10
1908	1975 Chasnala Colliery, Jharia, India	375
1912	1977 Porter Tunnel Mine. Tover City. Pa A	9
1917	1978 Moss No. 3. Dante. Va.	4
1918	1979 Mine No. 1. Poteau, Okla.	1
1923	1981 Harlan No. 5. Grays Knob, Ky.	3
1925	1983 Hurrilladih Colliery, Jharia, India	19
1927	1985 Lykens No. o, Lykens. Pa. A	1

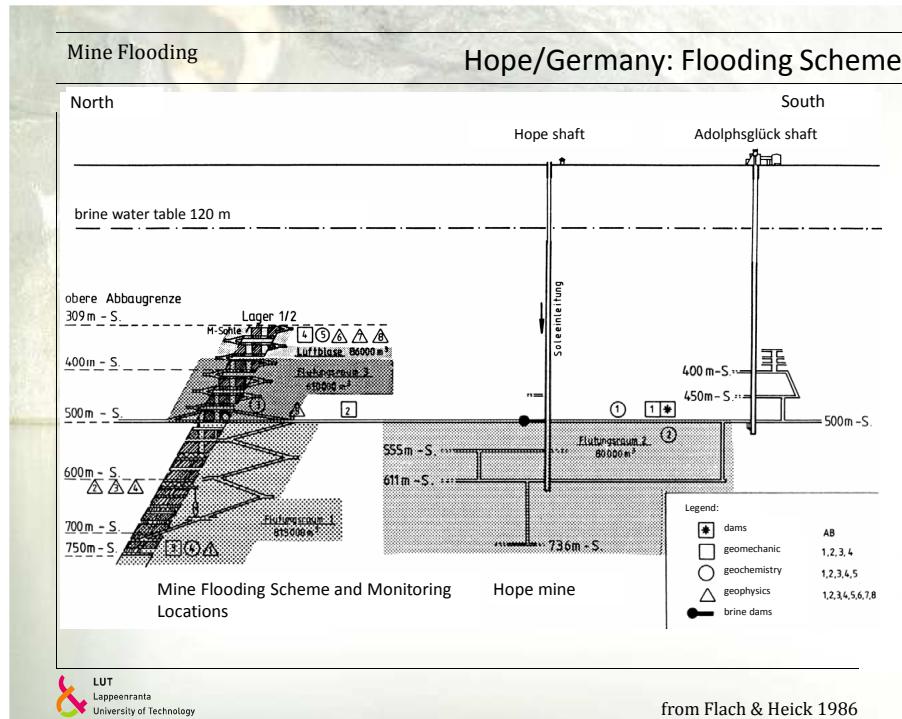
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Vutukuri & Singh 1995

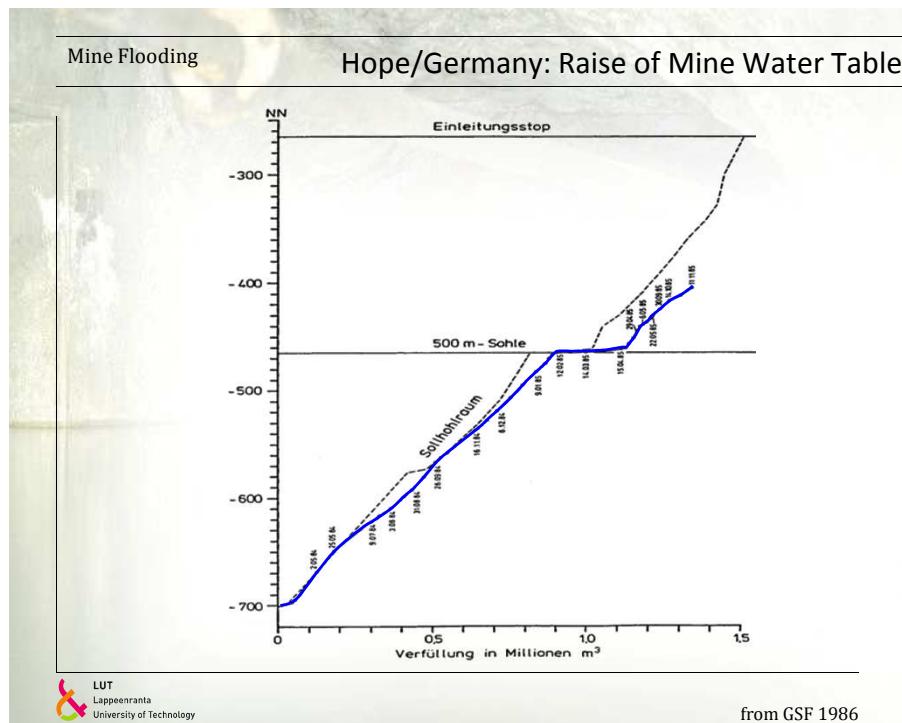




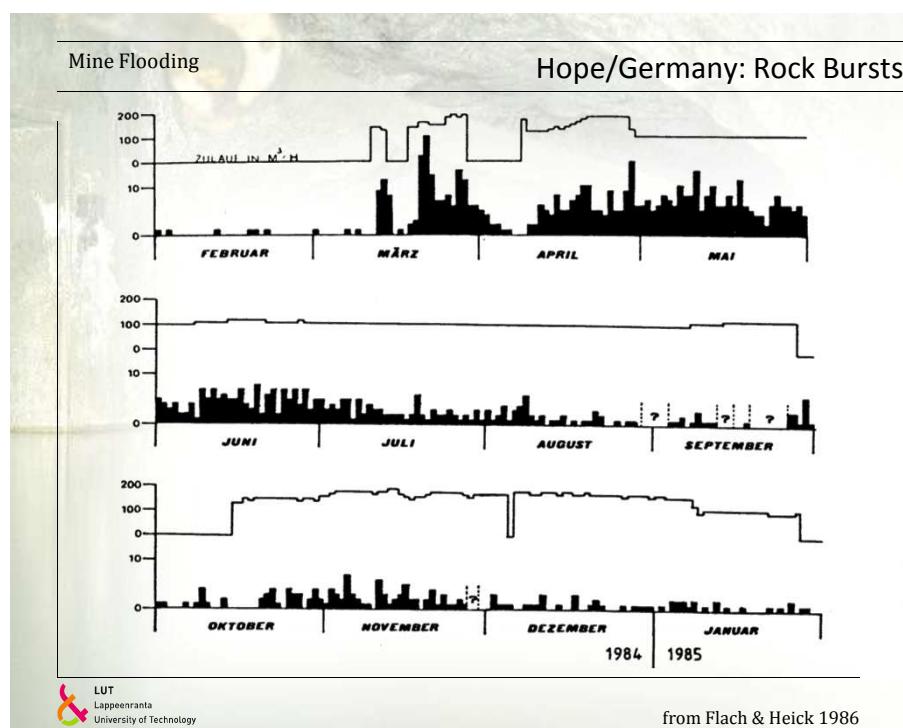
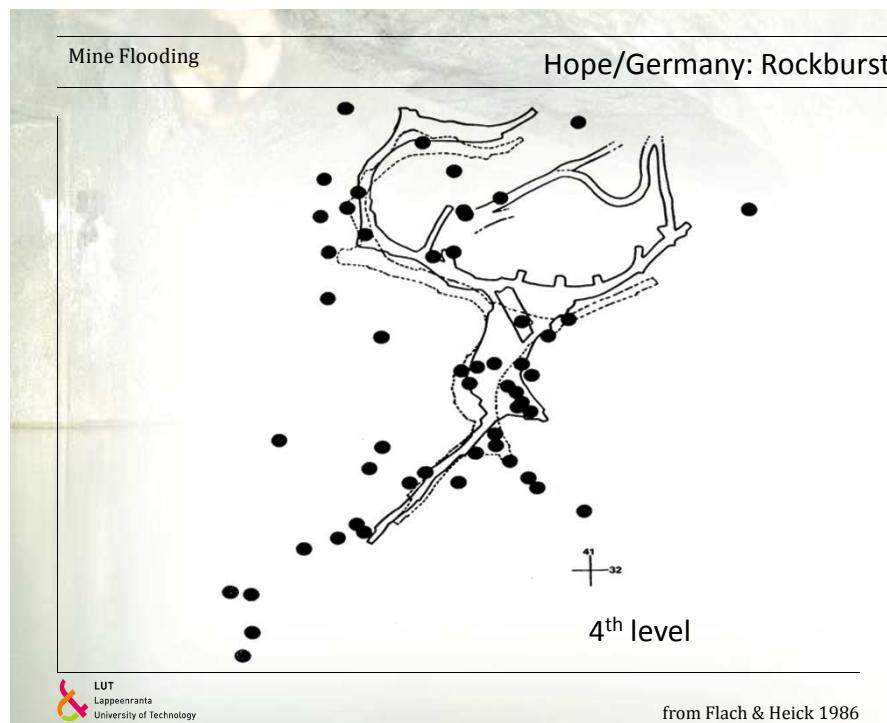


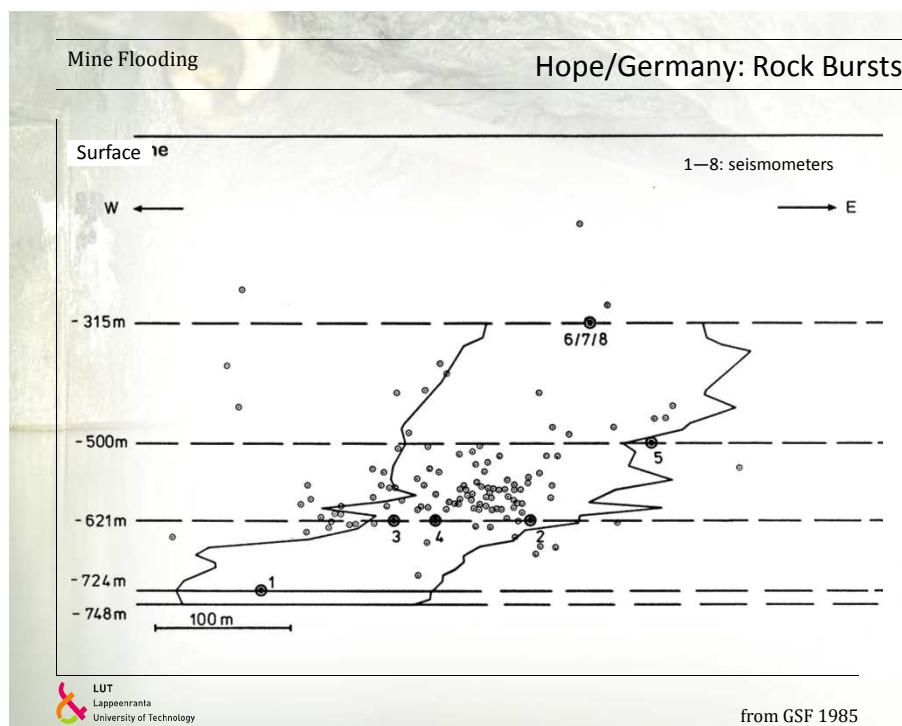
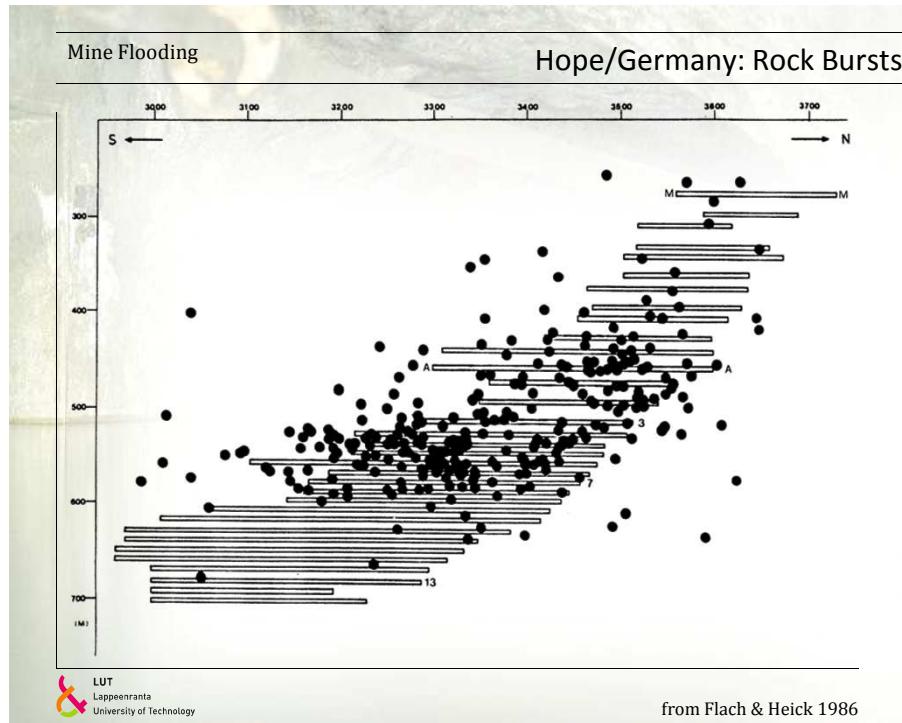


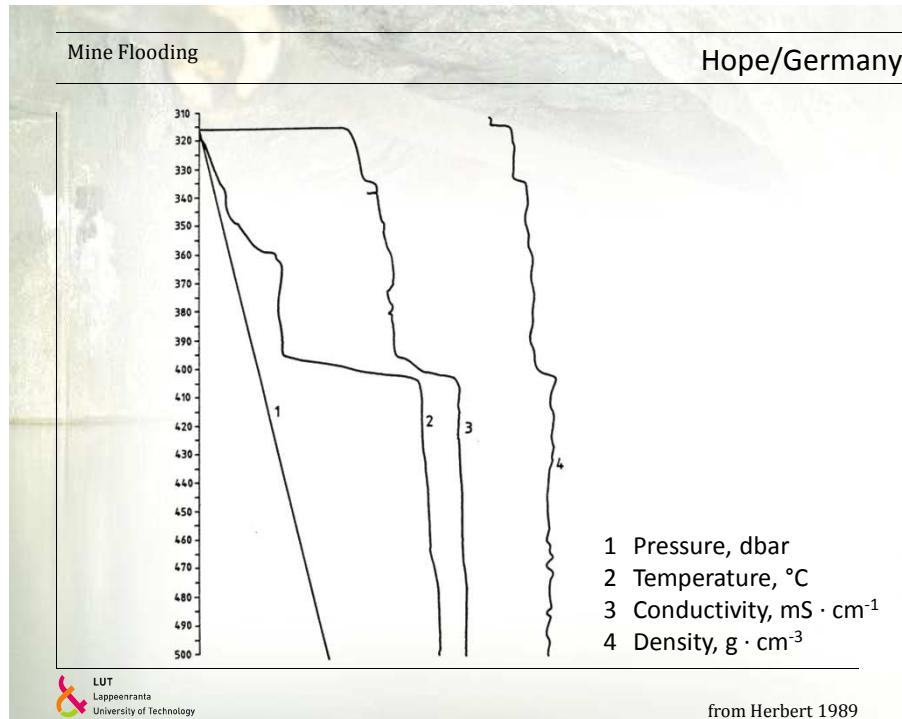
from Flach & Heick 1986



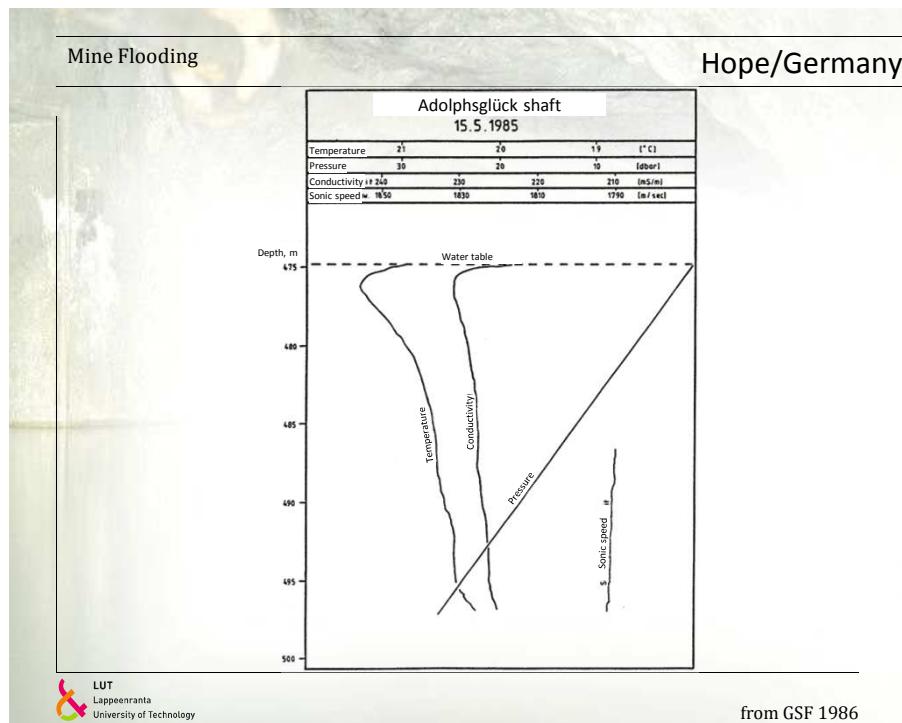
from GSF 1986





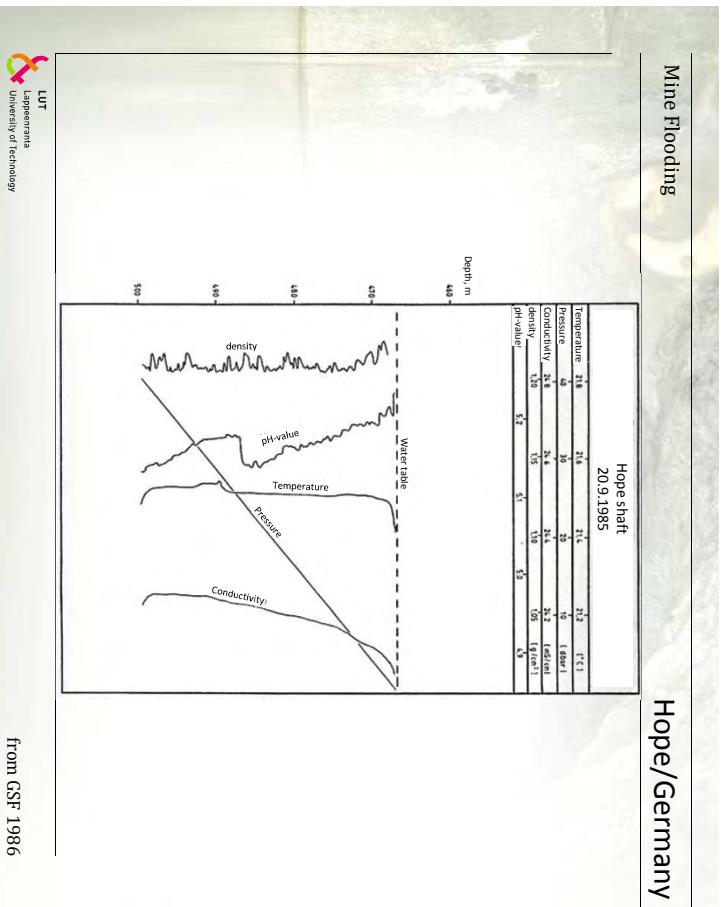
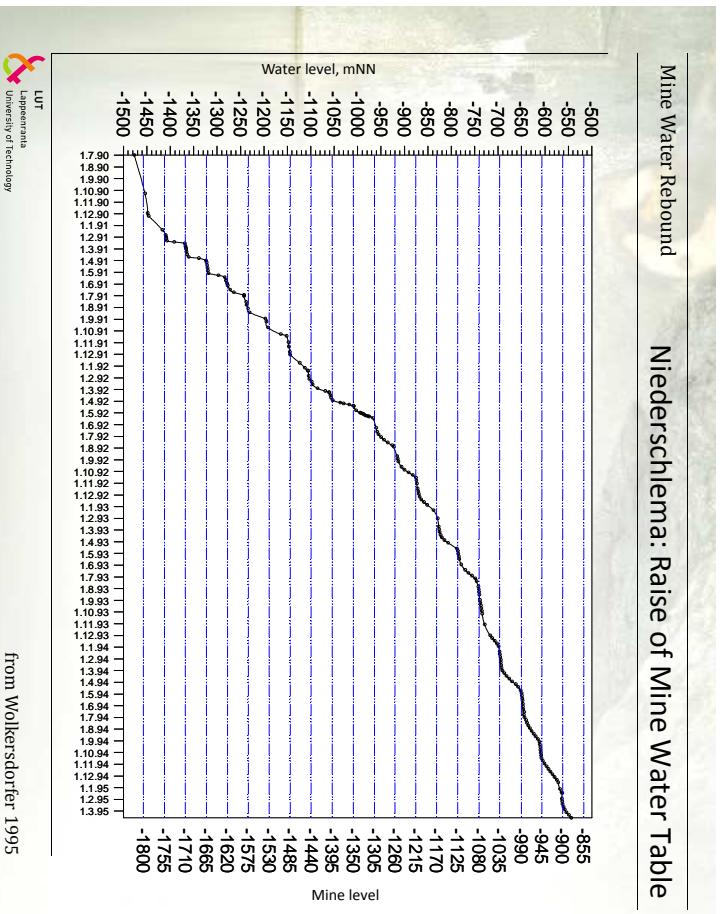


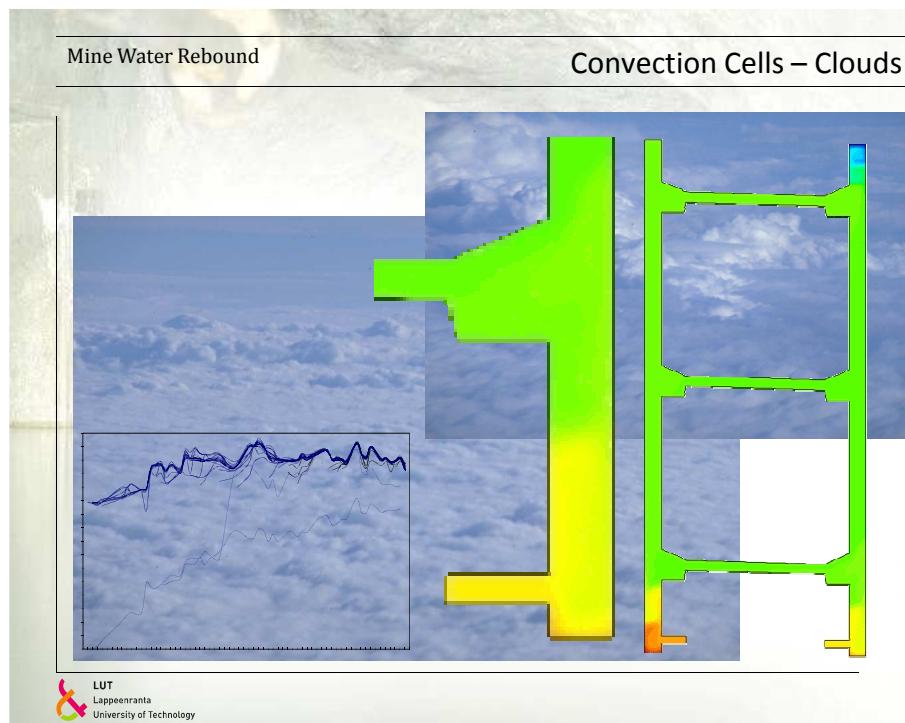
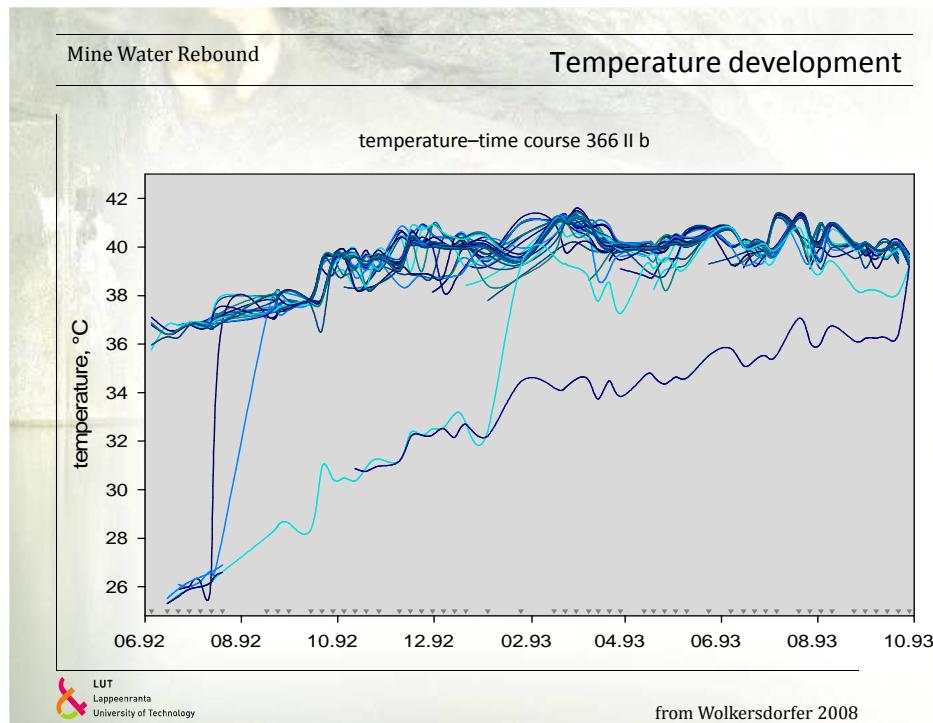
from Herbert 1989

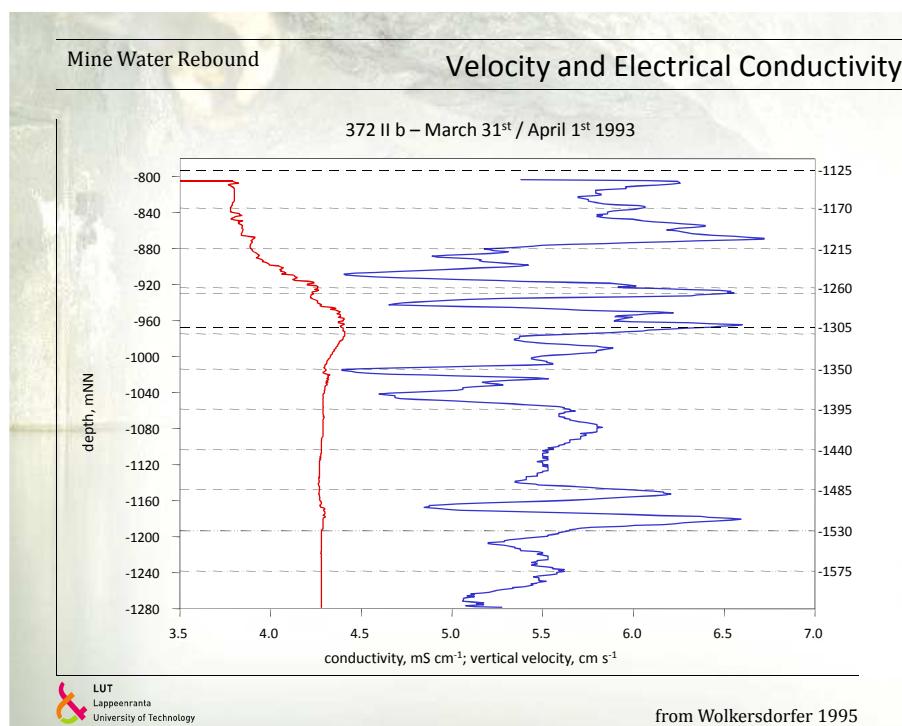
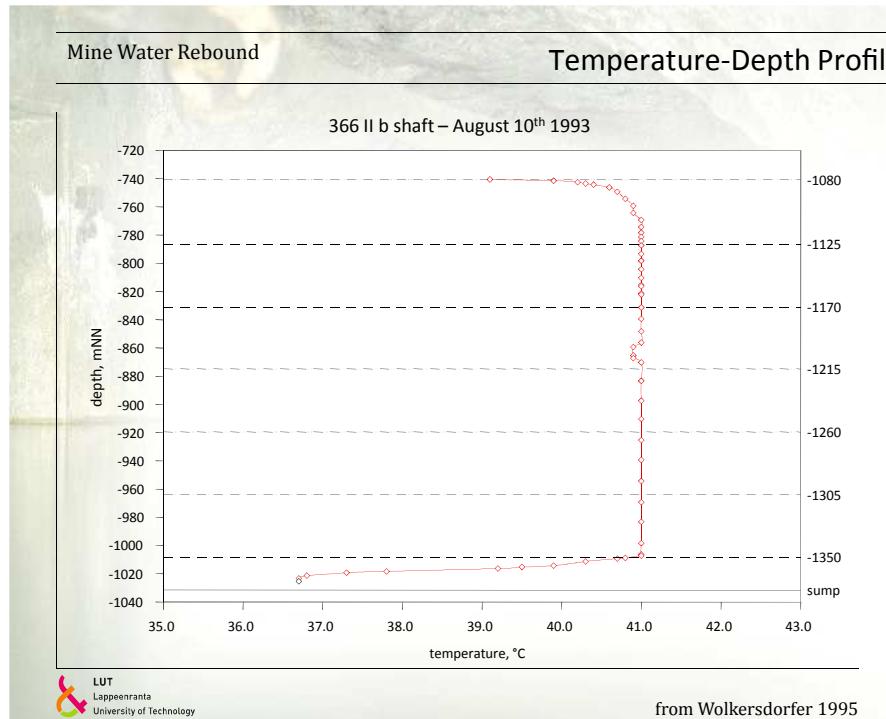


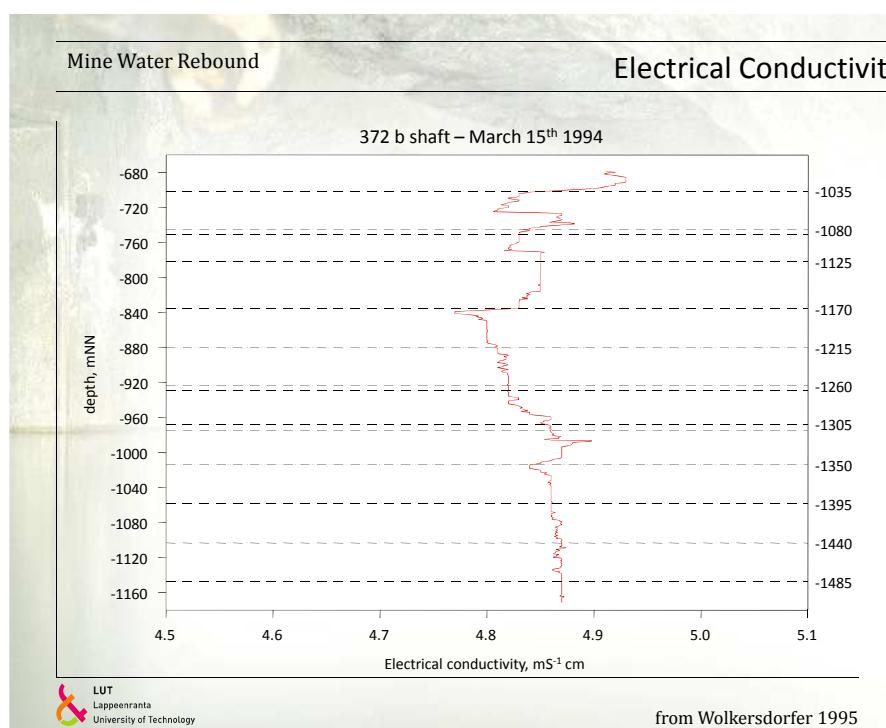
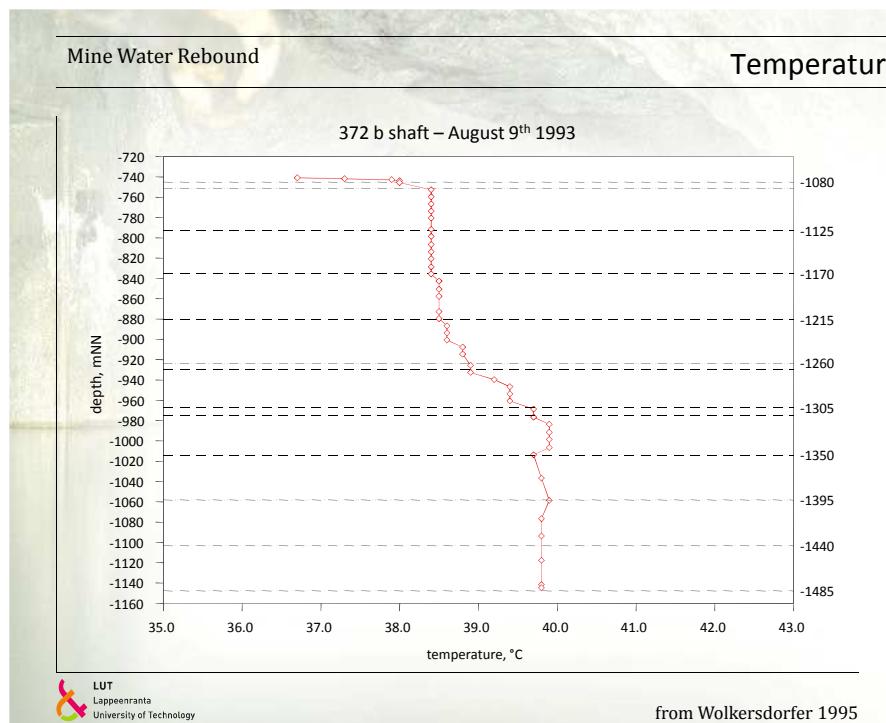
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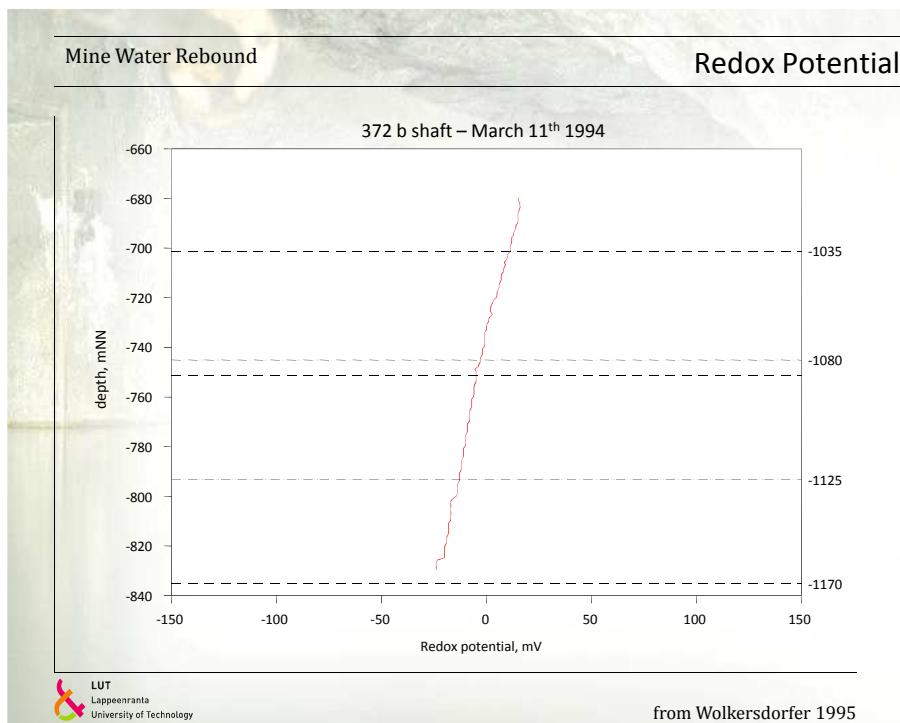
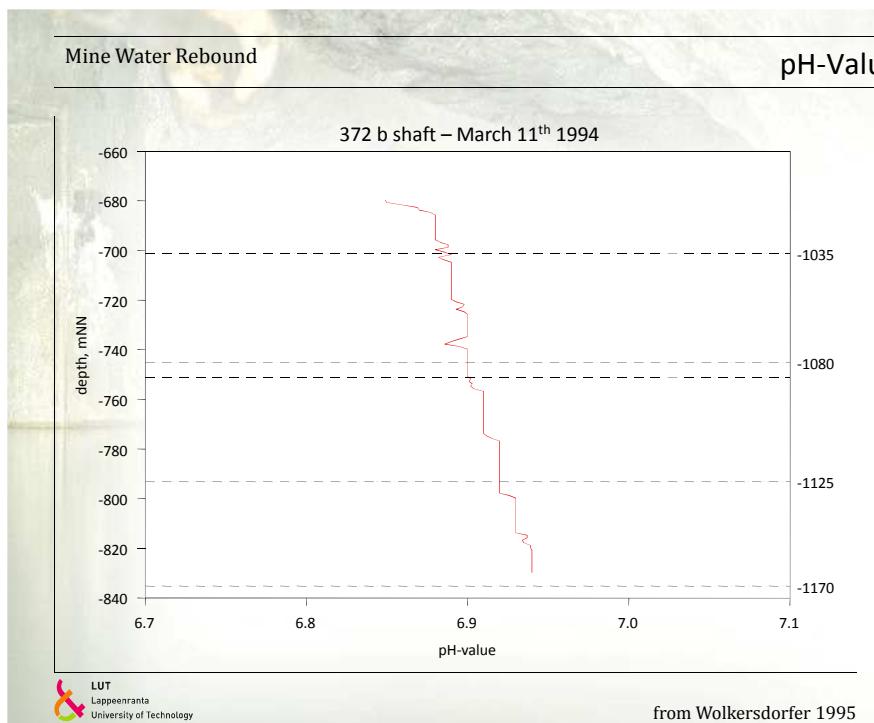
Mine Flooding

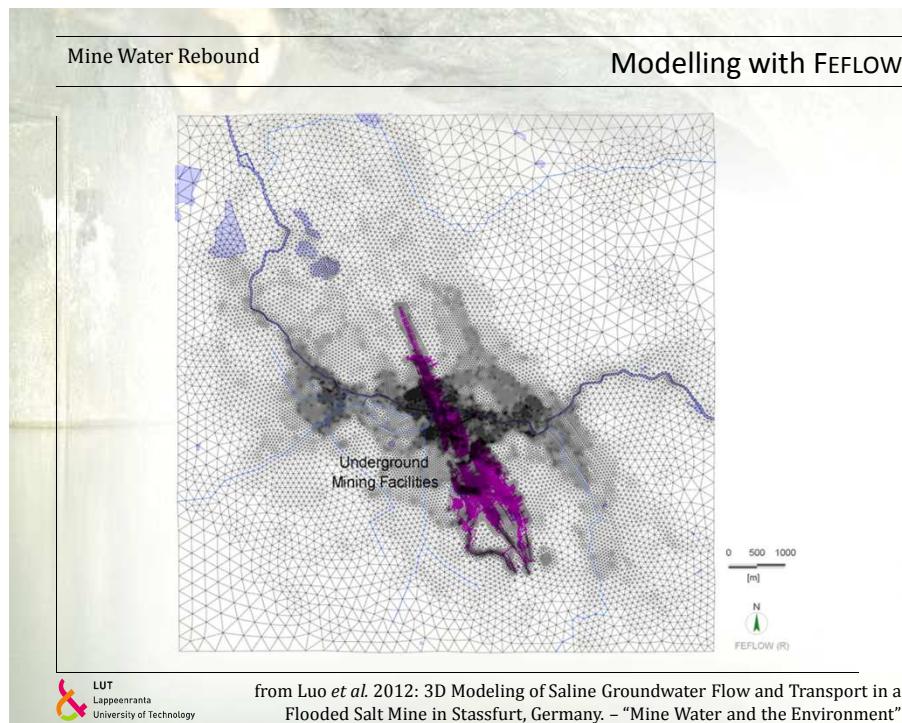
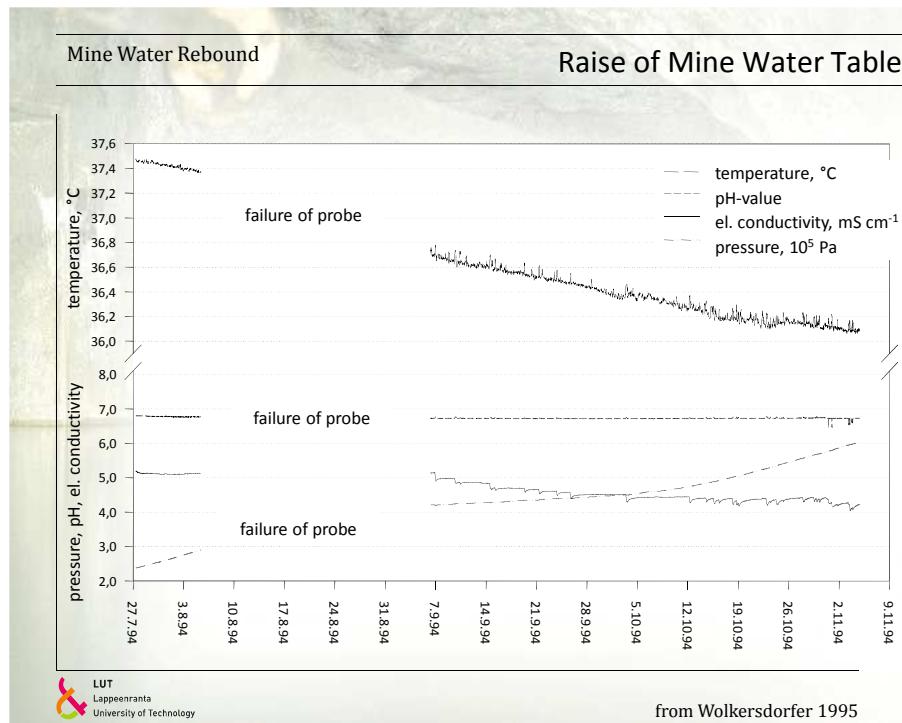


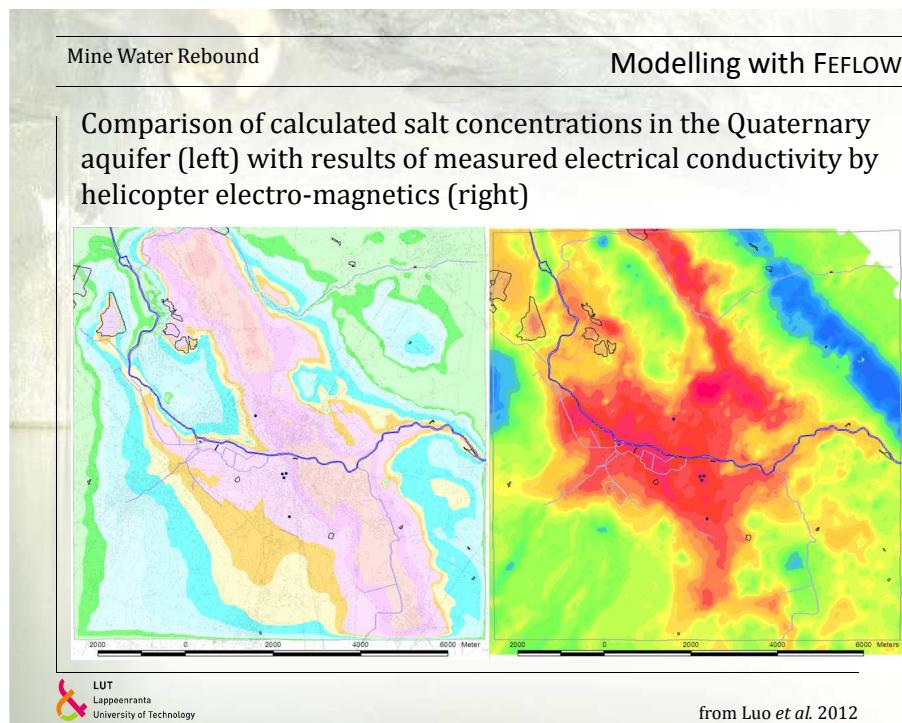
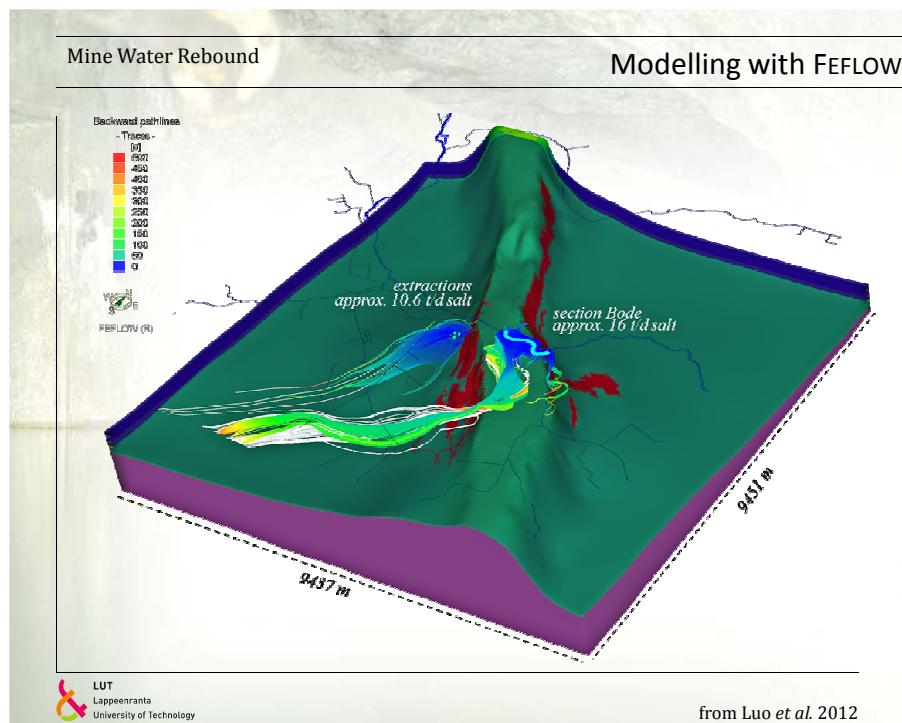








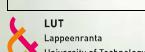




Mine Flooding	Legislation (e.g. Germany)
<ul style="list-style-type: none"> • Federal Mining Law (BBergG) <ul style="list-style-type: none"> – as of February 12th 1990 • Federal (WHG) and State Water Laws <ul style="list-style-type: none"> – as of November 12th 1996 – EU-Water Framework Directive • Environmental Acceptability Law (UVPG) <ul style="list-style-type: none"> – here: UVP-V Mining as of July 13th 1990 (EU: June 27th 1985) • Federal Administration Law (BVG) • Federal Immision Law (BImSchG) • State Planning Laws; State Coal Plans 	



Legislation	Federal Mining Law
<ul style="list-style-type: none"> • Types of operation companies: <ul style="list-style-type: none"> – Prospecting – Mining – Processing • Strategic working plan <ul style="list-style-type: none"> – does not include the right to start mining – simple (facultative), qualifying (compulsory) • Main working plan (2 years effective) • Special working plan • Common working plans • Closure plan 	

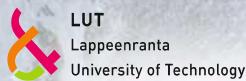


Legislation	Federal Mining Law
	<ul style="list-style-type: none">• <i>Strategic working plan</i>• Water authorities<ul style="list-style-type: none">– BBergG (facultative): hearing, participation Mining authorities not necessarily bound to recommendations– UVPG (qualified): participation Mining authorities are definitely bound to recommendations• <i>Main working plan</i>• Water authorities<ul style="list-style-type: none">– After corrections or clarifications of strategic working plan, water authorities have to be heard again



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Reinhardt, M. (1999): Bergrechtliche Determinanten wasserbehördlicher Entscheidungen. – In: Danwitz, T. v.: Bochumer Beiträge zum Berg- und Energierrecht 32. – S. 57–81; Stuttgart u.a. (Boorberg).



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Environmental Hydrogeology in Mining

Mine Water Geochemistry

Prof. Dr. Christian Wolkersdorfer (云村)

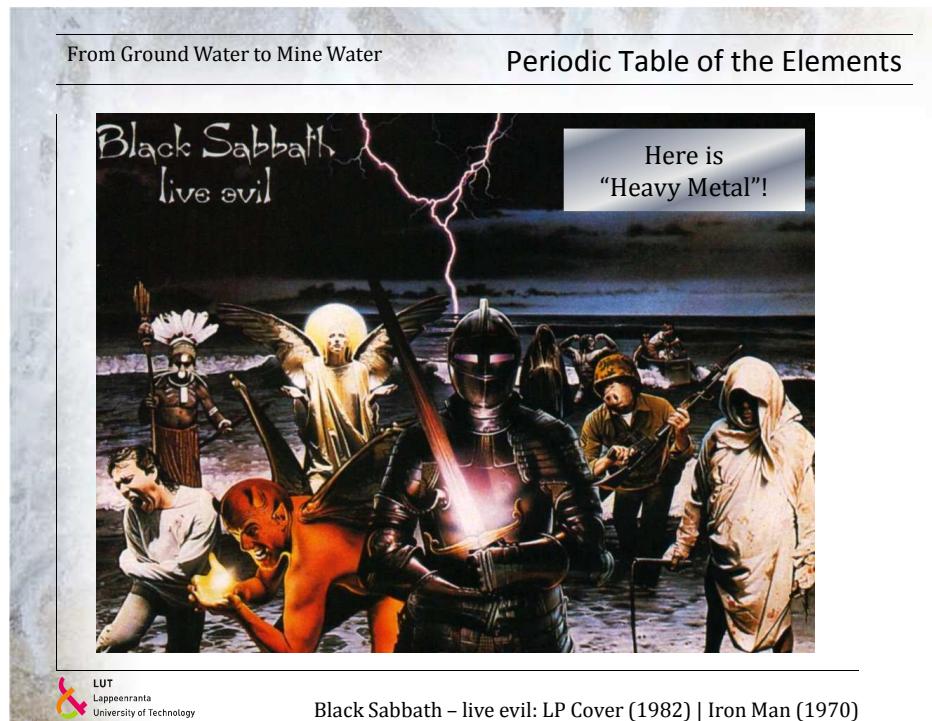
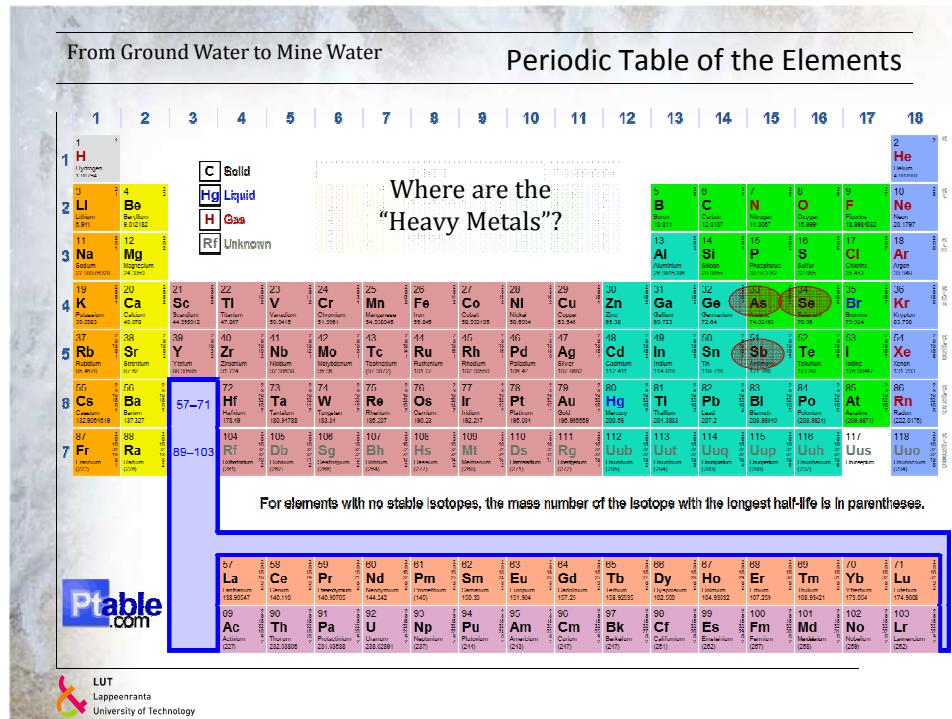
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Mine Water Geochemistry

Why to deal with mine water chemistry?



Cape Breton Island/Canada: Mine Water Outfall

Mine Water Geochemistry

Why to deal with mine water chemistry?



Eagle Picher Superfund Site/USA: Mark R. Boardman

Mine Water Geochemistry Why to deal with mine water chemistry?



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Former Königstein Uranium Mine / Saxony

Mine Water Geochemistry Why to deal with mine water chemistry?



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Pfunderer Berg/Southern Tyrol: Armin Hanneberg

Mine Water Geochemistry

Why to deal with mine water chemistry?



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Georgi Unterbau / Tyrol

Mine Water Geochemistry

Why to deal with mine water chemistry?



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Natural Acid Rock Drainage at Halifax Airport; Nova Scotia/Canada

Mine Water Geochemistry	Factors to be taken into Account
	<ul style="list-style-type: none">• Source — Pathway — Target-Concept• Type of mine water<ul style="list-style-type: none">- AMD: acid mine drainage ($< \approx \text{pH } 6$)- ND: neutral mine drainage ($> \approx \text{pH } 6$)- SD: saline mine drainage ($> \approx 1000 \text{ mgL}^{-1}$)• Pyrite weathering<ul style="list-style-type: none">- pH-dependence of metal dissolution• Natural attenuation of contaminants• Buffer reactions• Microbiological processes• Control of the source ("<i>in-situ</i>-methods")• Evaluation on a case-to-case basis: every site is unique



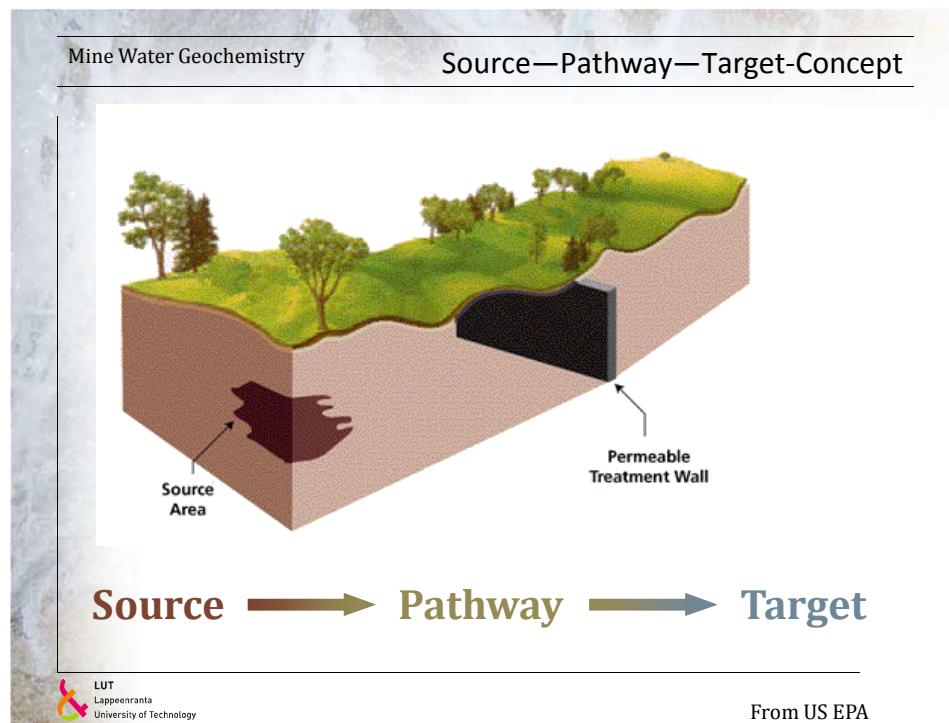
Mine Water Geochemistry	What affects Mobility and Bioavailability
	<ul style="list-style-type: none">• Speciation<ul style="list-style-type: none">- Hydrolyses, complexation- Solubility effects• Redox transformations<ul style="list-style-type: none">- e.g. $\text{U}^{4+} \rightarrow \text{U}^{6+} + 2 \text{ e}^-$• Sorption (Adsorption/Absorption)<ul style="list-style-type: none">- Especially onto iron hydroxide mineral- Silt, clay- Wood- Pore space

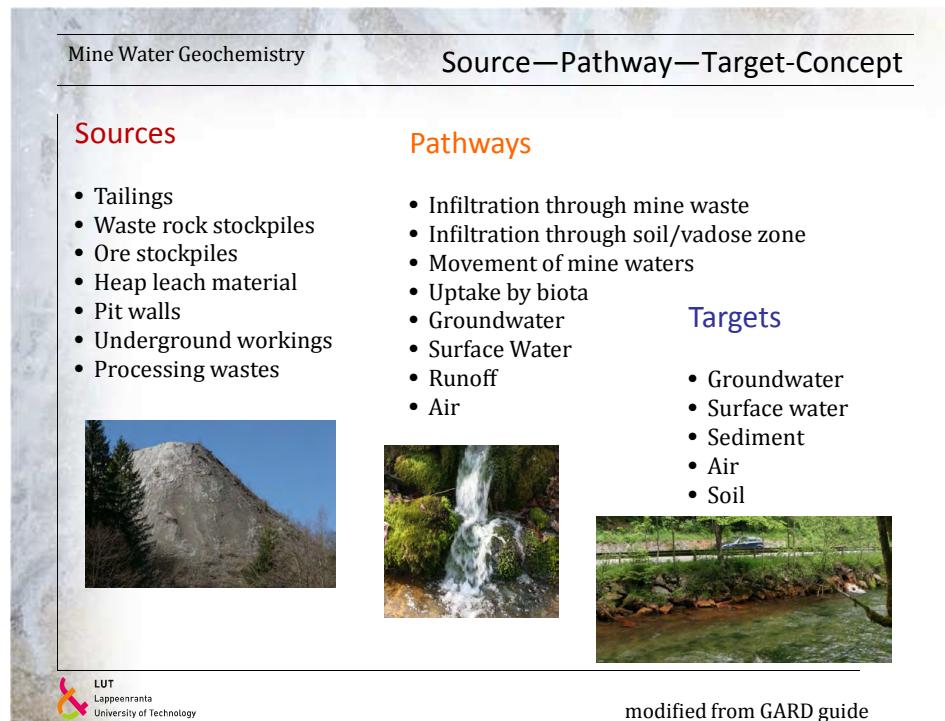


Mine Water Geochemistry Source—Pathway—Target-Concept

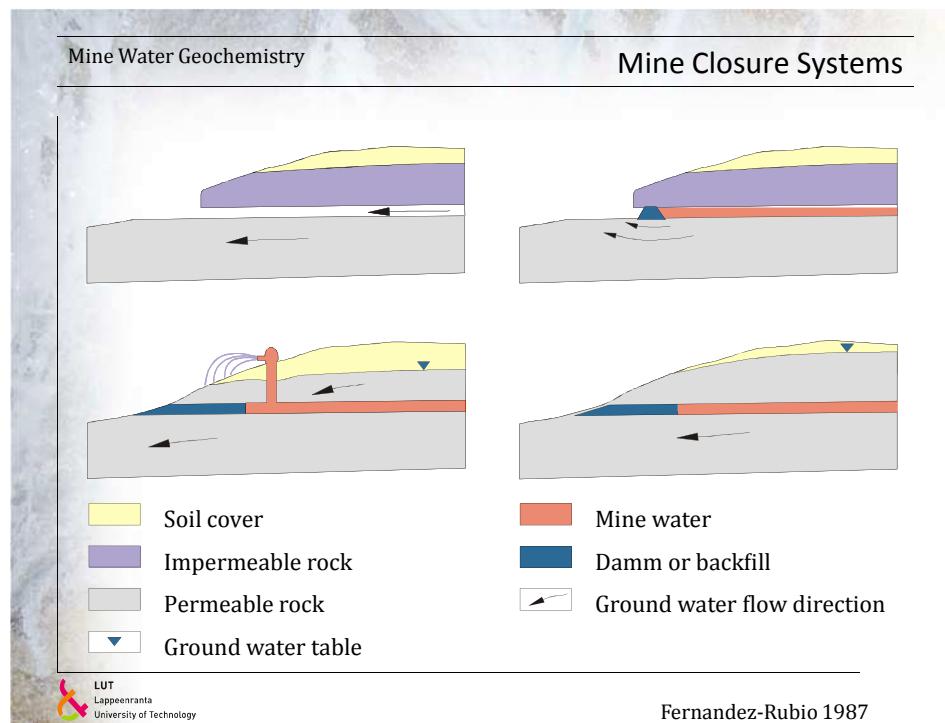
- Sources of contamination
 - Acidity: pyrite (“di-sulphide”) weathering
 - Metal ions: sulphide weathering
 - Chemical reactants (ore processing)
 - Organic substances (*e.g.* timber impregnation)
- Pathways
 - Alkalinity (calcite, aluminosilicate weathering)
 - Precipitation, sorption of metal ions
 - ochre precipitation
- “Targets”
 - Surface water
 - Ground water

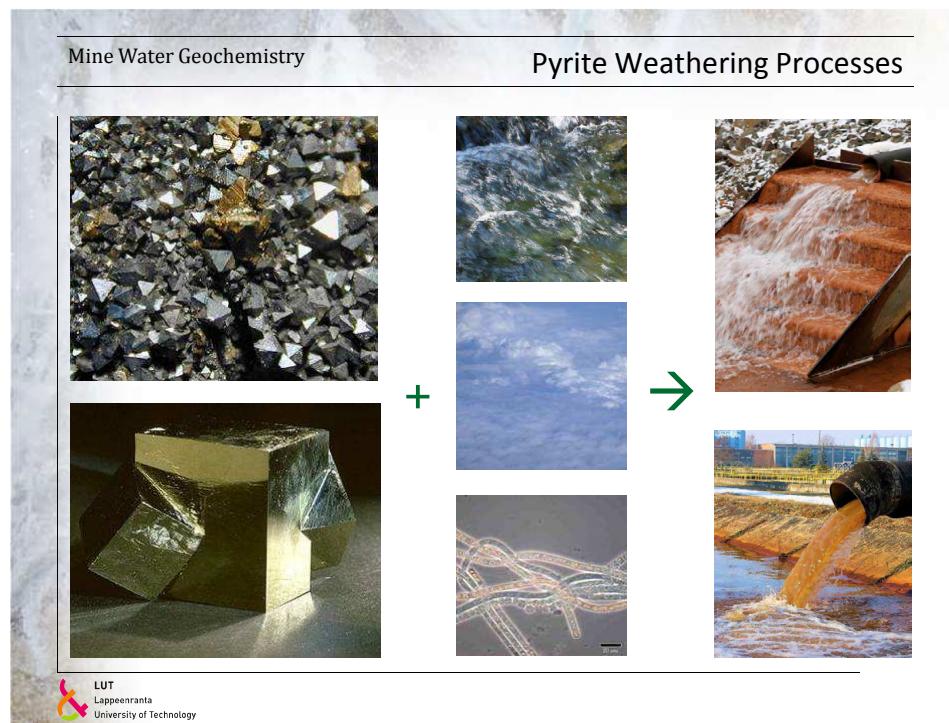
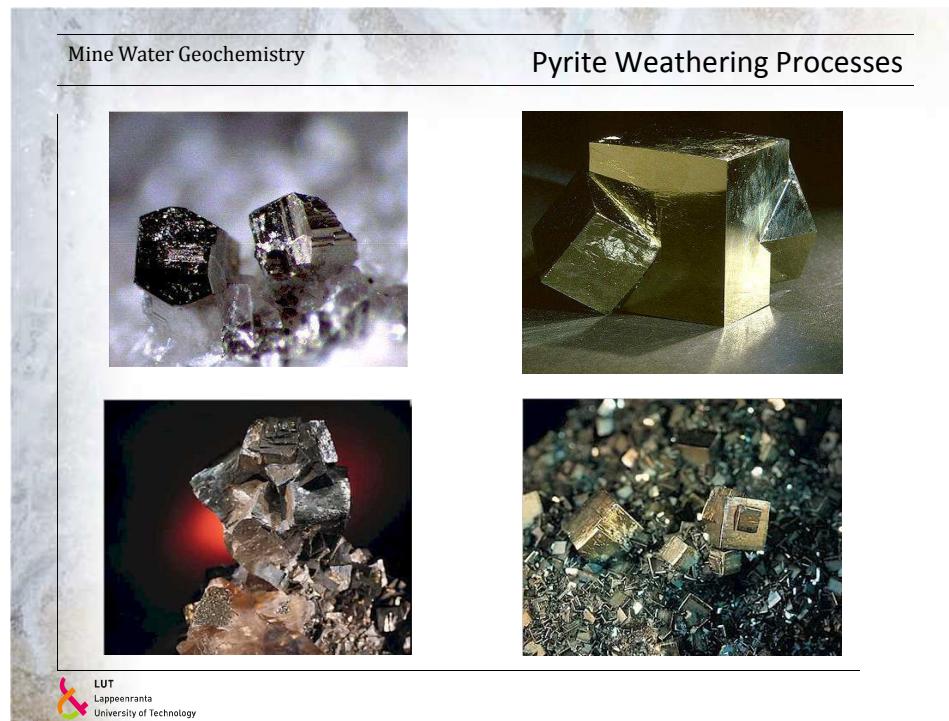
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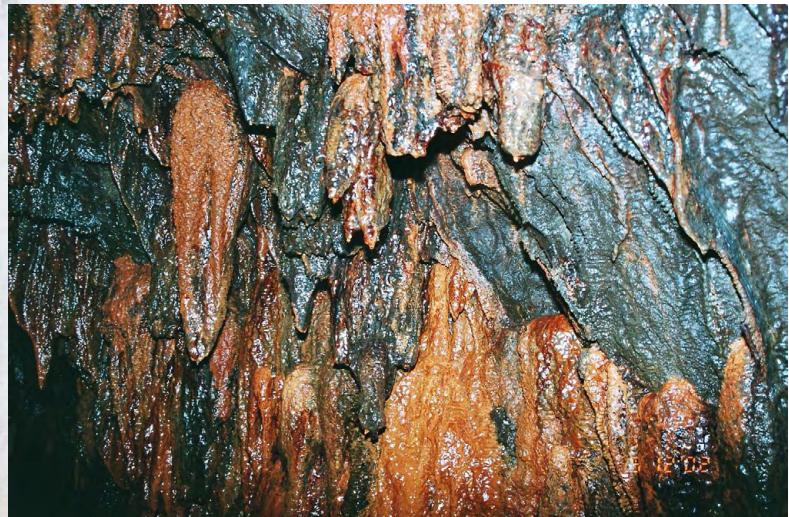


modified from GARD guide



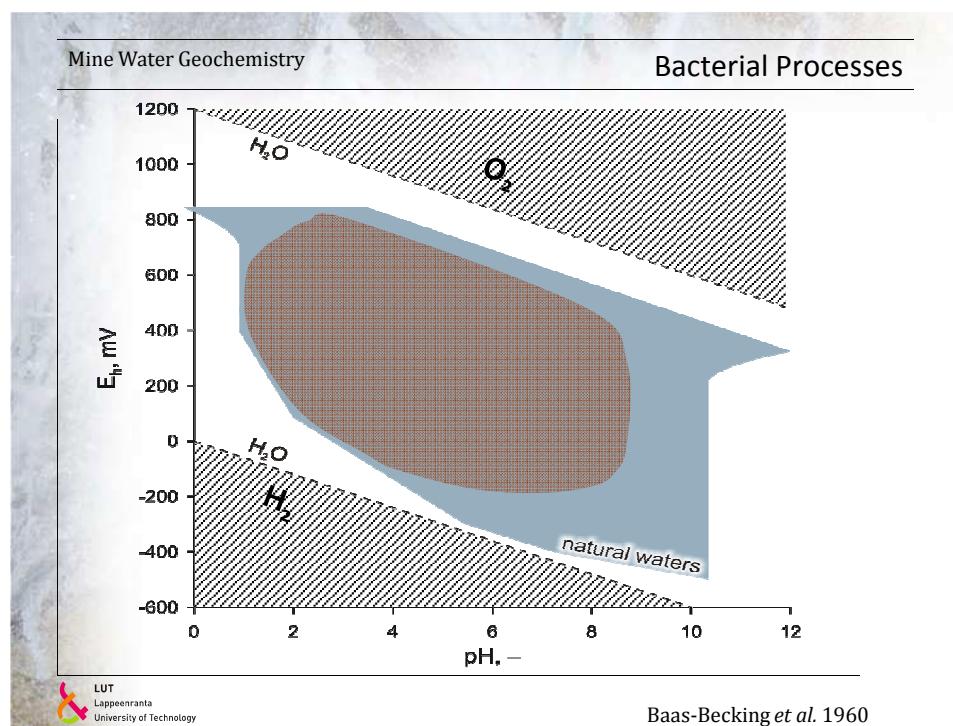


Mine Water Geochemistry	Pyrite Weathering Processes (½)
$(1) 2 \text{FeS}_2\text{(s)} + 7 \text{O}_{2\text{(aq)}} + 2 \text{H}_2\text{O} \rightarrow 2 \text{Fe}^{2+} + 4 \text{SO}_4^{2-} + 4 \text{H}^+$ $(2) 2 \text{Fe}^{2+} + \frac{1}{2} \text{O}_2 + 2 \text{H}^+ \rightarrow 2 \text{Fe}^{3+} + \text{H}_2\text{O}$ $(3) 2 \text{Fe}^{3+} + 6 \text{H}_2\text{O} \leftrightarrow 2 \text{Fe(OH)}_{3\text{(s)}} + 6 \text{H}^+$ $(4) 14 \text{Fe}^{3+} + \text{FeS}_2 + 8 \text{H}_2\text{O} \rightarrow 15 \text{Fe}^{2+} + 2 \text{SO}_4^{2-} + 16 \text{H}^+$ $(5) \text{Fe}^{2+} \text{ further reacts in reactions 2—4}$ <p>(1) and (2) are catalysed by bacteria: <i>e.g.</i> <i>Acidithiobacillus thiooxidans, Gallionella</i></p>	

Mine Water Geochemistry	Pyrite Weathering Processes (½)
	

Mine Water Geochemistry	Bacterial Processes	
<i>Acidithiobacillus thiooxidans, Gallionella, Beggiatoa and Thiothrix</i> increase the reaction speed 10 ⁶ -fold		
$\text{ADP} + \text{P}^- \leftrightarrow \text{ATP}$	$\Delta G^\circ = +32 \text{ kJ}$	
$2 \text{ S}^{2-} + 4 \text{ H}_3\text{O}^+ + \text{O}_2 \leftrightarrow 2 \text{ S} + 6 \text{ H}_2\text{O}$		
$2 \text{ S} + 6 \text{ H}_2\text{O} + 3 \text{ O}_2 \leftrightarrow 2 \text{ SO}_4^{2-} + 4 \text{ H}_3\text{O}^+$	$\Delta G^\circ = -498 \text{ kJ}$	
		
	pH-range Eh-range, mV	
Sulfate reducing	4.2 ... 9.9	- 450 ... + 115
Thiobacteria	1.0 ... 9.2	- 190 ... + 855
Niederschlema	6.4 ... 8.9	+ 3 ... + 530

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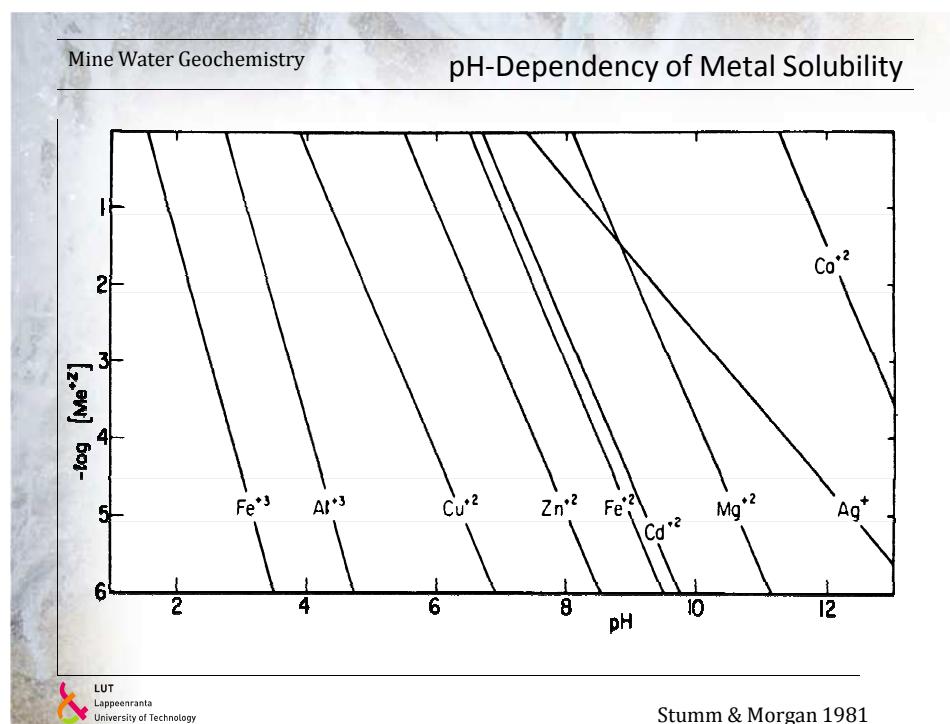
Mine Water Geochemistry	Sulphide Weathering
sphalerite	$\text{ZnS}_{(s)} + 2 \text{O}_{2(\text{aq})} \rightarrow \text{Zn}^{2+} + \text{SO}_4^{2-}$
galena	$\text{PbS}_{(s)} + 2 \text{O}_{2(\text{aq})} \rightarrow \text{Pb}^{2+} + \text{SO}_4^{2-}$
millerite	$\text{NiS}_{(s)} + 2 \text{O}_{2(\text{aq})} \rightarrow \text{Ni}^{2+} + \text{SO}_4^{2-}$
greenockite	$\text{CdS}_{(s)} + 2 \text{O}_{2(\text{aq})} \rightarrow \text{Cd}^{2+} + \text{SO}_4^{2-}$
covellin	$\text{CuS}_{(s)} + 2 \text{O}_{2(\text{aq})} \rightarrow \text{Cu}^{2+} + \text{SO}_4^{2-}$
copper pyrite	$\text{CuFeS}_{(s)} + 4 \text{O}_{2(\text{aq})} \rightarrow \text{Cu}^{2+} + \text{Fe}^{2+} + 2 \text{SO}_4^{2-}$
<ul style="list-style-type: none"> Release of potentially toxic metals and sulphate, but no acidity (except copper pyrite) 	

Mine Water Geochemistry	Mineral weathering
<ul style="list-style-type: none"> Depending on the pH-value, different metals coexist (“species”) pH-value controls the release of contaminants (“master variable”) At low pH-values the metal solubility, usually, is high Mobility and bioavailability at low pH-values is usually high 	

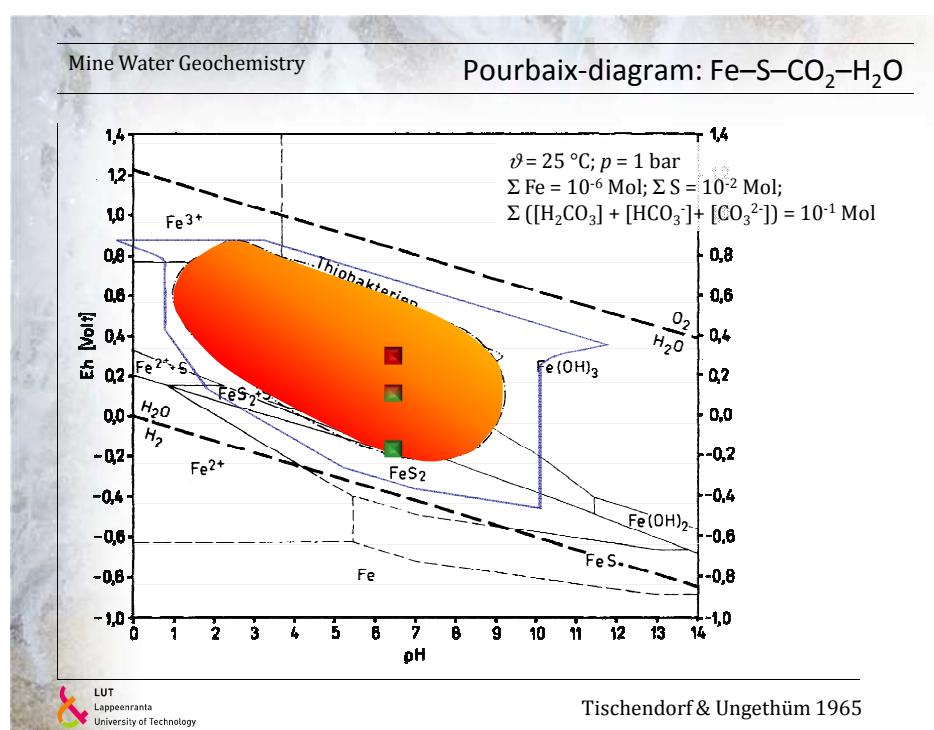
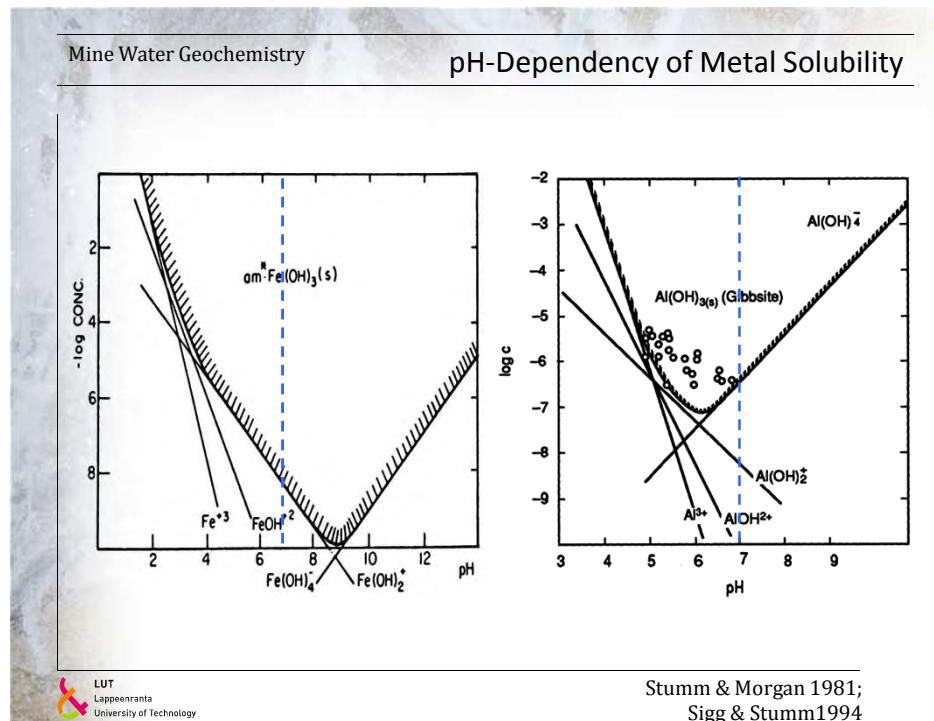
Mine Water Geochemistry		pH-Values and Metal Concentrations					
locality	pH	[SO ₄ ²⁻]	[Fe]	[Al]	[Mn]	[Zn]	[Cu]
Iron Mountain, Cal (copper)	0.4	108000	18600	2320		2060	290
Iron Mountain, Cal (copper)	1.1	41000	7820	1410	11	1860	360
Pyrite mine	2.5	5110	1460	84	3	1	0.2
abandoned coal mine	3.6	1044	101	17	4	0.2	0.007
abandoned coal mine	4.2	1554	180	< 0.5	6	0.06	
waste rock dump (coal)	5.5	146	287	1	5	0.05	< 0.007
Straßberg Germany	6.3	359	31		6	0.9	0.08
abandoned coal mine	6.3	210	11	< 0.05	2	< 0.007	
abandoned coal mine	6.3	83	5	0.08	0.4	0.05	0.005
metal mine	6.5	124	15	0.1	2	0.003	
Niederschlema Germany	7.1	1138	3	0.4	3	0.1	0.03
mine water (coal)	8.2	7	< 0.01	< 0.02	0.004	0.055	< 0.005

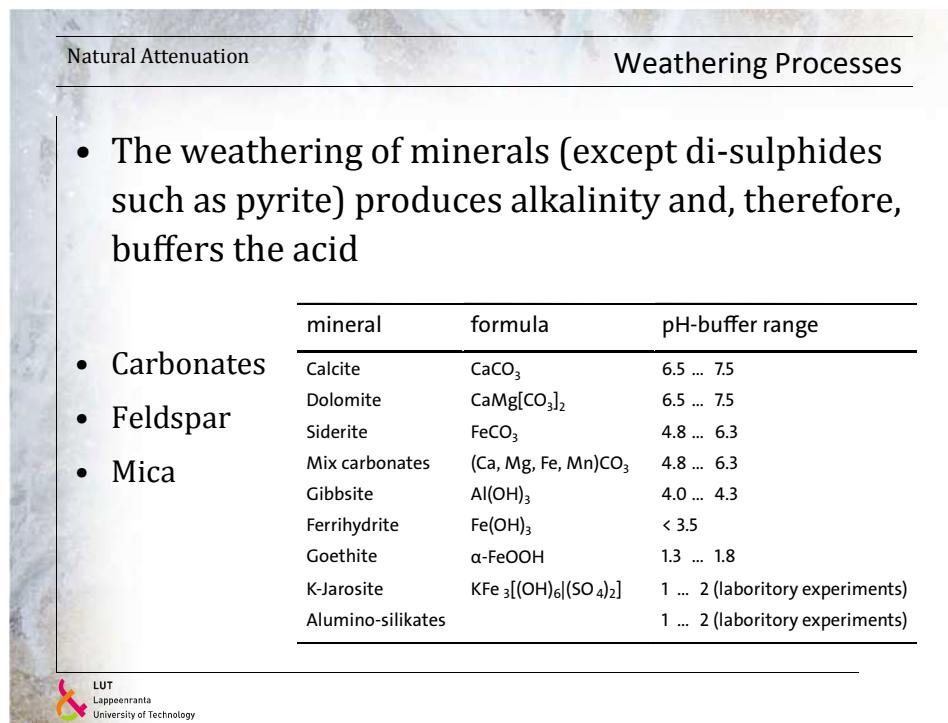
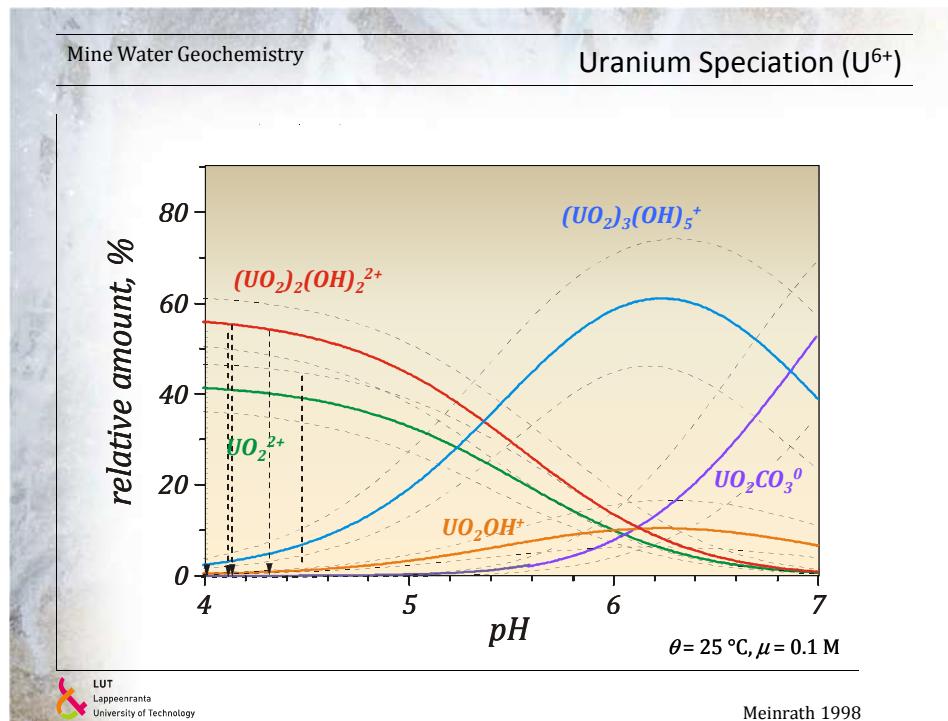
concentrations in mg L⁻¹

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Natural Attenuation	Weathering Processes
	<ul style="list-style-type: none"> • <i>Carbonates</i> • Calcite (buffers at pH 6.5...7.5) <ul style="list-style-type: none"> – $\text{CaCO}_3 + \textcolor{red}{H}^+ \leftrightarrow \text{Ca}^{2+} + \text{HCO}_3^-$ • Dolomite (buffers at pH 6.5...7.5) <ul style="list-style-type: none"> – $\text{CaMg}[\text{CO}_3]_2 + 2 \textcolor{red}{H}^+ \leftrightarrow \text{Ca}^{2+} + \text{Mg}^{2+} + 2 \text{HCO}_3^-$ • Siderite (buffers at pH 4.8 ...6.3) <ul style="list-style-type: none"> – $\text{FeCO}_3 + \textcolor{red}{H}^+ \leftrightarrow \text{Fe}^{2+} + \text{HCO}_3^-$ – $\text{Fe}^{2+} + \frac{1}{4} \text{O}_2 + \frac{5}{2} \text{H}_2\text{O} \rightarrow \text{Fe(OH)}_3 + 2 \textcolor{red}{H}^+$

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Natural Attenuation	Weathering Processes
	<ul style="list-style-type: none"> • <i>Feldspar</i> • K-Feldspar $\text{KAlSi}_3\text{O}_8 + \textcolor{red}{H}^+ + \frac{9}{2} \text{H}_2\text{O} \rightarrow 2 \text{H}_4[\text{SiO}_4] + \frac{1}{2} \text{Al}_2\text{Si}_2\text{O}_5(\text{OH})_4$ • Anorthite $\text{CaAl}_2\text{Si}_2\text{O}_8 + \textcolor{red}{H}^+ + \text{H}_2\text{O} \rightarrow \text{Ca}^{2+} + 2 \text{H}_4[\text{SiO}_4] + \frac{1}{2} \text{Al}_2\text{Si}_2\text{O}_5(\text{OH})_4$ • Albite $\text{NaAlSi}_3\text{O}_8 + \textcolor{red}{H}^+ + \frac{9}{2} \text{H}_2\text{O} \rightarrow \text{Na}^+ + 2 \text{H}_4[\text{SiO}_4] + \frac{1}{2} \text{Al}_2\text{Si}_2\text{O}_5(\text{OH})_4$

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Natural Attenuation	Weathering Processes
<ul style="list-style-type: none"> • <i>Mica</i> • Biotite $\text{KMg}_{3/2}\text{Fe}_{3/2}[\text{AlSi}_3\text{O}_{10}](\text{OH})_2 + 7 \textcolor{red}{H}^+ + \frac{1}{2} \text{H}_2\text{O} \rightarrow \text{K}^+ + \frac{3}{2} \text{Mg}^{2+} + \frac{3}{2} \text{Fe}^{2+} + 2 \text{H}_4[\text{SiO}_4] + \frac{1}{2} \text{Al}_2\text{Si}_2\text{O}_5(\text{OH})_4$	
<ul style="list-style-type: none"> • Muscovite $\text{KAl}_2[\text{AlSi}_3\text{O}_{10}](\text{OH})_2 + \textcolor{red}{H}^+ + \frac{3}{2} \text{H}_2\text{O} \rightarrow \text{K}^+ + \frac{3}{2} \text{Al}_2\text{Si}_2\text{O}_5(\text{OH})_4$	

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Natural Attenuation	Keep in Mind: Mineralogy and Kinetics
	<ul style="list-style-type: none"> • Disulphides are abundant in nearly all rocks as trace minerals • Other minerals, for example silicates, are far more abundant • Pyrite weathers more rapidly than silicates and therefore causes acid mine water (AMD) • Already small amounts of di-sulphide cause severe problems due to different weathering kinetics of the minerals

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Immobilisation of Metals	Secondary Minerals (½)
• Metal oxides and -hydroxides	
Gibbsite $\text{Al}(\text{OH})_3$	
Iron hydroxide $\text{Fe}(\text{OH})_3$	
Zinc hydroxide $\text{Zn}(\text{OH})_2$	
• Metal carbonates and hydroxy-carbonates	
Cerrusite PbCO_3	
Malachite $\text{Cu}_2(\text{OH})_2(\text{CO}_3)_2$	

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Immobilisation of Metals	Secondary Minerals (½)
• Metal sulphates and -hydroxy-sulphates	
Jarosite $\text{KFe}_3(\text{SO}_4)_2(\text{OH})_6$	
Melanterite $\text{FeSO}_4 \cdot 7\text{H}_2\text{O}$	
Szomolnokite $\text{FeSO}_4 \cdot \text{H}_2\text{O}$	
Epsomite $\text{MgSO}_4 \cdot 7\text{H}_2\text{O}$	
Alunite $\text{KAl}_3(\text{SO}_4)_2(\text{OH})_6$	
Jurbanite $\text{AlSO}_4(\text{OH}) \cdot 5\text{H}_2\text{O}$	
Basaluminite $\text{Al}_4\text{SO}_4(\text{OH})_{10} \cdot 5\text{H}_2\text{O}$	
Anglesite PbSO_4	

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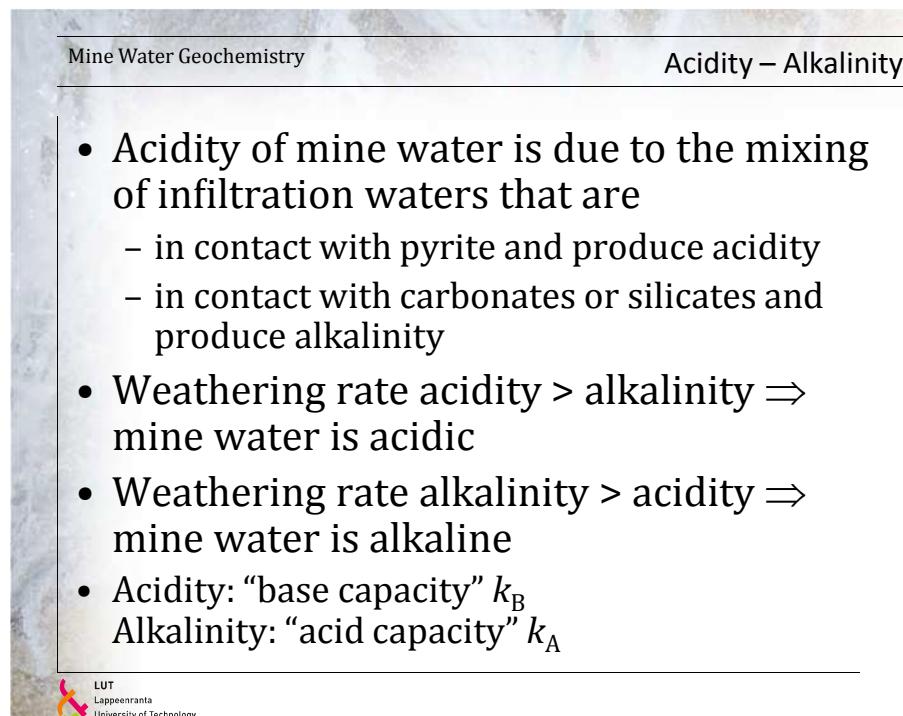
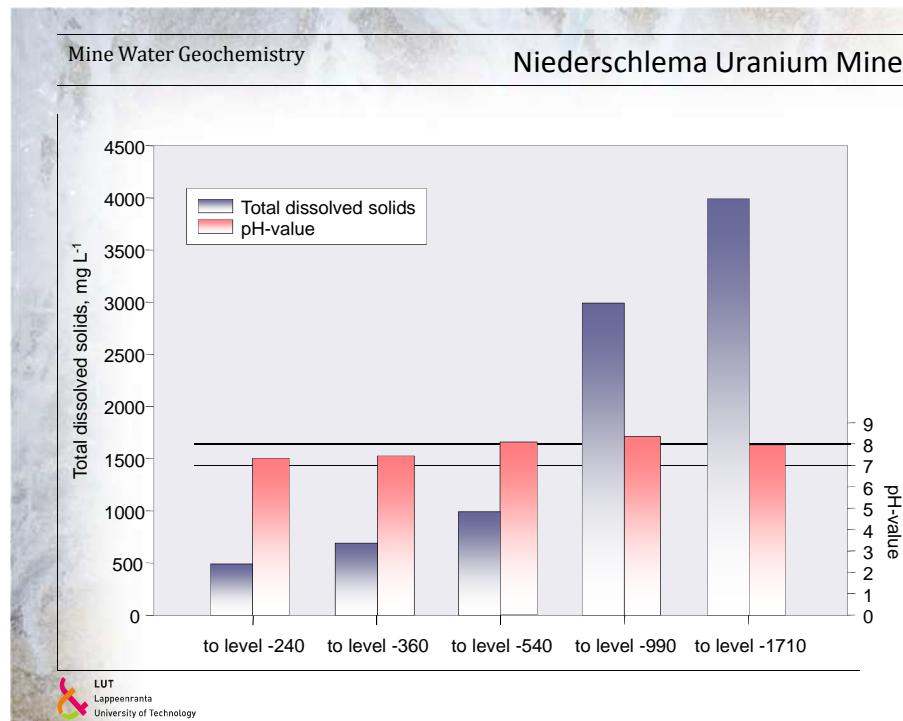
Alpers; Graeme

Mine Water Geochemistry	Control of Contamination Source
<ul style="list-style-type: none"> • Contaminant load (<i>e.g.</i> metals, acidity, sulphate) depends on: <ul style="list-style-type: none"> – Red-Ox conditions (does O₂ exist) – Weathering rate – Oxygen transport (diffusion) – Dissolving (transport: remain in mine or transport to ecosphere) – Bacteria 	

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Mine Water Geochemistry	First Estimation
<p>Metal loads released from a mine (or dump) reflect the weathering reactions involved</p> <p>Q_{in} (Infiltration):</p> <div style="background-color: #e6f2ff; padding: 10px;"> $\text{FeS}_2 + \frac{7}{2} \text{O}_2 + \text{H}_2\text{O} \rightarrow \text{Fe}^{2+} + 2 \text{SO}_4^{2-} + 2 \text{H}^+$ $\text{ZnS} + 2 \text{O}_2 \rightarrow \text{Zn}^{2+} + \text{SO}_4^{2-}$ $\text{PbS} + 2 \text{O}_2 \rightarrow \text{Pb}^{2+} + \text{SO}_4^{2-}$ $\text{NiS} + 2 \text{O}_2 \rightarrow \text{Ni}^{2+} + \text{SO}_4^{2-}$ $\text{CuS} + 2 \text{O}_2 \rightarrow \text{Cu}^{2+} + \text{SO}_4^{2-}$ $\text{CuFeS}_2 + 2 \text{O}_2 \rightarrow \text{Cu}^{2+} + \text{Fe}^{2+} + 2 \text{SO}_4^{2-}$ </div> <p>Q_{out} (mine water):</p> $\text{H}^+, \text{SO}_4^{2-}, \text{Fe}^{2+}, \text{Zn}^{2+}, \text{Pb}^{2+}, \text{Ni}^{2+}, \text{Cu}^{2+}$	

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Mine Water Geochemistry Acidity – Alkalinity

- Acidic waters have a pH-value < 5.6
- Alkaline waters have a pH-value > 5.6
 - boundary is due to the end point of carbon acid titration (use of buffer capacity)
- Acidic waters mobilize metal ions in a greater extend than alkaline ones
- Neutralisation of acidity also demobilizes metal loads (attenuation of metal contamination: *Natural Attenuation*)

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Mine Water Geochemistry Acidity – Alkalinity

- Relationship between alkalinity and acidity is of complex nature and results mainly from interplay of
 - Strong acids and bases
 - Weak acids and corresponding bases
 - Thermodynamic laws (mass action law, conservation of matter)
 - Mass and charge balance in aquatic systems
 - pH-value (“master variable”)
- Microorganisms *speed up* chemical reactions, but they never enable reactions that are thermodynamical impossible!
- Alkalinity: excess of strong base over strong acid in a natural water

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Acidity – Alkalinity	Strong Acids and Bases
	<ul style="list-style-type: none"> • Complete dissociation • Strong bases (base cation + OH⁻) <ul style="list-style-type: none"> - NaOH \leftrightarrow Na⁺ + OH⁻ - Mg(OH)₂ \leftrightarrow Mg²⁺ + 2 OH⁻ • Strong acids (acid anion + H⁺) <ul style="list-style-type: none"> - HCl \leftrightarrow Cl⁻ + H⁺ - H₂SO₄ \leftrightarrow SO₄²⁻ + 2 H⁺ • [Aci] = “Σ [H⁺] - Σ [OH⁻]” = 2 [SO₄²⁻] + [Cl⁻] - [Na⁺] - 2 [Mg²⁺] • [Alk] = -[Aci] = [Na⁺] + 2 [Mg²⁺] - 2 [SO₄²⁻] - [Cl⁻] • [Aci]_{calculated} = 2 [Fe²⁺]/56 + 3 [Fe³⁺]/56 + 3 [Al]/27 + 2 [Mn]/55 + 2 [Zn]/65 + 1000 (10^{-pH}), mol L⁻¹

Acidity – Alkalinity	Weak Acids and Bases								
	<ul style="list-style-type: none"> • Carbon acid is a weak acid resulting from the dissolution of CO₂ in water • Stepwise dissociation • Partly protonated, partly deprotonated species: <table style="width: 100%; border-collapse: collapse;"> <tr> <td style="width: 40%;">– CO₂ (g) + H₂O \leftrightarrow H₂CO₃</td> <td style="width: 60%; text-align: right;">$\log K_H = -1.27$</td> </tr> <tr> <td>– H₂CO₃ \leftrightarrow HCO₃⁻ + H⁺</td> <td style="text-align: right;">$\log K_1 = -6.35$</td> </tr> <tr> <td>– HCO₃⁻ \leftrightarrow CO₃²⁻ + H⁺</td> <td style="text-align: right;">$\log K_2 = -10.3$</td> </tr> <tr> <td>– H₂O \leftrightarrow H⁺ + OH⁻</td> <td style="text-align: right;">$\log K_W = -14.0$</td> </tr> </table> <p style="text-align: center;">for all K: $\vartheta = 25^\circ\text{C}$; $I = 0 \text{ mol}$</p> • at pH 5.6 [HCO₃⁻] significantly increases (\nearrow titration curve) 	– CO ₂ (g) + H ₂ O \leftrightarrow H ₂ CO ₃	$\log K_H = -1.27$	– H ₂ CO ₃ \leftrightarrow HCO ₃ ⁻ + H ⁺	$\log K_1 = -6.35$	– HCO ₃ ⁻ \leftrightarrow CO ₃ ²⁻ + H ⁺	$\log K_2 = -10.3$	– H ₂ O \leftrightarrow H ⁺ + OH ⁻	$\log K_W = -14.0$
– CO ₂ (g) + H ₂ O \leftrightarrow H ₂ CO ₃	$\log K_H = -1.27$								
– H ₂ CO ₃ \leftrightarrow HCO ₃ ⁻ + H ⁺	$\log K_1 = -6.35$								
– HCO ₃ ⁻ \leftrightarrow CO ₃ ²⁻ + H ⁺	$\log K_2 = -10.3$								
– H ₂ O \leftrightarrow H ⁺ + OH ⁻	$\log K_W = -14.0$								

Acidity – Alkalinity

Thermodynamic Laws

- Carbon acid balance (mass action law)

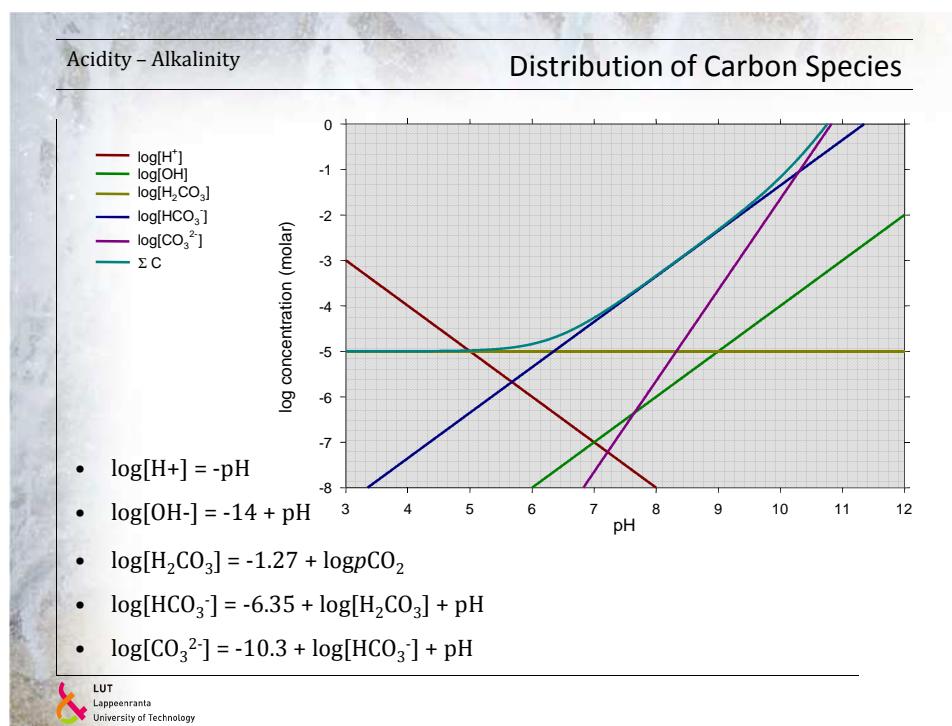
$$K_H = 10^{-1.27} = \frac{[\text{H}_2\text{CO}_3]}{[\text{H}_2\text{O}] p\text{CO}_2(g)} \quad (\vartheta = 25^\circ\text{C}; I = 0 \text{ mol}; p\text{CO}_2 = 10^{-3.5} \text{ atm})$$

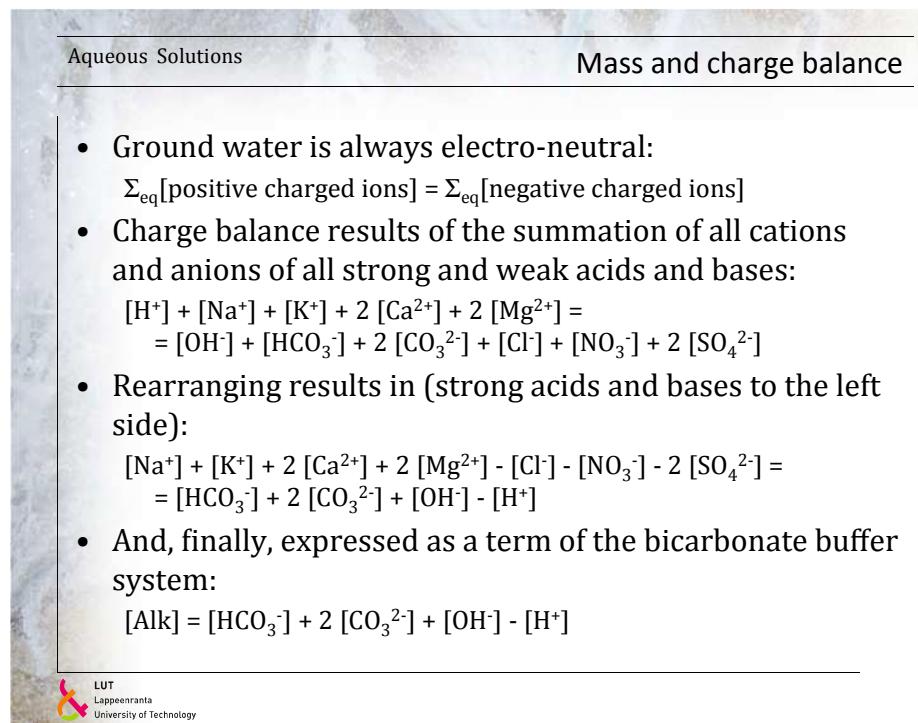
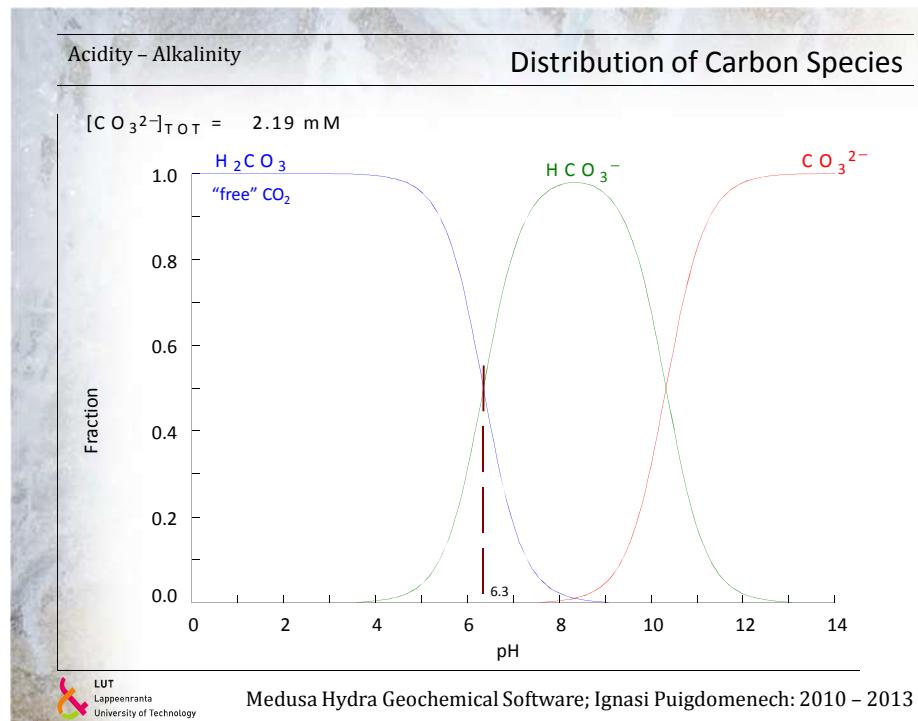
$$K_1 = 10^{-6.35} = \frac{[\text{HCO}_3^-][\text{H}^+]}{[\text{H}_2\text{CO}_3]} \quad (\vartheta = 25^\circ\text{C}; I = 0 \text{ mol})$$

$$K_2 = 10^{-10.3} = \frac{[\text{CO}_3^{2-}][\text{H}^+]}{[\text{HCO}_3^-]} \quad (\vartheta = 25^\circ\text{C}; I = 0 \text{ mol})$$

$$K_W = 10^{-14} = [\text{H}^+][\text{OH}^-] \quad (\vartheta = 25^\circ\text{C}; I = 0 \text{ mol})$$

CO_2
 (gaseos)
 $\uparrow\downarrow$
 $\text{CO}_2 + \text{H}_2\text{O} \leftrightarrow \text{H}_2\text{CO}_3 \leftrightarrow \text{H}^+ + \text{HCO}_3^-$
 (aqueous)





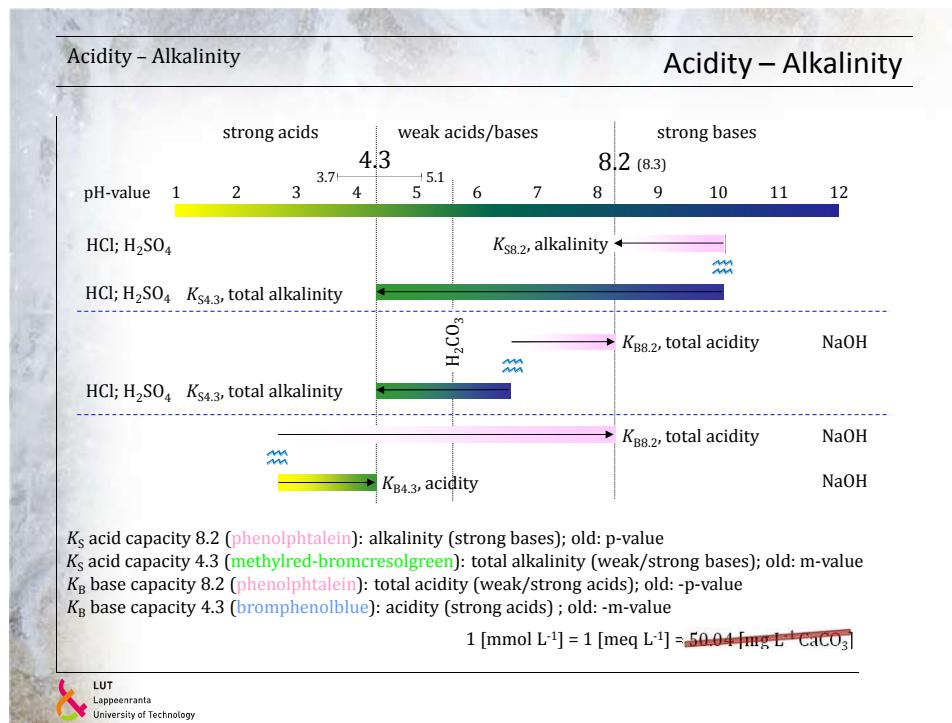
Acidity – Alkalinity	Bicarbonate Buffer System
<ul style="list-style-type: none"> Alkalinity in relation to the bicarbonate buffer system: $[\text{Alk}] = [\text{HCO}_3^-] + 2 [\text{CO}_3^{2-}] + [\text{OH}^-] - [\text{H}^+]$ Conservation of matter for HCO_3^-, CO_3^{2-}, OH^- results in a relation between alkalinity and pH-value: $[\text{Alk}] = \frac{p\text{CO}_2(\text{g}) K_1}{[\text{H}^+]} + \frac{[\text{HCO}_3^-] K_2}{[\text{H}^+]} + \frac{K_w}{[\text{H}^+]} - [\text{H}^+]$ for $6 < \text{pH} < 9$ the following simplification applies $[\text{CO}_3^{2-}], [\text{OH}^-], [\text{H}^+] \ll [\text{HCO}_3^-]$ consequently: $[\text{Alk}] = [\text{HCO}_3^-]$ for most <i>natural waters</i> 	

Acidity – Alkalinity	Relation to the pH-value
<ul style="list-style-type: none"> Within certain pH ranges, the relation between alkalinity and pH-value can be simplified. In the case of acidic mine waters the following simplification can be applied to: $[\text{Alk}] \approx \frac{[\text{H}_2\text{CO}_3] K_1}{[\text{H}^+]} - [\text{H}^+] \text{ mol L}^{-1} \quad (\text{pH} < 8.3)$ solving the equation for $[\text{H}^+]$: $[\text{H}^+] = \frac{-[\text{Alk}] + \sqrt{[\text{Alk}]^2 + 4 [\text{H}_2\text{CO}_3] K_1}}{2}$	

Acidity – Alkalinity

- Water usually between pH 7 and 8
- Within broad pH-ranges water is of good quality and consequently good bioactivity
- Acidic water consumes alkalinity and results in low pH-values
- Under acidic conditions, that means at pH < 5.6, the pH-decreases rapidly and metals will dissolve
- High mobility and bioavailability

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Acidity - Alkalinity

Mixing of Mine and Surface Waters

The mixing of mine water with ground or surface water is conservative, because cations and anions won't interact with each other (no chemical interactions):

$$[\text{Alk}]_M = \frac{V_M(-[\text{Aci}]_M) + V_R[\text{Alk}]_R}{V_M + V_R}$$

V_M : quantity of mine water, $\text{m}^3 \text{ s}^{-1}$

V_R : quantity of surface water, $\text{m}^3 \text{ s}^{-1}$

$[\text{Aci}]_M$ = acidity of mine water, mmol L^{-1}

$[\text{Alk}]_M$ = alkalinity downstream of mine water discharge

$[\text{Alk}]_R$ = alkalinity of surface water, mmol L^{-1}



Models

Chemical-Thermodynamic ("Geochemical") Models

- A large number of models available
 - PHREEQC
 - WATEQ4F
 - MINTEQA2
 - CE-QUAL-W2
 - EPA-NET
 - GOLDSIM
 - KYBL-7
 - NETPATH
 - SOLMINEQ



Mine Water Geochemistry				Example (1/4)			
Working example							
<p>The following mine water analyses shows, that sulphate and copper are abundant. Both are a result of pyrite (FeS_2) and copper pyrite (CuFeS_2) weathering. Assumed, that no natural attenuation takes place ("no buffering"), the number of protons originating for the weathering shall be equal to the pH-value. Calculate the acidity due to the di-sulphide weathering and determine the degree of neutralization.</p>							
pH	7.6	SO_4^{2-}	1350	Ca	271	Mg	180
Al	0.5	Cu	0.02	Fe	7	Mn	4
Na	511	K	43	Si	30	Cl	142
analyses Niederschlema/Alberoda (Wismut GmbH) 11.8.1994: 366b (m-331). Also: 4.3 mg L ⁻¹ U and 4.2 mg L ⁻¹ As							

Mine Water Geochemistry				Example (2/4)											
<p>1. Calculation of sulphate and copper molecular weight</p> <table style="margin-left: 40px;"> <tr> <td>element</td> <td>S</td> <td>O</td> <td>Cu</td> </tr> <tr> <td>atomical mass</td> <td>32.066</td> <td>15.9994</td> <td>63.546, g mol⁻¹</td> </tr> </table> $M_{\text{SO}_4^{2-}} = 32.066 + 4 \cdot 15.9994 = 96.064 \text{ g mol}^{-1}$								element	S	O	Cu	atomical mass	32.066	15.9994	63.546, g mol ⁻¹
element	S	O	Cu												
atomical mass	32.066	15.9994	63.546, g mol ⁻¹												
<p>2. Molar concentration of sulphate and copper in the mine water</p> $[\text{SO}_4^{2-}] = 1350 / 96.064 = 14.05 \text{ mmol L}^{-1}$ $[\text{Cu}] = 0.02 / 63.546 = 0.003 \text{ mmol L}^{-1}$															
<p>3. Release of sulphate from pyrite</p> $[\text{SO}_4^{2-}]_{\text{Py}} = [\text{SO}_4^{2-}]_{\text{T}} - 2 [\text{Cu}^{2+}]$ $[\text{SO}_4^{2-}]_{\text{Py}} = 14.05 - 2 \cdot 0.003 = 14.04 \text{ mmol L}^{-1}$															

Mine Water Geochemistry	Example (3/4)
<p>4. Protons from pyrite weathering: 2 protons, assumed that pyrite weathers to sulphate and ochre</p> $[\text{H}^+] = 2 [\text{SO}_4^{2-}]_{\text{Py}} = 2 \cdot 14.04 \text{ mmol L}^{-1} = 28.08 \text{ mmol L}^{-1}$ <p>Annotation: the 7 mg L⁻¹ of iron (0.13 mmol L⁻¹) prove, that nearly all Fe²⁺ (14.04 mmol L⁻¹ = 784 mg L⁻¹) precipitates as ochre</p> <p>5. pH-value from proton activity</p> $\text{pH} = -\log[\text{H}^+] = -\log[2.808 \cdot 10^{-2}] = 1.6$ <p>The pH-value measured is 7.6 and therefore 6 units above the pH calculated. Therefore, buffering must be assumed, resulting from the carbonate and silicate weathering. These reactions can be proved by the existence of "base cations" (Na⁺, Ca²⁺, K⁺, Mg²⁺). $[\text{Aci}]_{\text{calculated}} = 23 \text{ mg CaCO}_3$; $[\text{Alk}]_{\text{calculated}} = 308 \text{ mg CaCO}_3$</p> $[\text{Aci}]_{\text{calculated}} = 50 \{2 [\text{Fe}^{2+}] / 56 + 3 [\text{Fe}^{3+}] / 56 + 3 [\text{Al}] / 27 + 2 [\text{Mn}] / 55 + 2 [\text{Zn}] / 65 + 1000 (10^{-\text{pH}})\}$ $[\text{Alk}] \cong \frac{[\text{H}_2\text{CO}_3] K_1}{[\text{H}^+]} - [\text{H}^+] \text{ mol L}^{-1} \quad (\text{pH} < 8.3)$	

Mine Water Geochemistry	Example (4/4)
<p>6. Calculate the annual sulphate and calcite flux from the mine discharge with a quantity $Q = 220 \text{ L s}^{-1}$</p> $[\text{SO}_4^{2-}]_{\text{Py}} = 0.014 \text{ mol L}^{-1}$ $[\text{Ca}^{2+}] = 0.271 \text{ g L}^{-1} = (0.271 / 40.08) \text{ mol L}^{-1} = 6.76 \cdot 10^{-3} \text{ mol L}^{-1}$ <p>7. Multiply concentration with mine water make</p> $F_S = Q \cdot [\text{SO}_4^{2-}]_{\text{Py}} = 220 \text{ L s}^{-1} \cdot 0.014 \text{ mol L}^{-1} = 3.08 \text{ mol s}^{-1}$ $F_{\text{Ca}} = Q \cdot [\text{Ca}^{2+}] = 220 \text{ L s}^{-1} \cdot 6.76 \cdot 10^{-3} \text{ mol L}^{-1} = 1.49 \text{ mol s}^{-1}$ <p>8. Annual weathering rate pyrite and calcite ($1 \text{ y} = 3.15 \cdot 10^7 \text{ s}$)</p> $R_{\text{Py}} = \frac{1}{2} F_S = 1.54 \text{ mol s}^{-1} = 4.85 \cdot 10^7 \text{ mol y}^{-1} = 5500 \text{ t FeS}_2$ $R_{\text{Calcit}} = F_{\text{Ca}} = 1.49 \text{ mol s}^{-1} = 4.69 \cdot 10^7 \text{ mol y}^{-1} = 4700 \text{ t CaCO}_3$	

Mine Water Geochemistry	Literature
	<ul style="list-style-type: none">• Fernández-Rubio, R., Fernández-Lorca, S. & Esteban Arlegui, J. (1987): Preventive techniques for controlling acid water in underground mines by flooding. – Int. J. Mine Water, 6 (3): 39–52.• Nordstrom, D. K. (1977): Hydrogeochemical and microbiological factors affecting the heavy metal chemistry of an acid mine drainage system. – 230 p.; United States (Degree: Doctoral).• Strömberg, B. & Banwart, S. (1994): Kinetic modelling of geochemical processes at the Aitik mining waste rock site in northern Sweden. – Applied Geochemistry, 9: 583–595; Oxford.• Stumm, W. & Morgan, J. I. (1996): Aquatic chemistry – Chemical Equilibria and Rates in Natural Waters. – 3rd edn., 1022 p.; New York (Wiley & Sons).• Wolkersdorfer, Ch. (2008): Water Management at Abandoned Flooded Underground Mines – Fundamentals, Tracer Tests, Modelling, Water Treatment. – 466 p.; Heidelberg (Springer).



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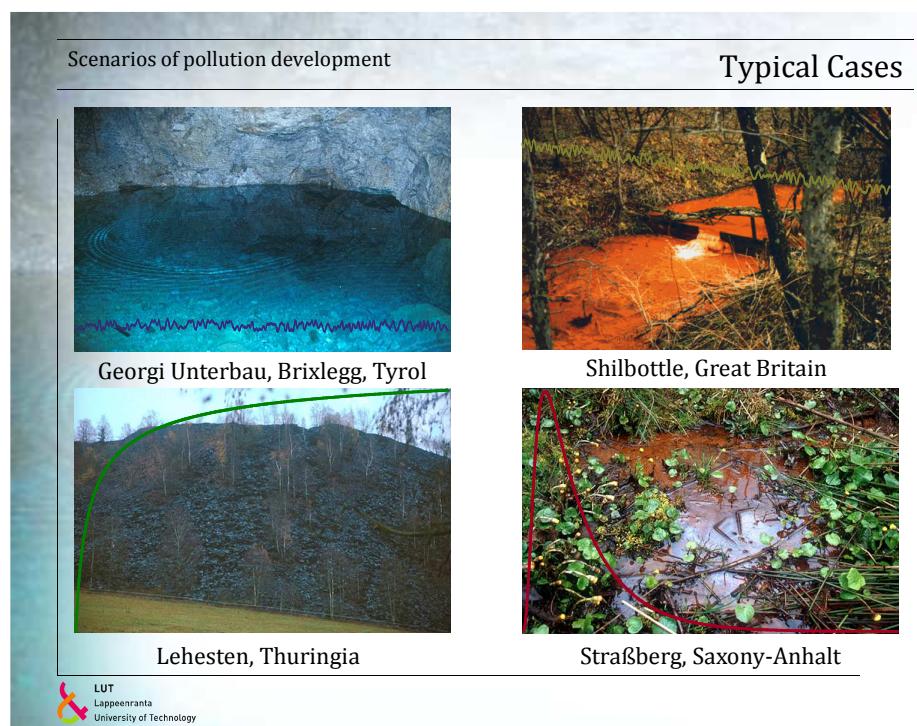
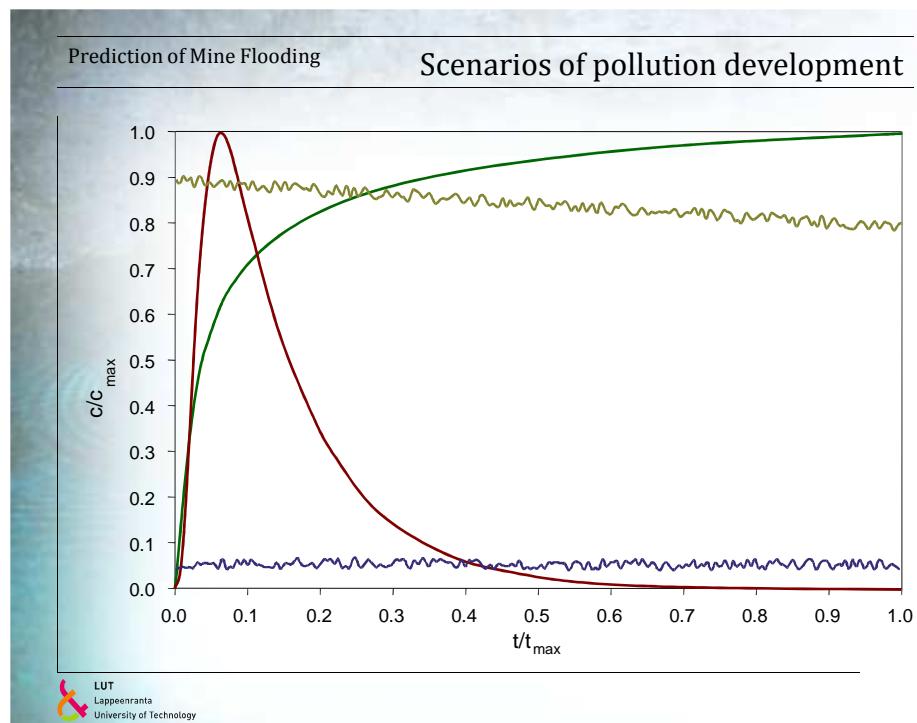
The cover of the book features a background image of water ripples. In the top left corner is the LUT Lappeenranta University of Technology logo. The title 'From Ground Water to Mine Water' is at the top, followed by 'Environmental Hydrogeology in Mining' and 'Prediction of Mine Flooding' in red. The author's name 'Prof. Dr. Christian Wolkersdorfer (云村)' is in blue. Below the author's name is the text 'Finnish Distinguished Professor – Lappeenranta University of Technology' and 'South African Research Chair for Acid Mine Drainage Treatment'.

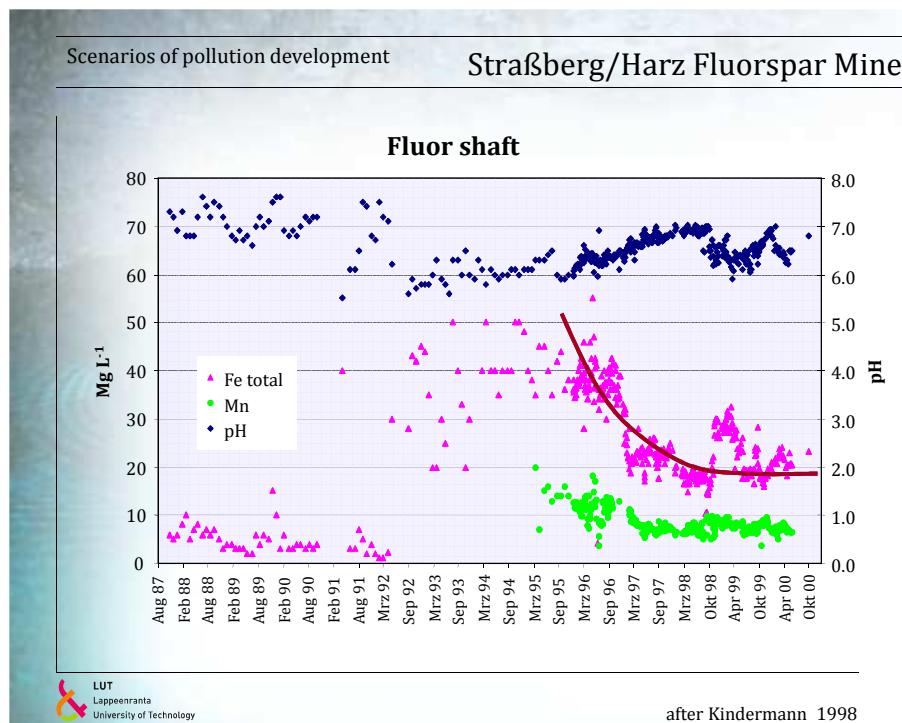
From Ground Water to Mine Water

Contents

- Introduction, Historical Background
- Mining Methods, Technical Terms
- Water and Water Inrushes
- Dewatering methods; Recharge
- Mine Flooding
- Mine Water Geochemistry
- **Prediction of Mine Flooding**
- Mine Water Treatment

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- Prediction of Mine Flooding Prediction Methods
- Acid – Base Accounting: pyrite and carbonate contents of rocks
 - Acid neutralisation: consumption of hot hydrochloride acid
 - Humidity cell tests: dissolution test by the use of periodic flushing
 - Batch- and column reactor tests: dissolution rate of pollutants
 - Bore hole oxygen consumption: sulphide weathering in the field
 - Discharge solute fluxes: net rate of contaminant production and attenuation
 - Statistics
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Prediction of Mine Flooding Acid-Base Calculations

- Neutralization Potential

$$\text{APP} = 31.25 \cdot [\text{S}^{2-}], \text{ g kg}^{-1} \text{ CaCO}_3$$

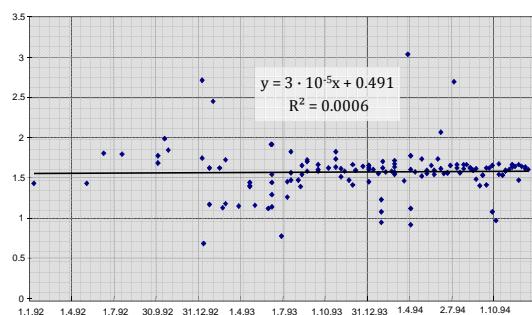
$$\text{NP} = 10 \cdot [\text{CaCO}_3] + 11.9 \cdot [\text{MgCO}_3], \text{ g kg}^{-1} \text{ CaCO}_3$$

$$\text{Net NP} = \text{NP} - \text{APP}, \text{ g kg}^{-1} \text{ CaCO}_3$$

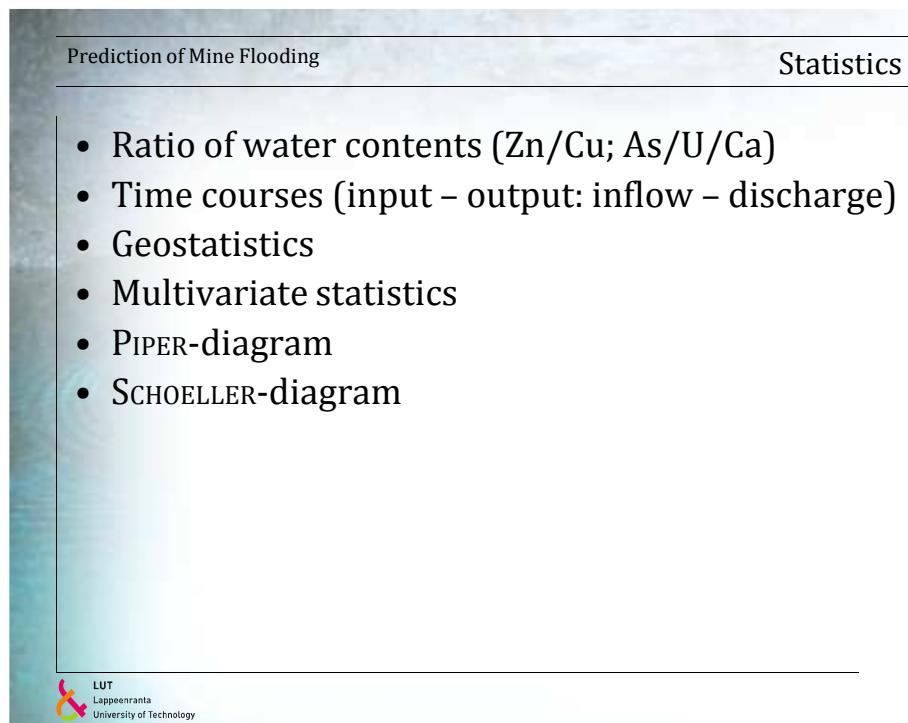
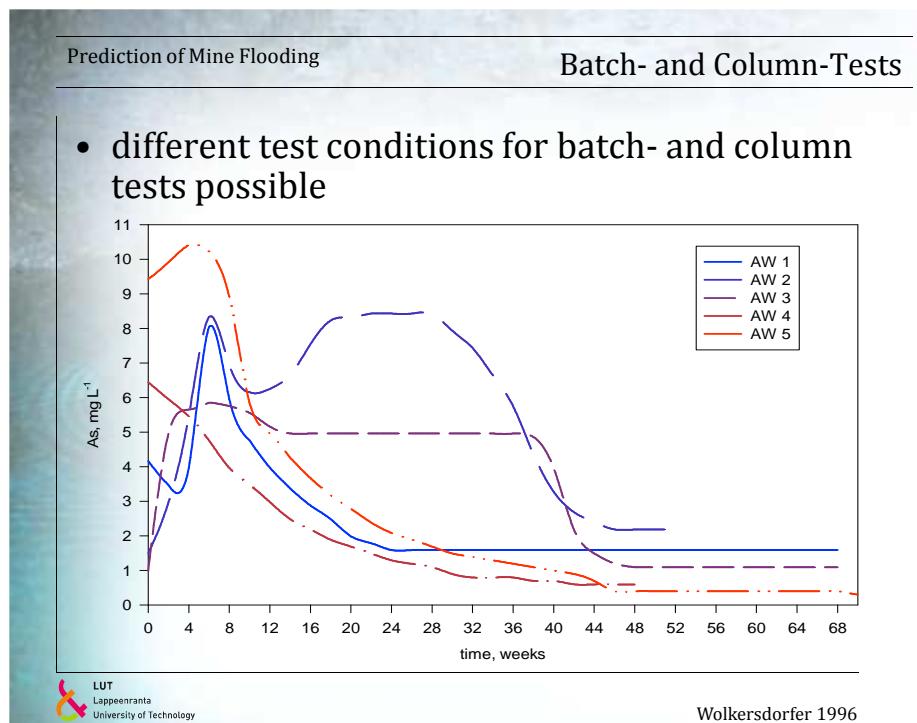
	ud	td	sk	ks/l	ks/k	ds	s	qs	G	Kb/Kh
MgO, %	5.30	4.30	1.70	1.68	5.70	2.94	2.11	1.30	0.64	4.14
CaO, %	8.40	11.75	0.59	1.64	28.88	0.95	0.51	0.56	1.28	5.84
S(ges), %	0.2	0.4	0.05	1.7	1.2	0.2	0.1	—	0.1	0.2
S-SO ₄ ²⁻ , %	<0.10	<0.10	<0.10	<0.1	<0.1	<0.1	<0.1	—	—	—
CO ₂ , %	0.18	0.34	0.30	0.18	25.25	0.51	0.45	0.38	0.3	6.43
Pyrit, %	0.3	0.7	—	3	2	0.3	0.2	—	0.2	0.3
MgCO ₃ , %	0.3	0.4	0.7	0.3	16.4	1.3	1.2	—	0.4	9.6
CaCO ₃ , %	0.3	0.8	0.2	0.3	70.8	0.3	0.2	—	0.6	11.6
APP	6	13	2	53	38	6	3	—	3	6
NP	6	12	11	6	903	18	16	—	11	230
Net NP	0	-1	9	-47	865	12	13	—	8	224

Prediction of Mine Flooding Hardness – Alkalinity Relation

- Ratio of total hardness and alkalinity
- Already a small increase in the ratio, even in well buffered media, can show an acidification on a long term basis

$$R = \frac{2([\text{Ca}^{2+}] + [\text{Mg}^{2+}])}{([\text{HCO}_3^{2-}] + 2[\text{CO}_3^{2-}])}$$


Voigt 1990, Jacks *et al.* 1984, Norberg 1985

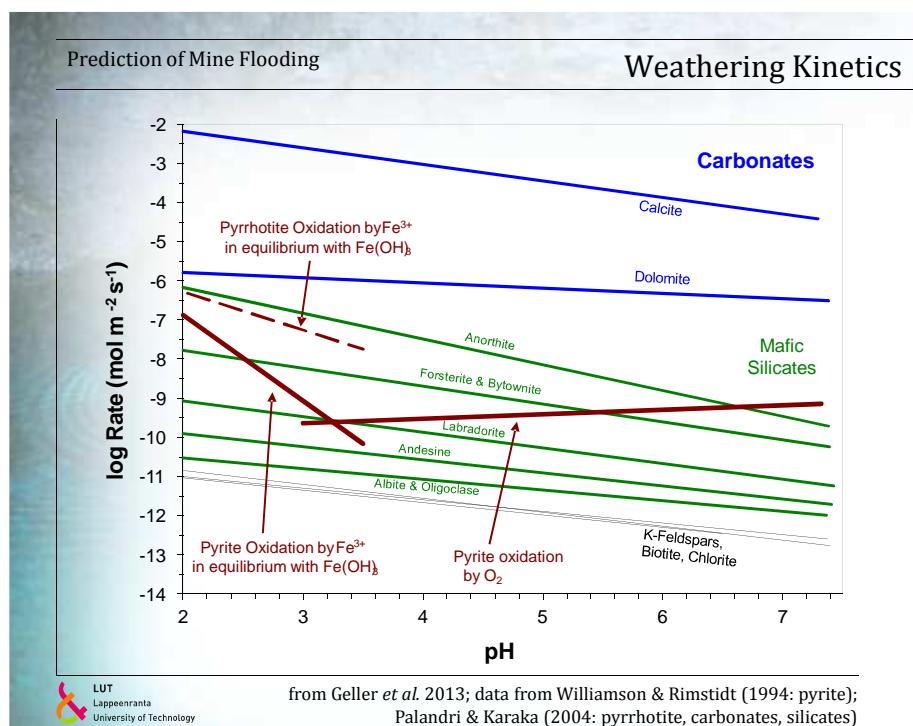


Prediction of Mine Flooding

Weathering Kinetics

- Weathering rate at pH 7
 - Calcite weathering is more than 10^3 times faster than pyrite weathering
 - Pyrite weathering is 10^2 – 10^3 times faster than weathering of silicates
 - Don't forget: silicates are more abundant than sulphides, which are usually trace minerals – even in many ore deposits

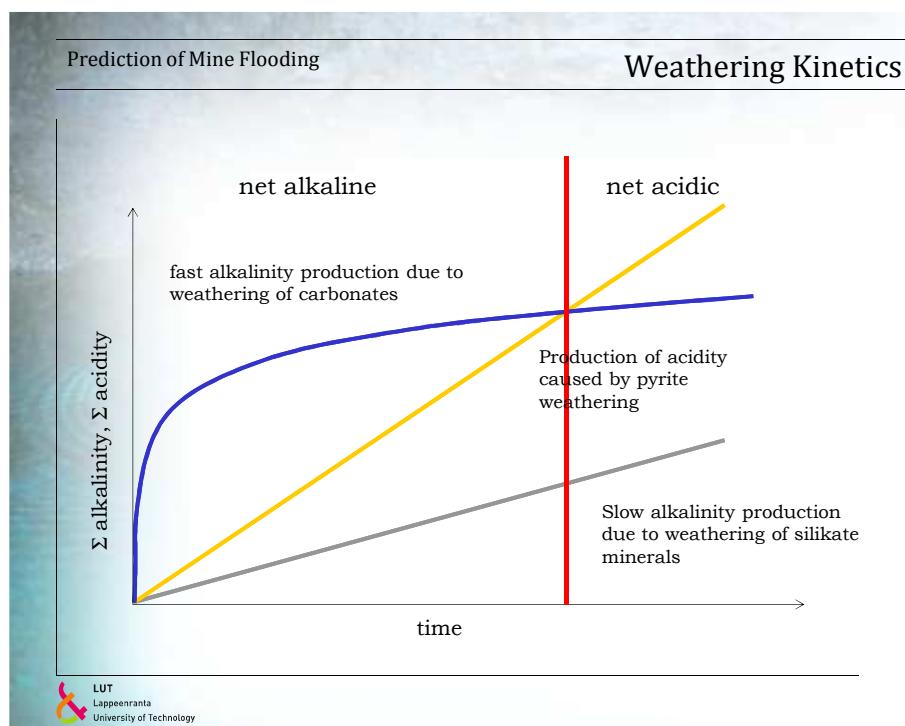
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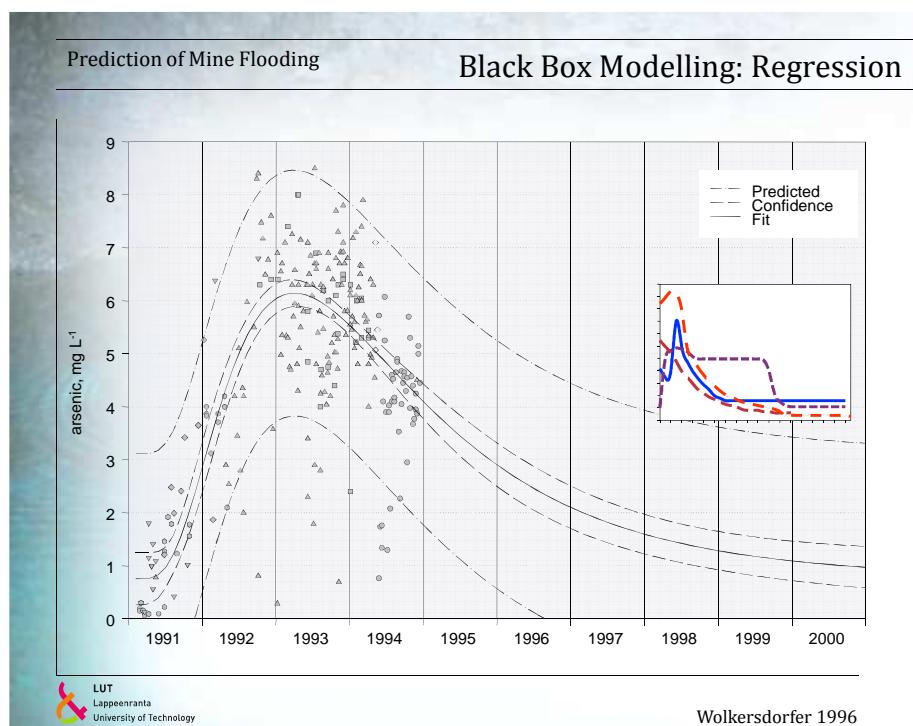
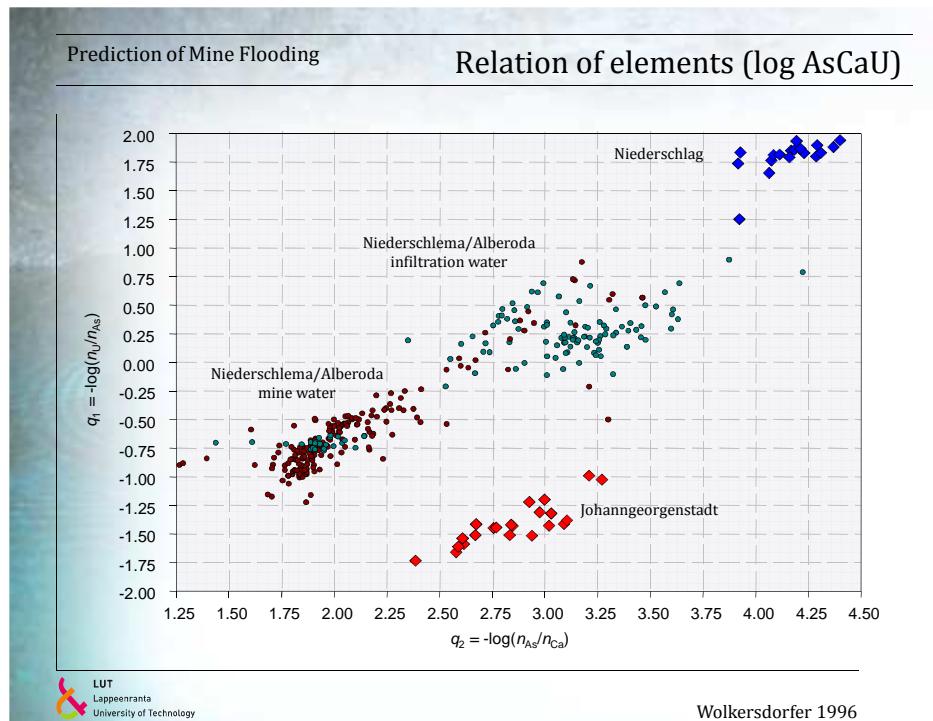


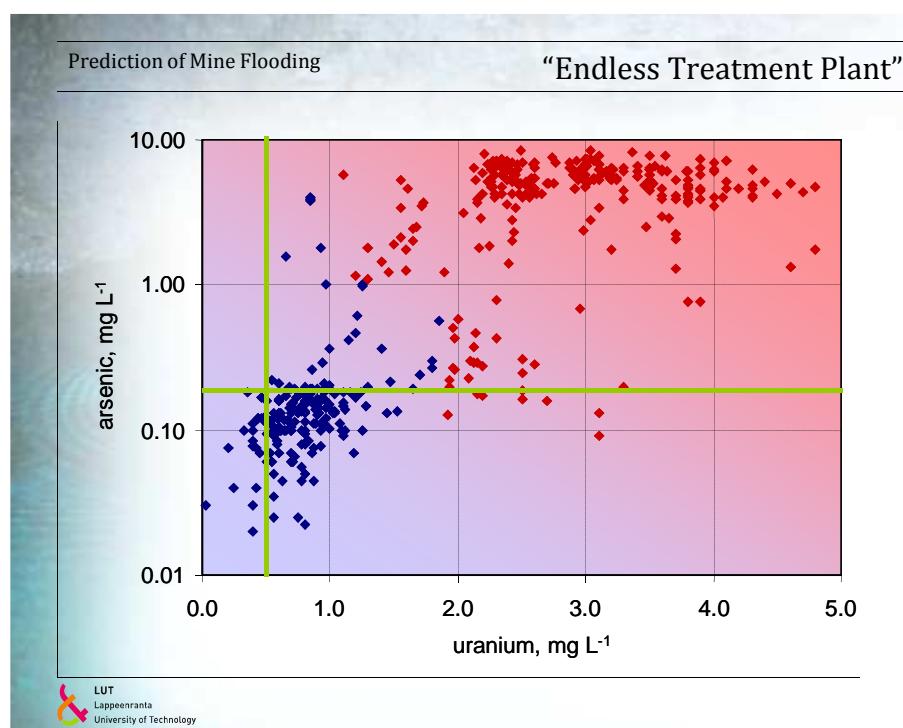
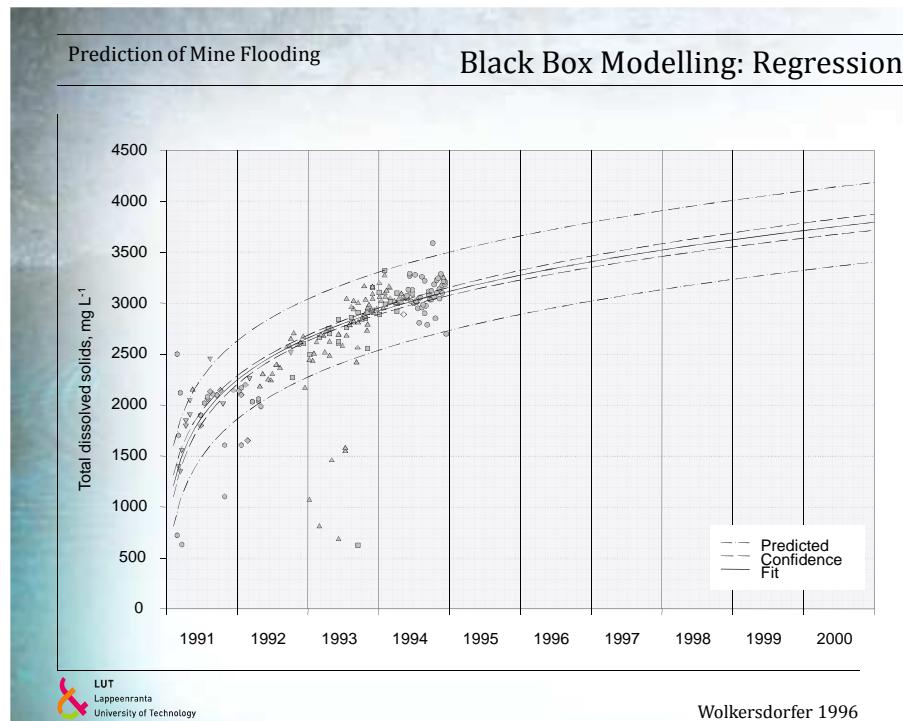
Prediction of Mine Flooding Weathering Kinetics

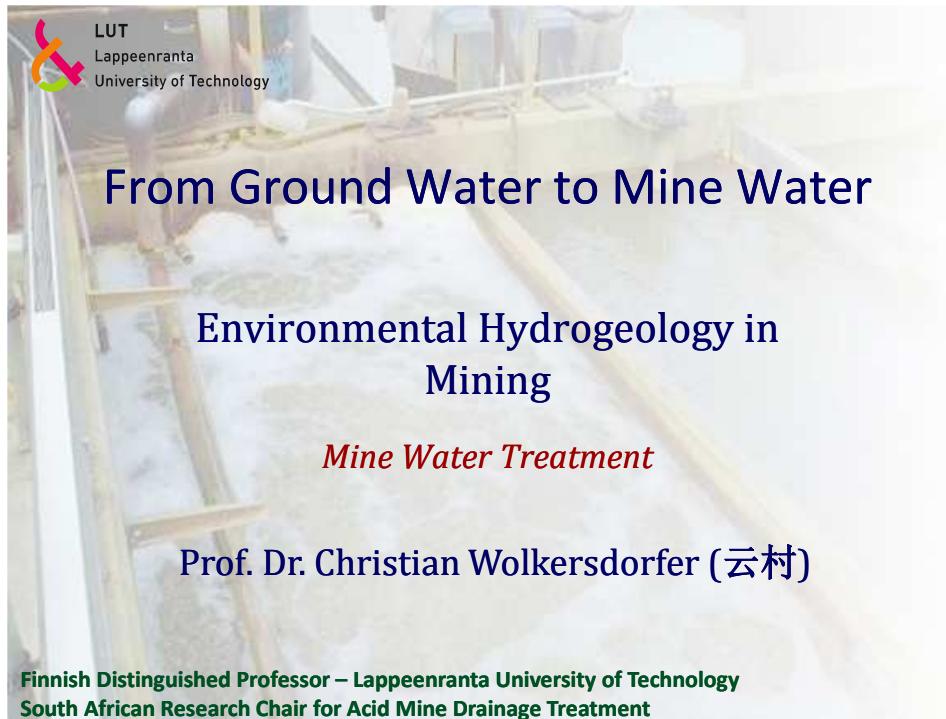
- The weathering rates have decisive effects on the development of the mine water or the tailings drainage water
 - At the beginning, the fast carbonate weathering dominates and the mine water is well buffered (alkalinity production)
 - The pH decreases as soon as all the carbonates are weathered
 - At a later stage, after all of the pyrite has been weathered, the pH can increase again (buffer capacity of silicates)

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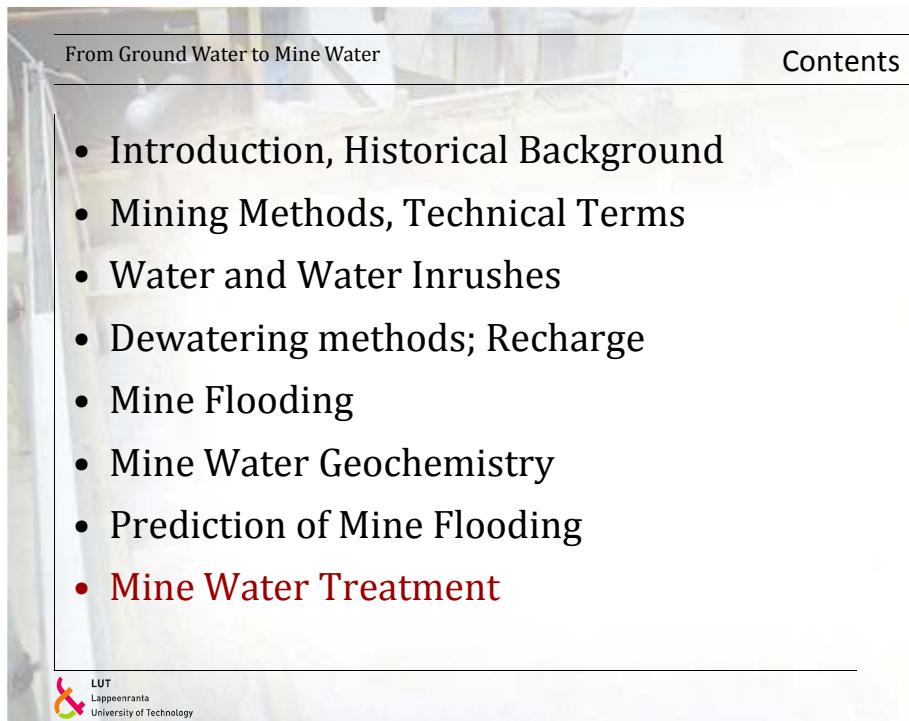
From Ground Water to Mine Water

Environmental Hydrogeology in Mining

Mine Water Treatment

Prof. Dr. Christian Wolkersdorfer (云村)

Finnish Distinguished Professor – Lappeenranta University of Technology
South African Research Chair for Acid Mine Drainage Treatment



From Ground Water to Mine Water

Contents

- Introduction, Historical Background
- Mining Methods, Technical Terms
- Water and Water Inrushes
- Dewatering methods; Recharge
- Mine Flooding
- Mine Water Geochemistry
- Prediction of Mine Flooding
- Mine Water Treatment

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Mine Water Treatment	Treatment Technology Categories ($\frac{1}{2}$)
	<ul style="list-style-type: none"> • Neutralisation <ul style="list-style-type: none"> – Lime based – Sodium-based – Ammonia – Biological sulphate reduction – Constructed wetlands • Metals Removal <ul style="list-style-type: none"> – Precipitation <ul style="list-style-type: none"> • Hydroxides • Carbonates • Sulphates – Constructed wetlands

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Mine Water Treatment	Treatment Technology Categories ($\frac{2}{2}$)
	<ul style="list-style-type: none"> • Desalination <ul style="list-style-type: none"> – Biological Sulphate Removal – Ettringite Process – Membrane Processes – Ion Exchange – Constructed wetlands • Special Treatment Options <ul style="list-style-type: none"> – Cyanide removal – Radioactive compounds – Arsenic removal – Electrocoagulation • <i>In-situ</i> treatment

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From Ground Water to Mine Water

Mine Water Treatment: Overview



- Active treatment methods
 - Neutralization
 - Ion Exchange
 - Reverse Osmosis
 - Distillation
- Passive treatment methods
 - Constructed wetlands
 - Limestone Drains
 - Reactive Barriers
 - Vertical Flow Reactors

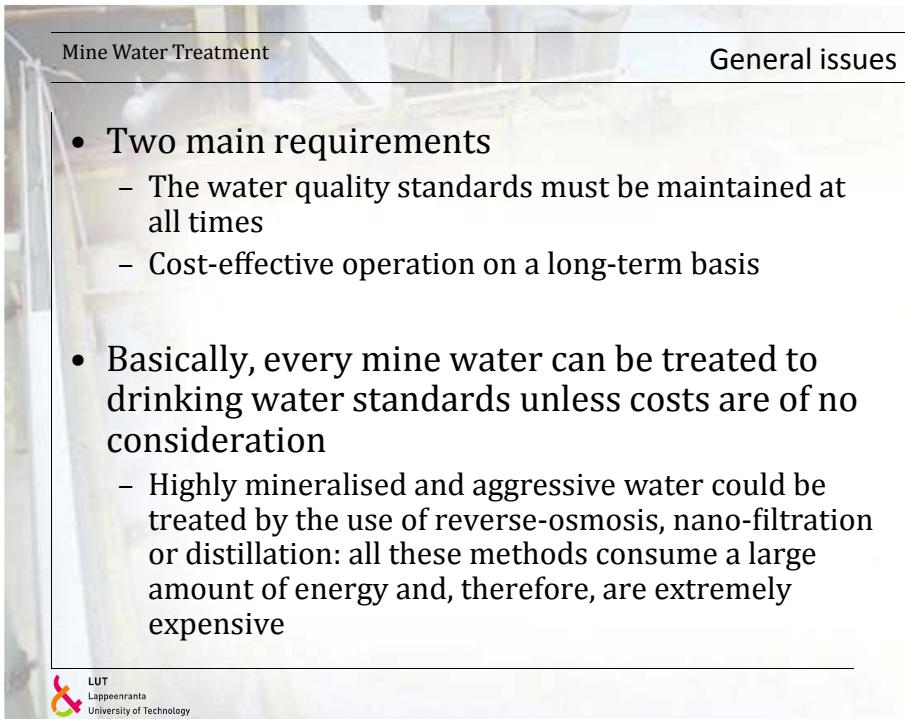


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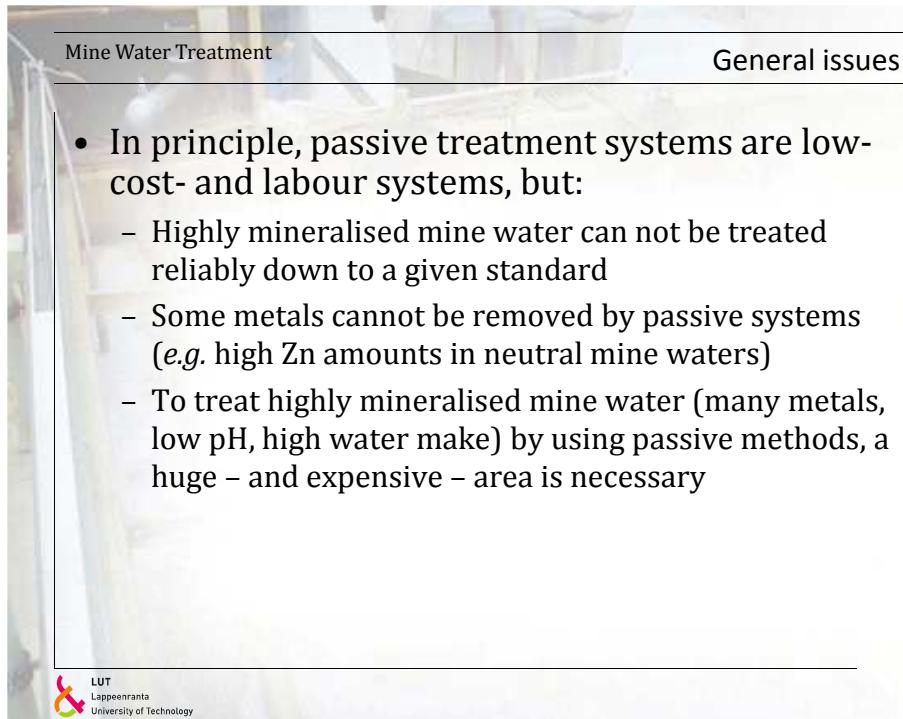
Mine Water Treatment

General issues

- Two main requirements
 - The water quality standards must be maintained at all times
 - Cost-effective operation on a long-term basis
- Basically, every mine water can be treated to drinking water standards unless costs are of no consideration
 - Highly mineralised and aggressive water could be treated by the use of reverse-osmosis, nano-filtration or distillation: all these methods consume a large amount of energy and, therefore, are extremely expensive



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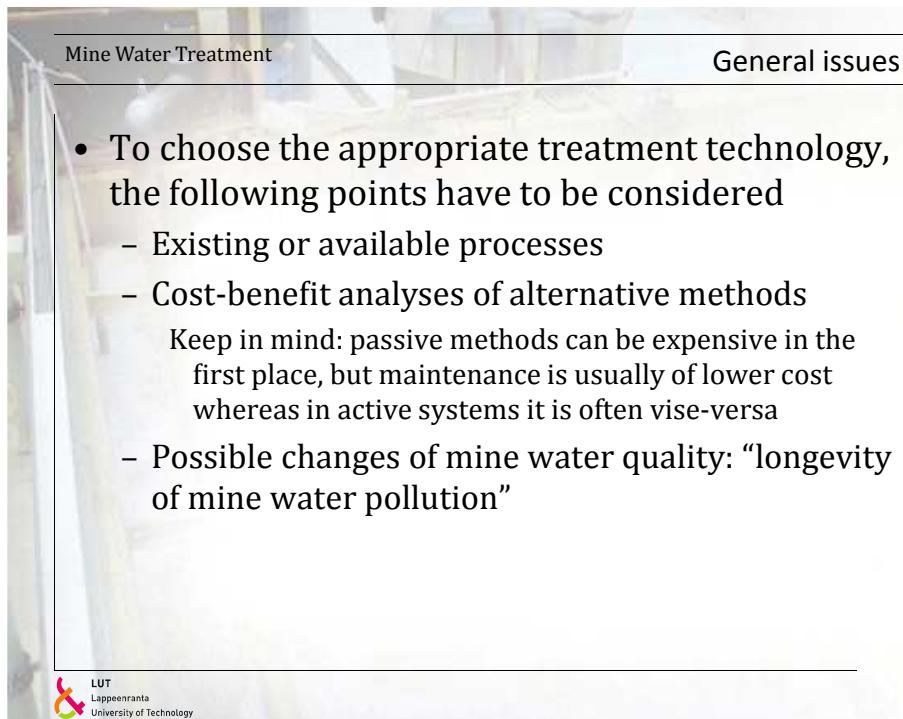


Mine Water Treatment

General issues

- In principle, passive treatment systems are low-cost- and labour systems, but:
 - Highly mineralised mine water can not be treated reliably down to a given standard
 - Some metals cannot be removed by passive systems (*e.g.* high Zn amounts in neutral mine waters)
 - To treat highly mineralised mine water (many metals, low pH, high water make) by using passive methods, a huge – and expensive – area is necessary

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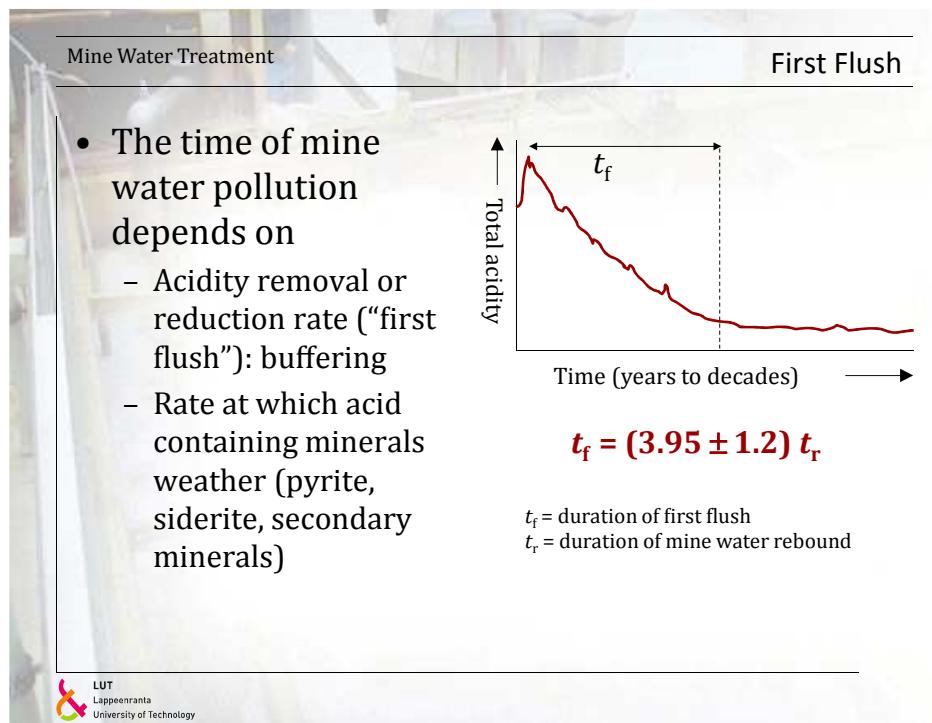
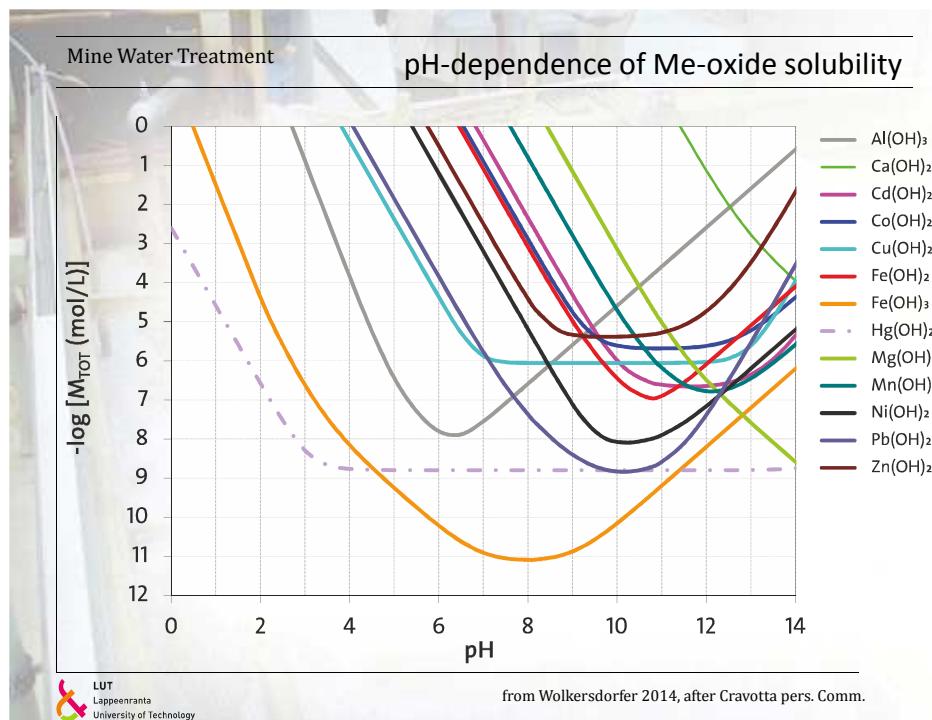


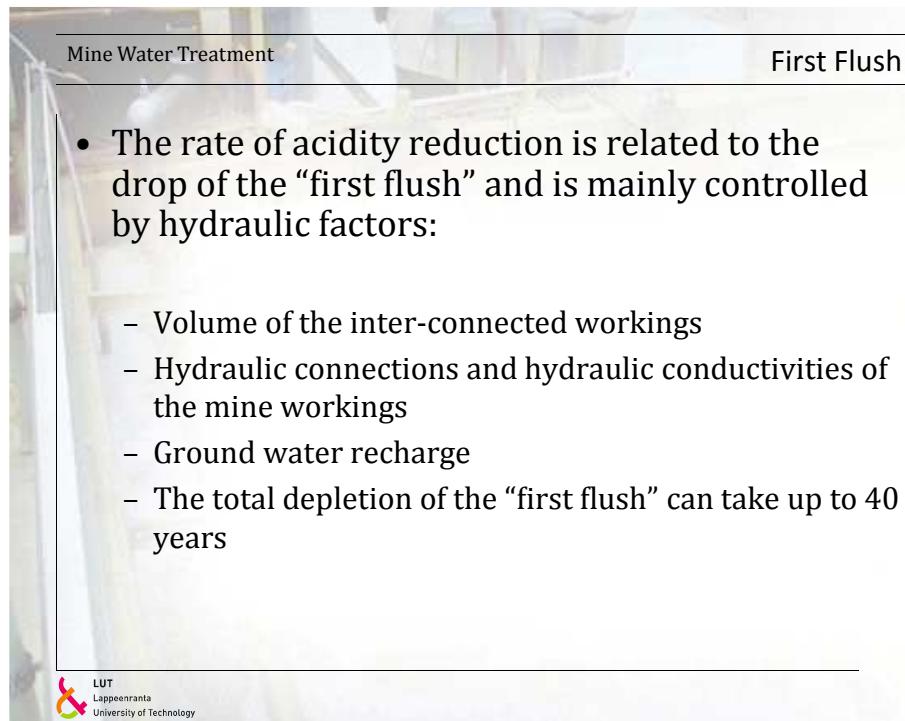
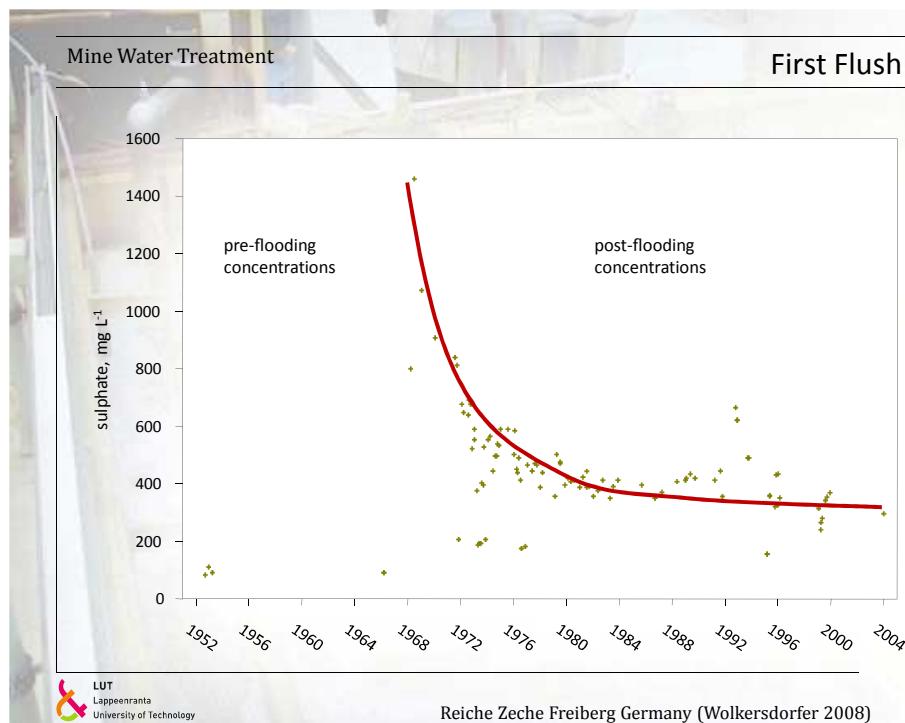
Mine Water Treatment

General issues

- To choose the appropriate treatment technology, the following points have to be considered
 - Existing or available processes
 - Cost-benefit analyses of alternative methods
 - Keep in mind: passive methods can be expensive in the first place, but maintenance is usually of lower cost whereas in active systems it is often vise-versa
 - Possible changes of mine water quality: “longevity of mine water pollution”

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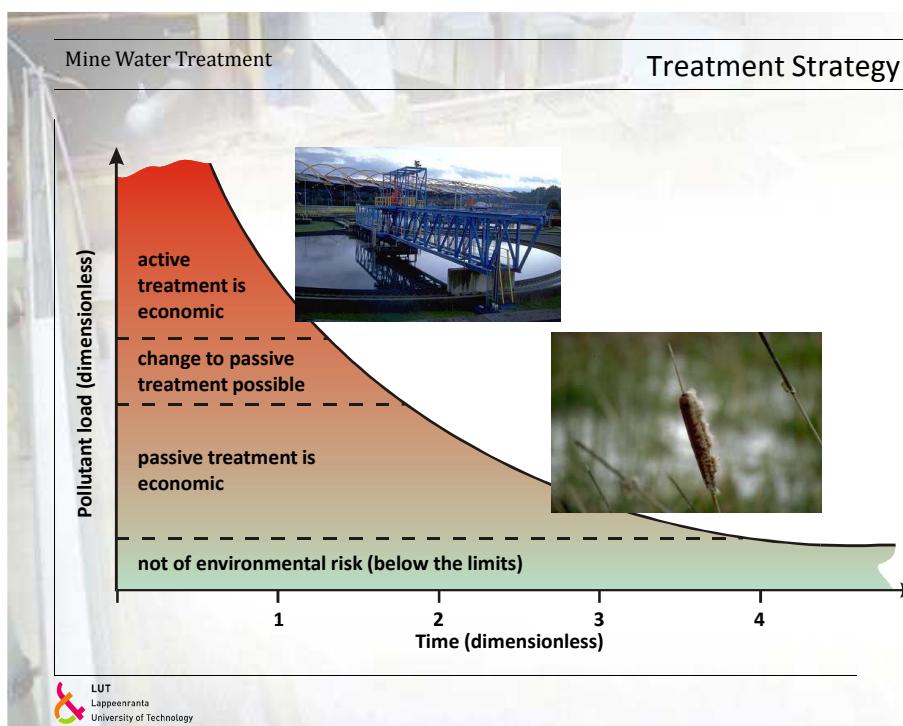


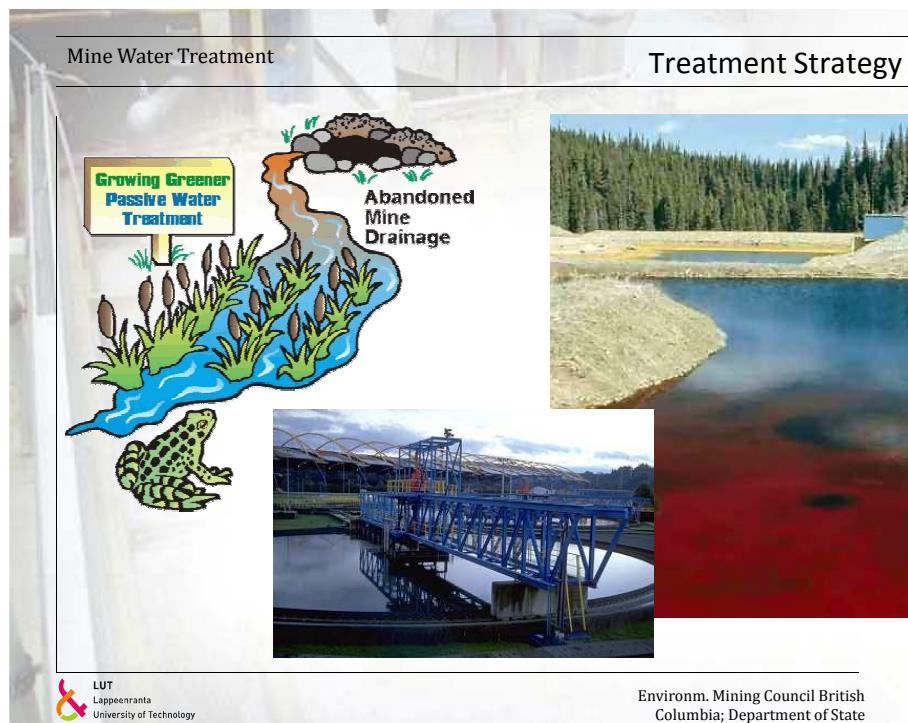
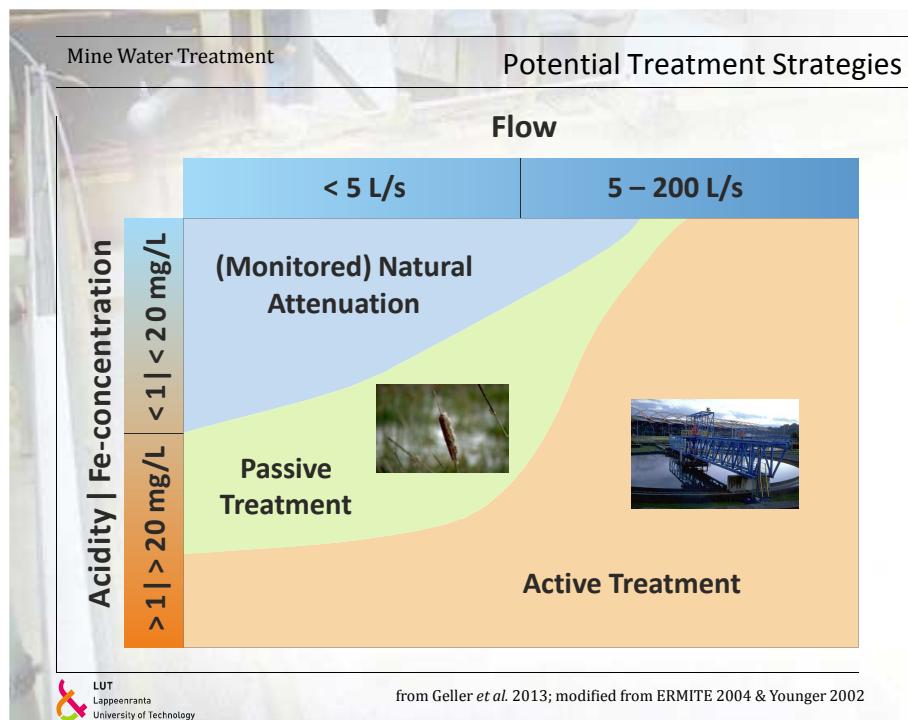
Mine Water Treatment

How to plan the plant

- In many cases of polluted mine water discharges, the following approach proves to be useful
 - Treat the mine water actively until all the acidity has been depleted (as a rule: during the time of the first flush, sometimes up to 40 years)
 - Thereafter, for the long term treatment of the mine water, install passive treatment systems (buffering of juvenile acidity)

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Mine Water Treatment

Treatment Strategy

- Advantages of this step-wise approach:
 - Design and construction of active and passive systems is done in different stages
 - The required water limits can be fulfilled at all time
 - Passive systems can be constructed before they are necessary and, therefore, have enough time to mature before their first use



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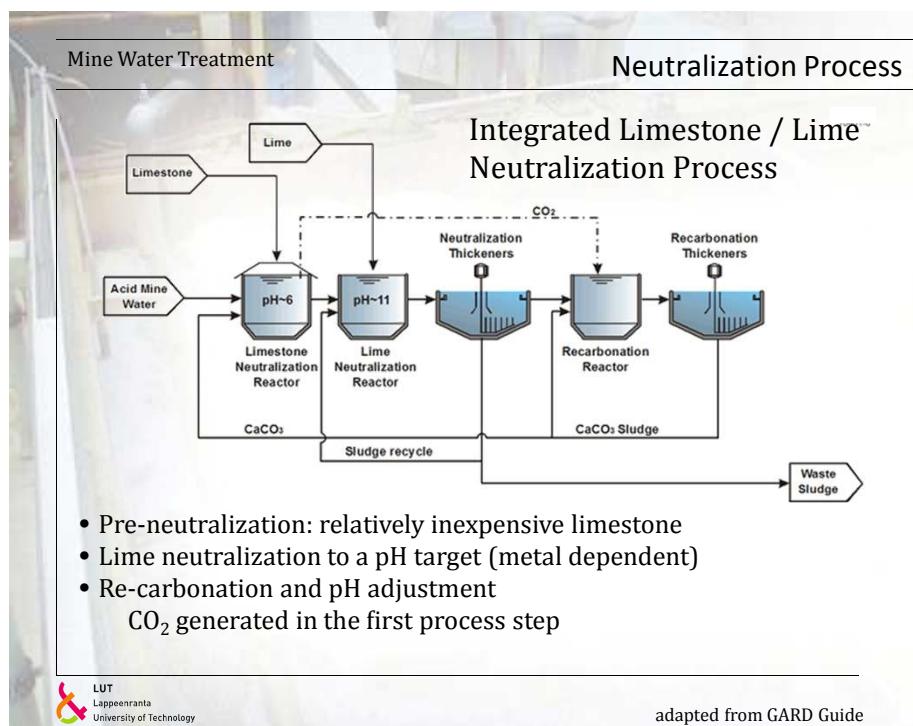
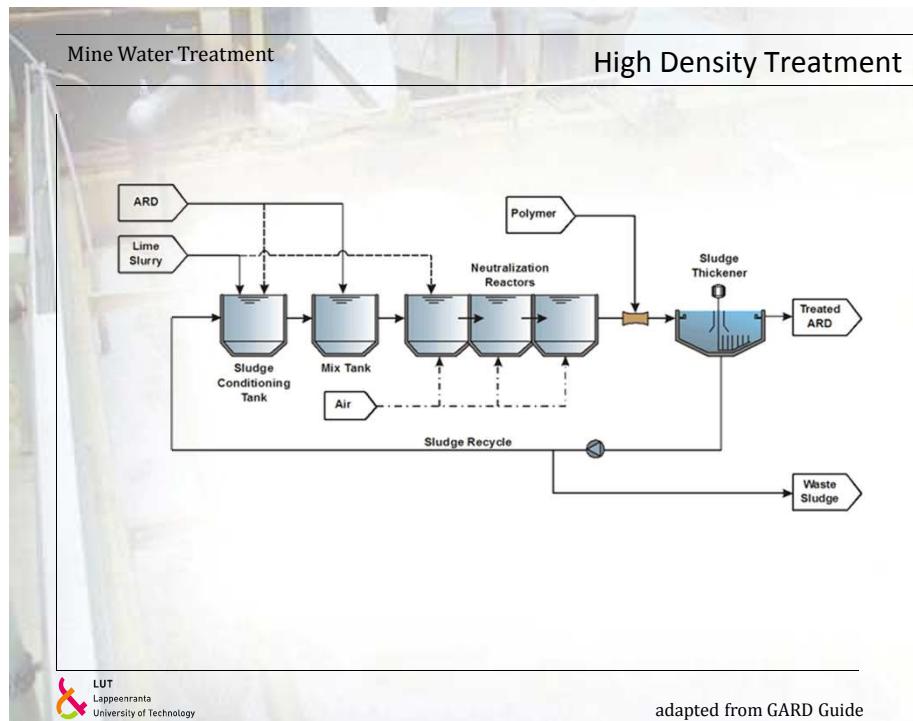
Mine Water Treatment

Active treatment systems



- Neutralization
- Ionic exchange
- Reverse osmosis
- Nano-filtration
- Distillation
- Electro-dialyses
- Solvent extraction
- Freeze separation
- Electrocoagulation

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Mine Water Treatment Neutralization

- Aeration
 - Conversion of $\text{Fe}^{2+} \rightarrow \text{Fe}^{3+}$ (ferrous → ferric)
 $\text{Acidothiobacillus ferrooxidans}, \text{Galonella}$

The diagram illustrates the process of aeration within a bacterial cell. Inside the cell, the pH is 6, while outside it is 2, creating a $\Delta\text{pH} = 4$. A red circular protein pump moves 3 H^+ from the outside into the cell, using $\text{ADP} + \text{P}^-$ to produce ATP . Simultaneously, $2 \text{ H}^+ + \frac{1}{2} \text{ O}_2$ are reduced to H_2O . Outside the cell, 2 Fe^{2+} (ferrous) are oxidized to 2 Fe^{3+} (ferric) by enzymes like cytochrome oxidase, rusticyanin, and cytochrome. The diagram shows a membrane with various proteins and electron flow paths.

enzymes involved:
 cytochrome oxidase
 rusticyanin
 cytochrome

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Mine Water Treatment Neutralization

- Liming
 - pH raise to increase reaction rate of Fe(OH)_3 precipitation (optimum: pH 11)
- Coagulation and flocculation
 - Larger and – hopefully more dense – Fe(OH)_3^- particles to increase the sedimentation rate
- Settlement (settling ponds)

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Mine Water Treatment

Aeration

- Cascades (potential energy)
 - 50 mg L⁻¹ Fe²⁺ can be oxidized, if necessary, install a second stage
- Aeration (electro energy)
- Reactions involved:

$$\text{Fe}^{2+} + \frac{1}{4} \text{O}_2 + \text{H}^+ \rightarrow \text{Fe}^{3+} + \frac{1}{2} \text{H}_2\text{O}$$

$$\text{Fe}^{3+} + 3 \text{H}_2\text{O} \rightarrow \text{Fe(OH)}_3 + 3 \text{H}^+$$
- Take care: two protons will be released!
- In the case, there is still too much Fe²⁺ after approximately 10 minutes: hydrogen peroxide (H₂O₂), ozone or hypochloride (OCl⁻) might be necessary

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Mine Water Treatment

Neutralisation: Alkali materials

Alkali Compound/ Material	Alkali Requirements ton/ton of acidity	Neutralisation Efficiency % of applied alkali used	Relative Cost € / tonnes bulk
Limestone, CaCO ₃	1.00	30 – 50	8 – 12
Hydrated Lime, Ca(OH) ₂	0.74	90	50 – 80
Un-hydrated (quick) Lime, CaO	0.56	90	60 – 190
Soda Ash, Na ₂ CO ₃	1.06	60 – 80	150 – 270
Caustic Soda, NaOH	0.80	100	500 – 700
Magna Lime, MgO	0.4	90	project specific
Fly ash	material specific	–	project specific
Kiln dust	material specific	–	project specific
Slag	material specific	–	project specific

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adapted from GARD Guide

Mine Water Treatment

Liming

- Acidic mine water will be neutralized
- (Semi-)Metal hydroxides will co-precipitate (*e.g.* Cd, As)
- Fast but partly incomplete reaction
- Calcium oxide: CaO (very reactive)
- Calcium hydroxide: Ca(OH)₂ (extensive mixing)

$$\text{Ca}(\text{OH})_2 + \text{H}_2\text{SO}_4 \rightarrow \text{CaSO}_4 \cdot 2\text{H}_2\text{O}$$
$$3 \text{Ca}(\text{OH})_2 + \text{Fe}_2(\text{SO}_4)_3 + 6 \text{H}_2\text{O} \rightarrow 2 \text{Fe}(\text{OH})_3 + 3 \text{CaSO}_4 \cdot 2\text{H}_2\text{O}$$

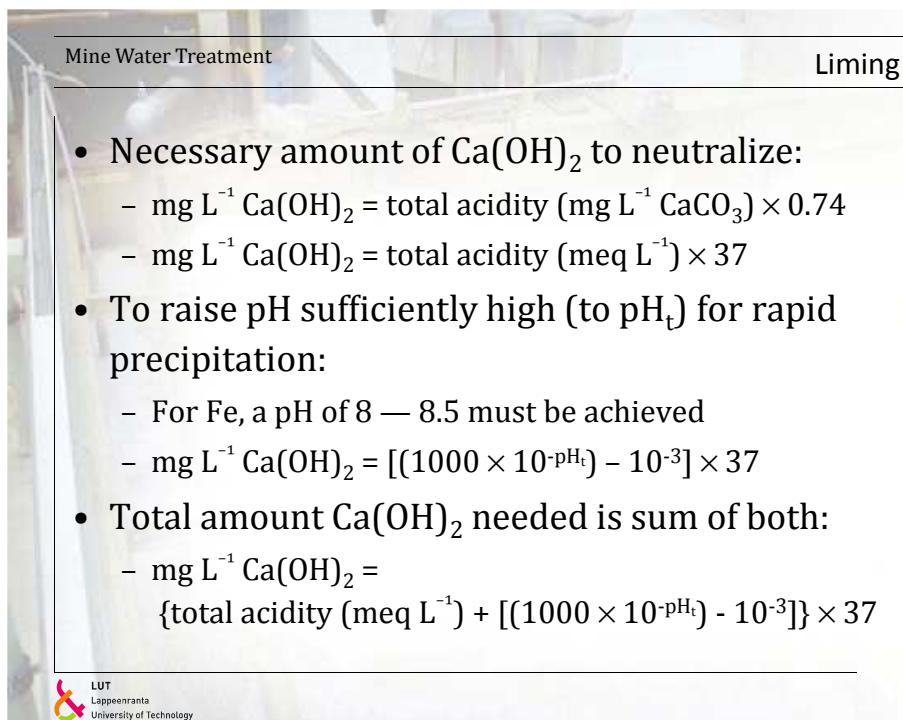
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Mine Water Treatment

Liming

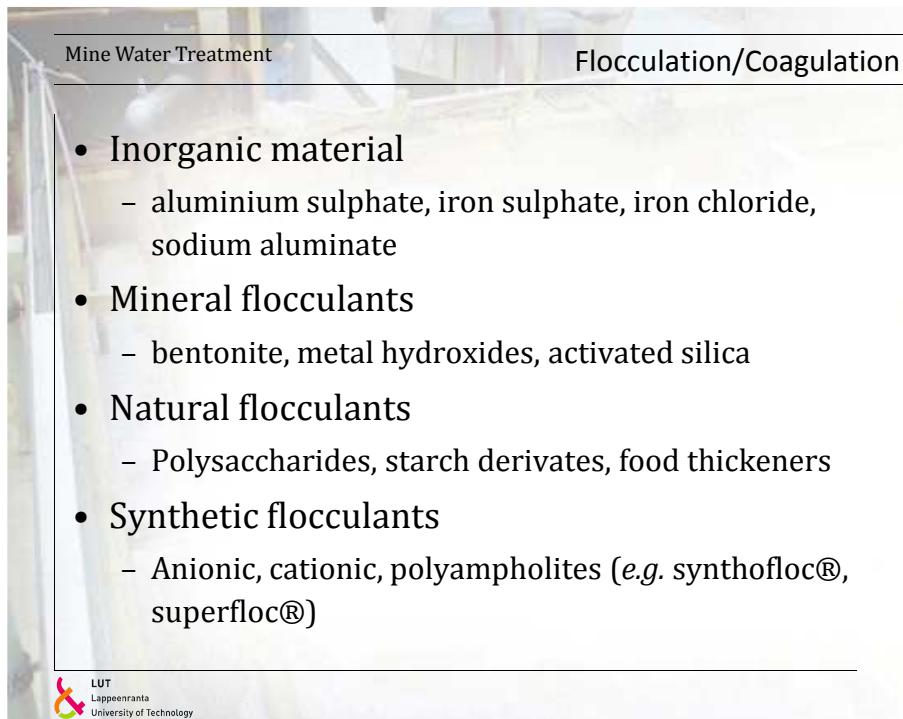
- Minimum pH-values needed to fully precipitate metals as their oxy-hydrates

Metal	Minimum pH
Fe^{3+}	4.3
Al^{3+}	5.2
Pb^{2+}	6.3
Cu^{2+}	7.2
Zn^{2+}	8.4
Ni^{2+}	9.3
Fe^{2+}	9.5
Cd^{2+}	9.7
Mn^{2+}	10.6

 Mine Water Treatment Liming

- Necessary amount of $\text{Ca}(\text{OH})_2$ to neutralize:
 - $\text{mg L}^{-1} \text{Ca}(\text{OH})_2 = \text{total acidity } (\text{mg L}^{-1} \text{CaCO}_3) \times 0.74$
 - $\text{mg L}^{-1} \text{Ca}(\text{OH})_2 = \text{total acidity } (\text{meq L}^{-1}) \times 37$
- To raise pH sufficiently high (to pH_t) for rapid precipitation:
 - For Fe, a pH of 8 — 8.5 must be achieved
 - $\text{mg L}^{-1} \text{Ca}(\text{OH})_2 = [(1000 \times 10^{-\text{pH}_t}) - 10^{-3}] \times 37$
- Total amount $\text{Ca}(\text{OH})_2$ needed is sum of both:
 - $\text{mg L}^{-1} \text{Ca}(\text{OH})_2 = \{\text{total acidity } (\text{meq L}^{-1}) + [(1000 \times 10^{-\text{pH}_t}) - 10^{-3}]\} \times 37$

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 Mine Water Treatment Flocculation/Coagulation

- Inorganic material
 - aluminium sulphate, iron sulphate, iron chloride, sodium aluminate
- Mineral flocculants
 - bentonite, metal hydroxides, activated silica
- Natural flocculants
 - Polysaccharides, starch derivates, food thickeners
- Synthetic flocculants
 - Anionic, cationic, polyampholites (*e.g.* synthofloc®, superfloc®)

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Mine Water Treatment

Settlement and Sludge Management

- Enough storage space must be available
 - Sludge contains: Fe-Hydroxide, Me-hydroxides, unused lime, gypsum, calcium carbonate
- Sludge: 10 % of mine water make
- LDS (Low Density Sludge)
 - 1 — 2 weight % solids
- HDS (High Density Sludge)
 - Sludge circuit
 - Sludge density is 6-fold higher than in LDS
- Deposition



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Mine Water Treatment

Plate Filter Press



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Žirovski Vrh/Slovenia (Kovinarska Industrija/Ajdovščina)

Mine Water Treatment

Sludge Disposal

- High amounts of metals (*e.g.* Pb, Zn, Cd) could cause the sludge to be classified as hazardous waste
- HDS or Fe-rich sludge might be used as pigments or in brick industry
- Experience has shown (“ $\pi \cdot \phi^2$ ”-rule):
 - Retention time must be greater than 24 hours
- No settlement lagoons are necessary if $[Fe] < 2 \text{ mg L}^{-1}$ and sand filters are installed

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Mine Water Treatment

Sulphate Removal

- Barium sulphate process (pilot scale)
- Ettringite precipitation process (pilot scale)
 - SAVMIN™
 - $\text{Ca}_6\text{Al}_2(\text{SO}_4)_3(\text{OH})_{12} \cdot 26\text{H}_2\text{O}$

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adapted from GARD Guide

Mine Water Treatment Ion exchange

- Cationic or anionic resins
- Residues mainly gypsum
- regeneration
 - Sulphuric acid (cationic)
 - Sodium hydroxide (anionic)
- Desal-process
- Sul-Bisul-process

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Mine Water Treatment Ion exchange

- Conceptual GYPCIX®-Ion Exchange Treatment Process
- high sulphate type mine drainage

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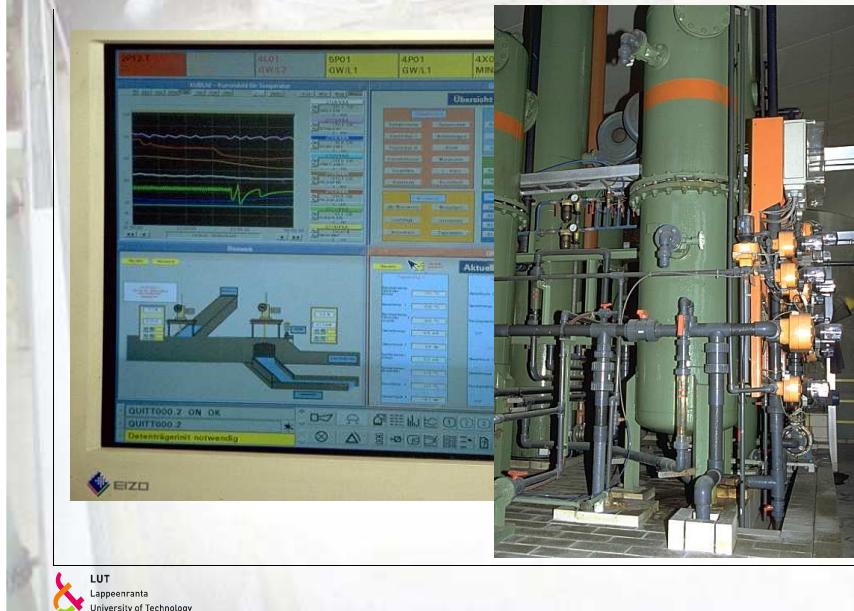
graph LR
    MW[Mine Water] --> CR[ ]
    SA[Sulphuric Acid] --> RR1[Resin Regeneration]
    L[Lime] --> RR2[Resin Regeneration]
    CR --> DT[Degassing Tank]
    RR1 --> GS1[Gypsum Sludge]
    RR2 --> GS2[Gypsum Sludge]
    DT --> AL[Anion Resin Loading]
    AL --> PW[Product Water]
    GS1 --> GS2
  
```

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Mine Water Treatment

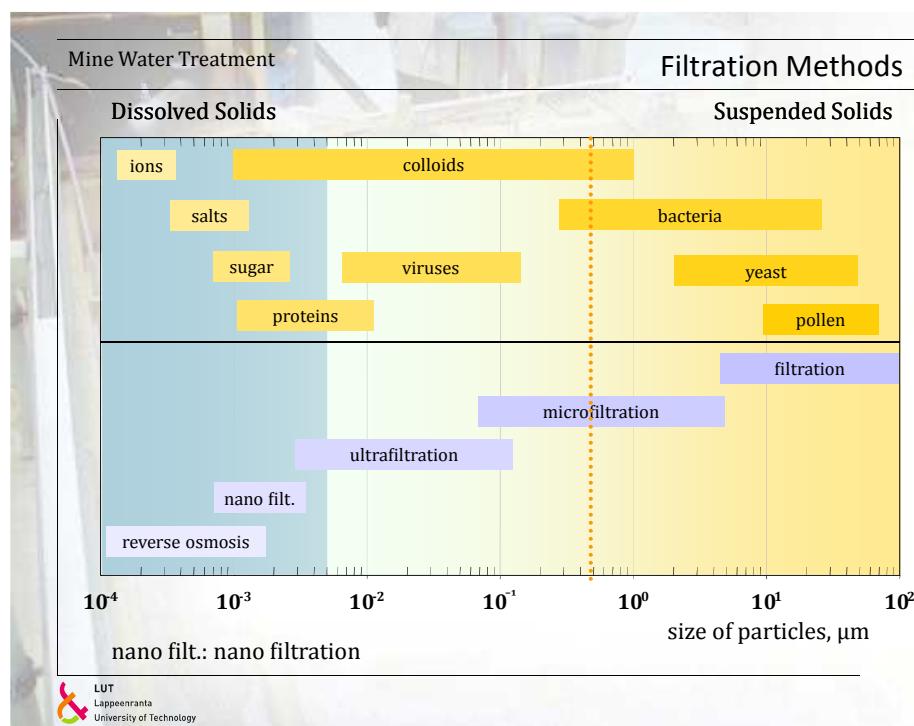
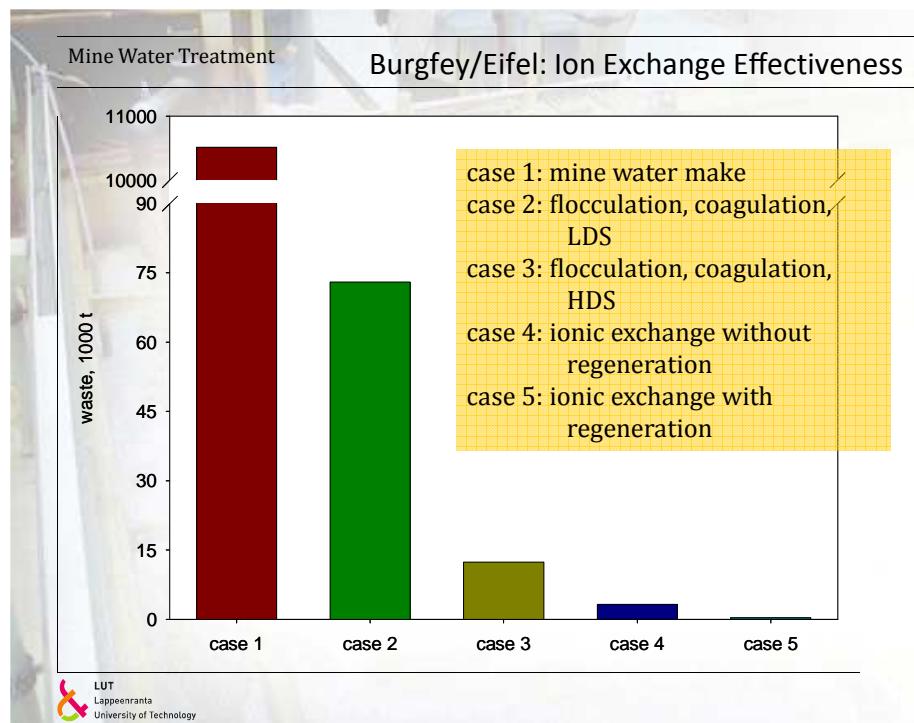
Brixlegg/Tyrol, Ion Exchange Reactor

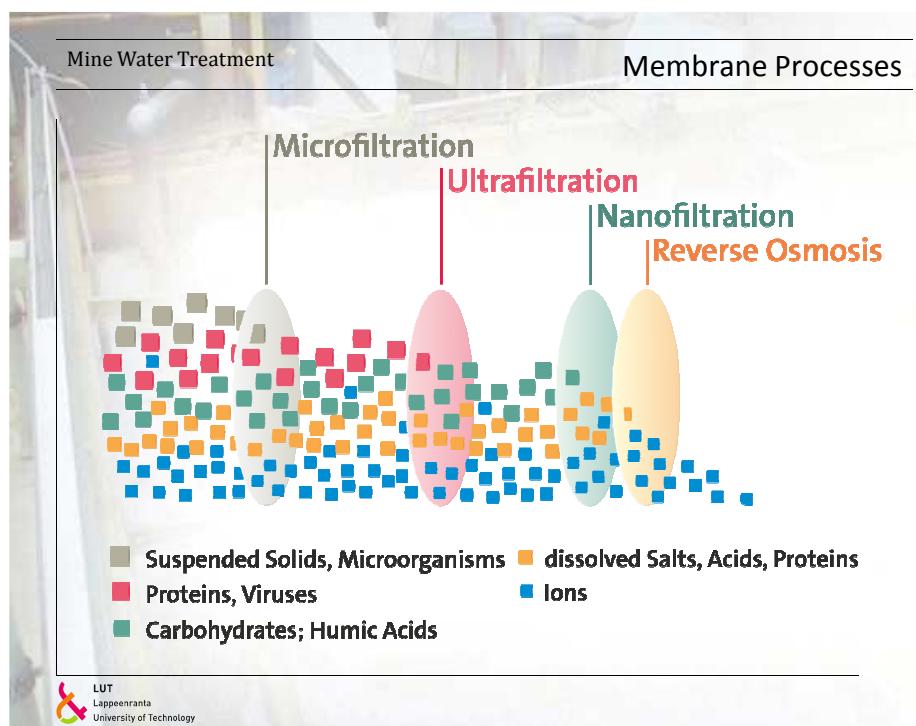
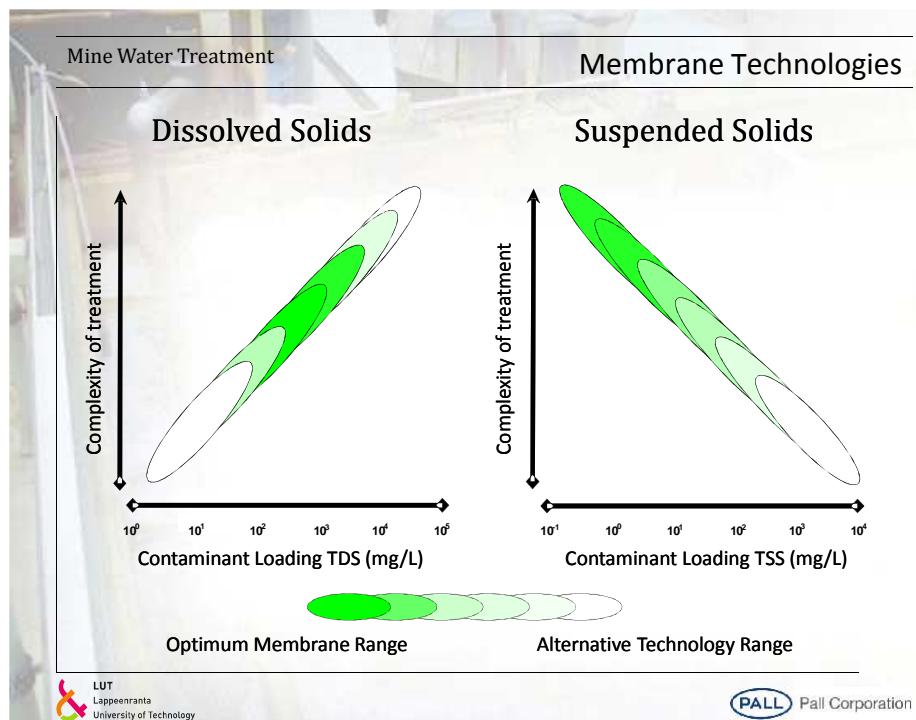


Mine Water Treatment

Burgfey/Eifel: Pilot Plant





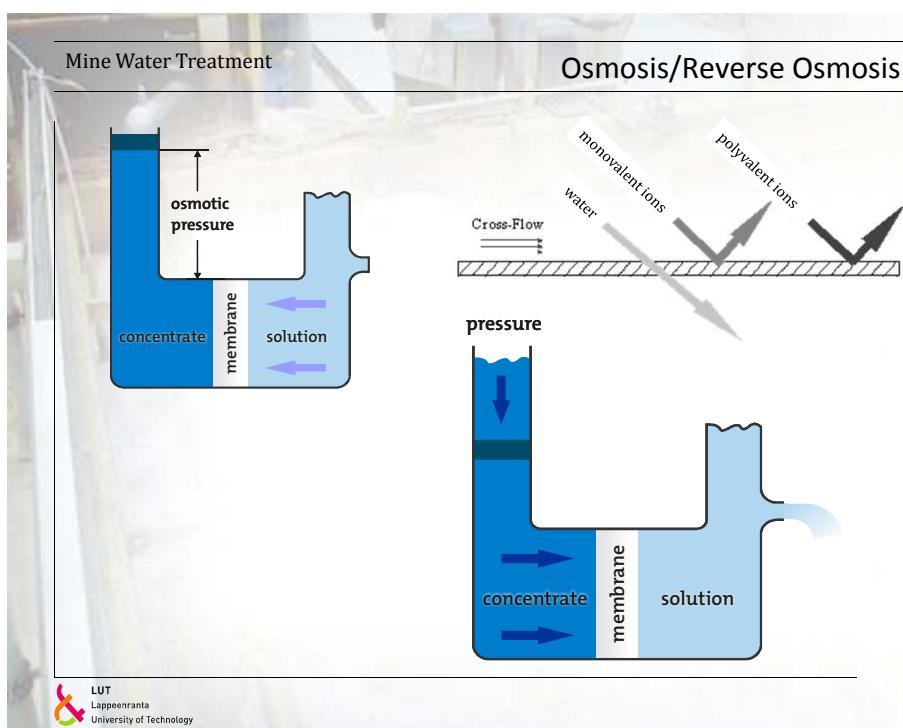


Mine Water Treatment

Reverse Osmosis

- Hydrostatic pressure difference: 10 — 100 bar
- Characteristic retardation: 98 — 99.9 % (50 — 300 dalton)
- Besides distillation the most common, and very often less cost-intensive, method to fully or partly desalinate fluids
- Usually: sea water desalination for drinking water supplies
- In the past years the method became important in the purification of heavily polluted drainage waters of waste dumps
- Material used: *e.g.* polyamides, poly sulfons

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Mine Water Treatment

Osmosis/Reverse Osmosis: Example

- St. Aidans open cast coal site; Leeds/England
- Mine flooded after overflow of River Aire in 1996
- World's largest low-pressure reverse osmosis plant at its time
- Capacity: $20,000 \text{ m}^3 \text{ d}^{-1}$ (Israel: $274,000 \text{ m}^3 \text{ d}^{-1}$)
- Water available for public water supply

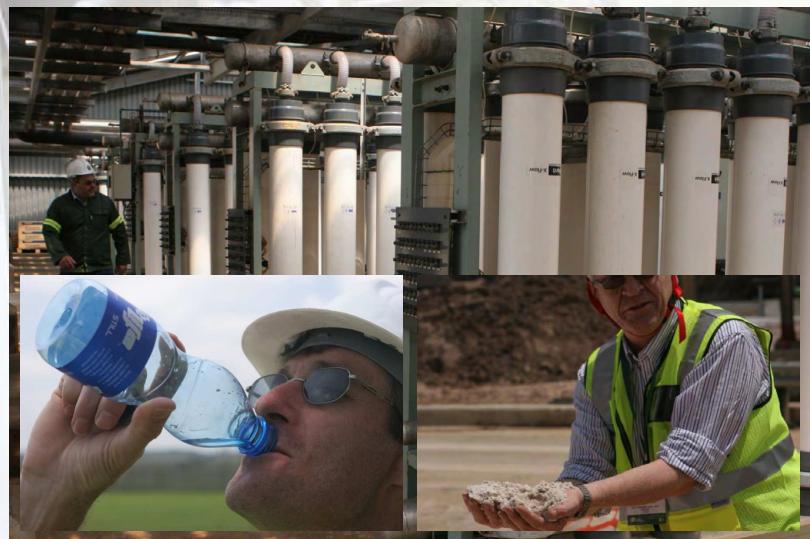


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Wilson & Brown 1997; ACWA Services Limited

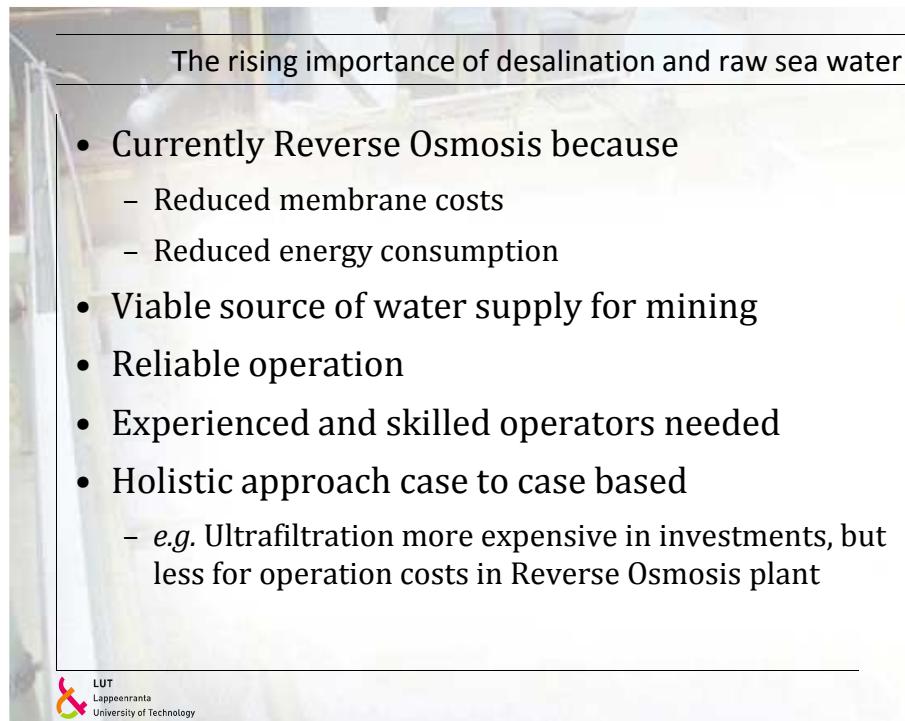
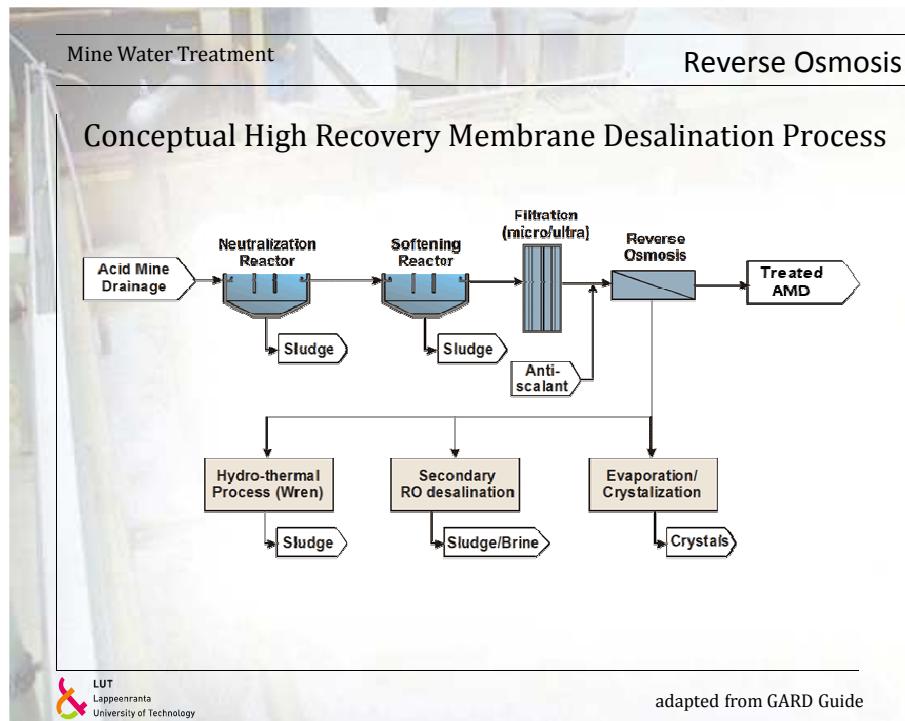
Mine Water Treatment

Reverse Osmosis



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Emalahleni/South Africa



The rising importance of desalination and raw sea water

- Other technologies
 - Multi-Stage Flashing
 - Multi-Effect Distillation

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The rising importance of desalination and raw sea water

- Currently becoming important:
 - Namibia (UraMin project: Trekkopje)
 - Chile; Southern Peru
- Less precipitation

Percentage of ensemble members enclosed:
— 100% — 66% — 33% — 10% — Median

Precipitation anomaly relative to the 1901–1995 mean

Laguna Mar Chiquita

Central Chile

Year

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The rising importance of desalination and raw sea water

- Concurrent water use of two industries
 - Mining
 - Agriculture



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Chilean Grapes | Intendenta Atacama Region Viviana Ireland | El Salvador Mine

Desalination: Pre-treatment

- The membranes need protection
- Potential Problems
 - Nutrients
 - Bacteria
 - Algae
 - Plankton
 - macro-organisms
- Dissolved air flotation
- Dual Media Filters
- Ultrafiltration

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Pre-treatment: Dissolved air flotation

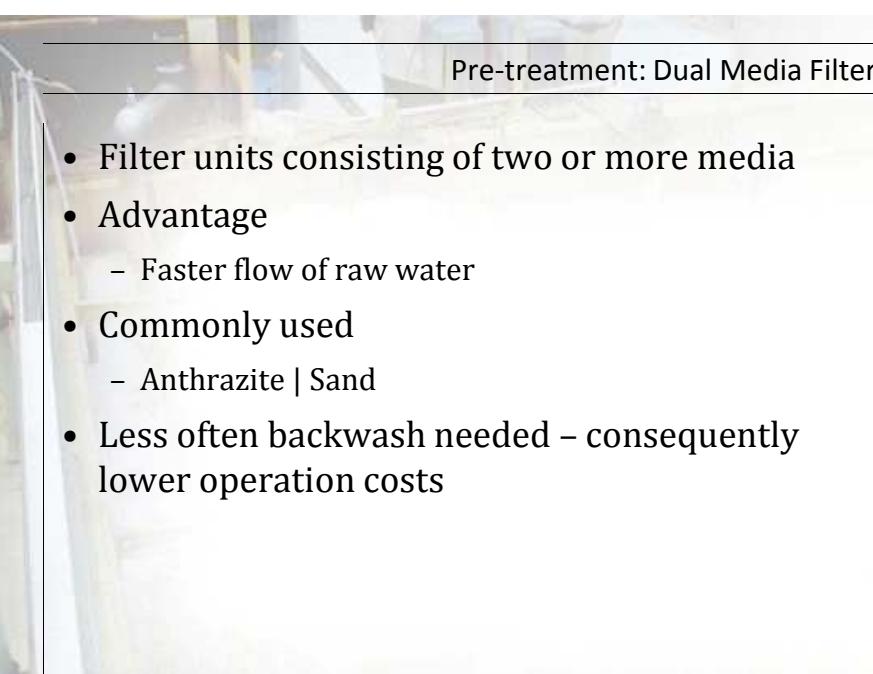
- Removes suspended matter
 - Oil
 - Solids
- Dissolve air in water by using pressure
- Release air under atmospheric conditions
 - Flotation tank
 - Basin
- Bubbles form around suspended matter and flow to surface
- Bubbles removed with *e.g.* a skimmer



Northland Engineering MN
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Pre-treatment: Dual Media Filters

- Filter units consisting of two or more media
- Advantage
 - Faster flow of raw water
- Commonly used
 - Anthrazite | Sand
- Less often backwash needed – consequently lower operation costs



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Pre-treatment: Ultrafiltration

- Removes all suspended solids
- Reduces microbiological activity
- Eliminates plugging of the reverse osmosis membranes



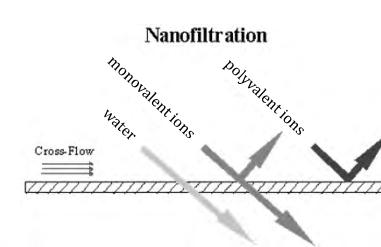
Knops et al. 2012

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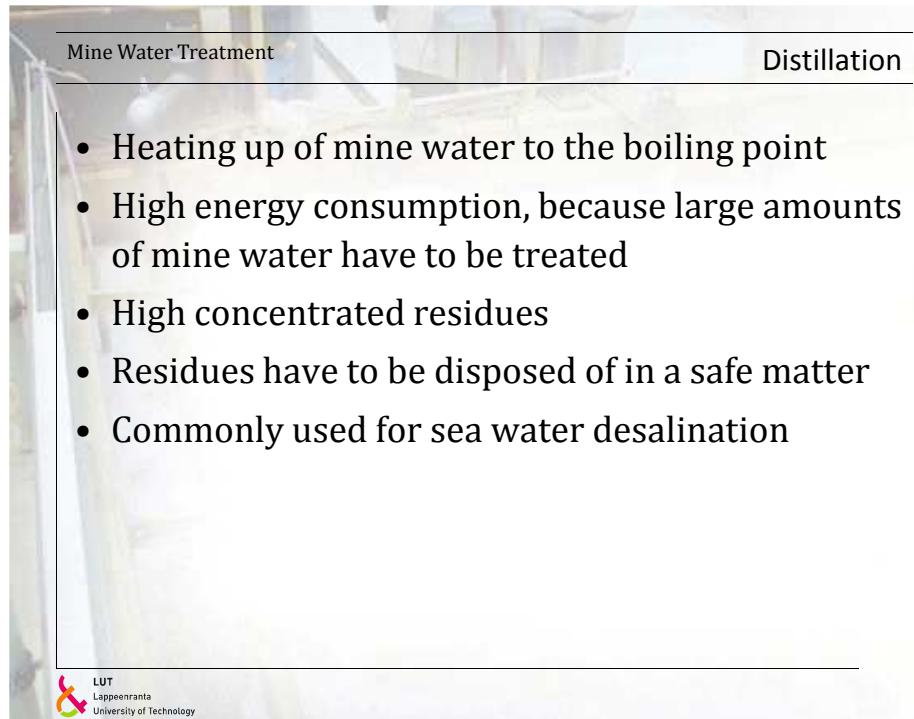
Mine Water Treatment

Nanofiltration

- Pressure driven filtration method with membranes
- Hydrostatic pressure difference: 5 — 80 bar
- Molecular separation limits: 300 — 2000 Dalton
- Membranes for nano filtration often are charged electrically to give the ability of separation differently charged molecules
- Materials used: polyamides, polysulfone, polydimethyl siloxane



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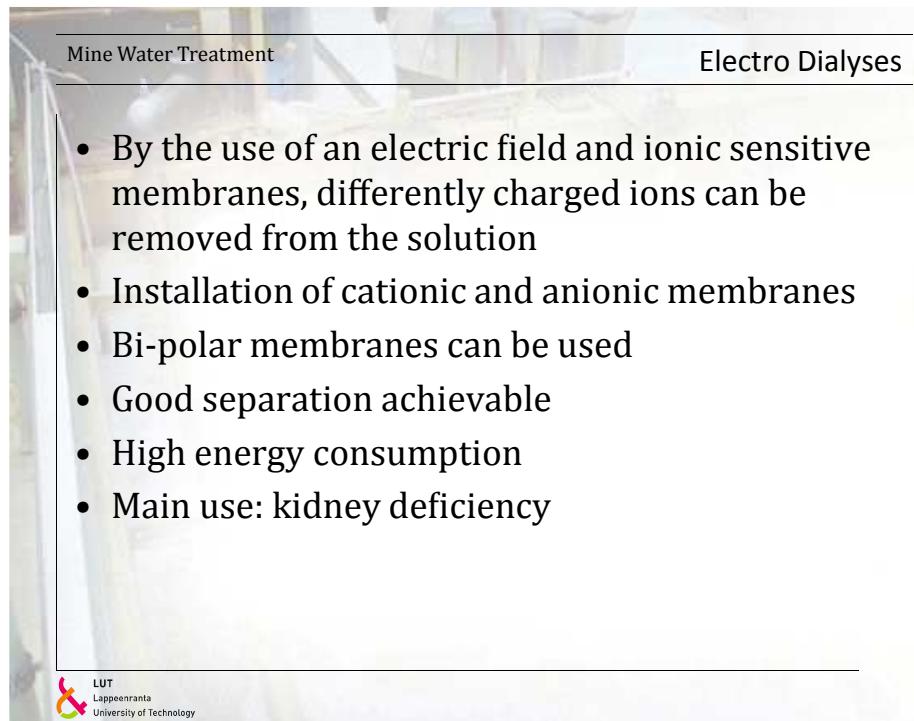


Mine Water Treatment

Distillation

- Heating up of mine water to the boiling point
- High energy consumption, because large amounts of mine water have to be treated
- High concentrated residues
- Residues have to be disposed of in a safe manner
- Commonly used for sea water desalination

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Mine Water Treatment

Electro Dialyses

- By the use of an electric field and ionic sensitive membranes, differently charged ions can be removed from the solution
- Installation of cationic and anionic membranes
- Bi-polar membranes can be used
- Good separation achievable
- High energy consumption
- Main use: kidney deficiency

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Mine Water Treatment

Electro Dialyses

- mono polar, bi-polar membranes

The diagram illustrates two types of Electro Dialysis (ED) configurations:

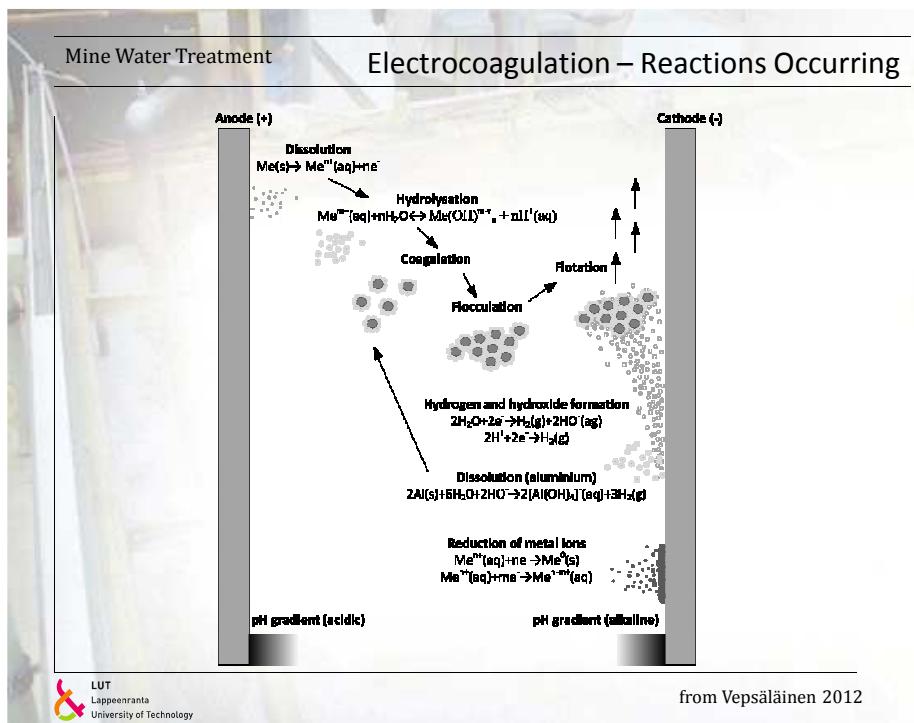
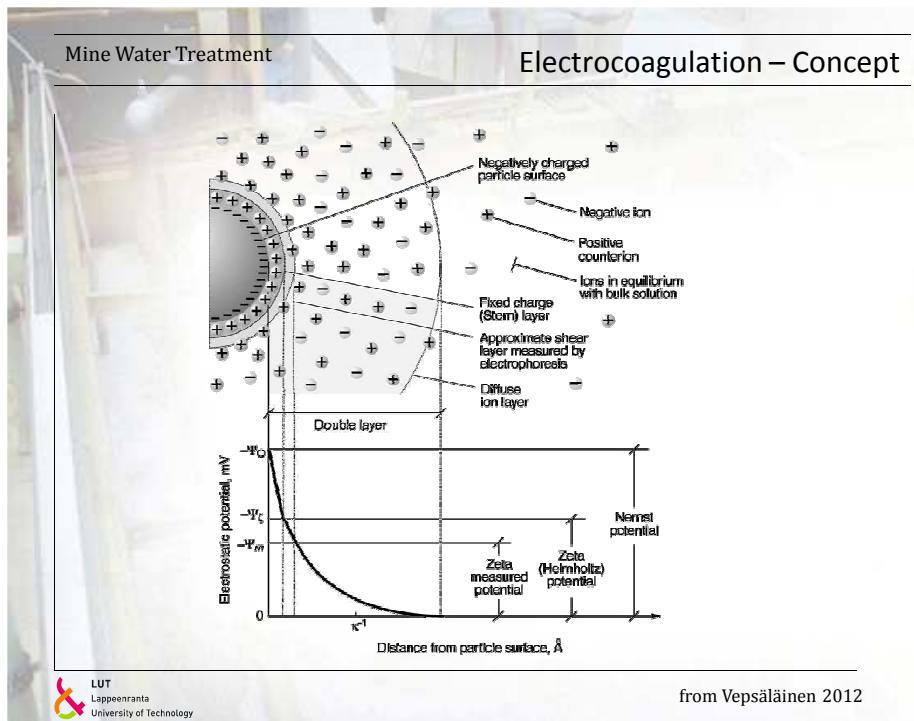
- Left Diagram (Mono-Polar Membranes):** Shows a setup with a cathode (blue circle) and an anode (red circle). A solution (Rohlösung (NaCl)) enters from the top. It passes through a CEM (Cation Exchange Membrane) layer, then an AEM (Anion Exchange Membrane) layer, then another CEM layer. The resulting stream is labeled "Konzentrat zur Kochsalzgewinnung" (Concentrate for salt production). The final product is "Diluat" (Diluate) collected in an "Innentank" (Inner tank).
- Right Diagram (Bi-Polar Membranes):** Shows a more complex setup. A solution (Rohlösung (NaCl)) enters from the top and passes through a series of membranes: BM (Bipolar Membrane), CEM, AEM, and BM. The process involves the generation of H₂O (Water) and the separation of NaOH (Sodium Hydroxide) and HCl (Hydrochloric Acid). The NaOH is collected at the bottom left, and the HCl is collected at the bottom right. The final products are "Natron-Lauge (NaOH)" and "Salz-Saure (HClO₄)".

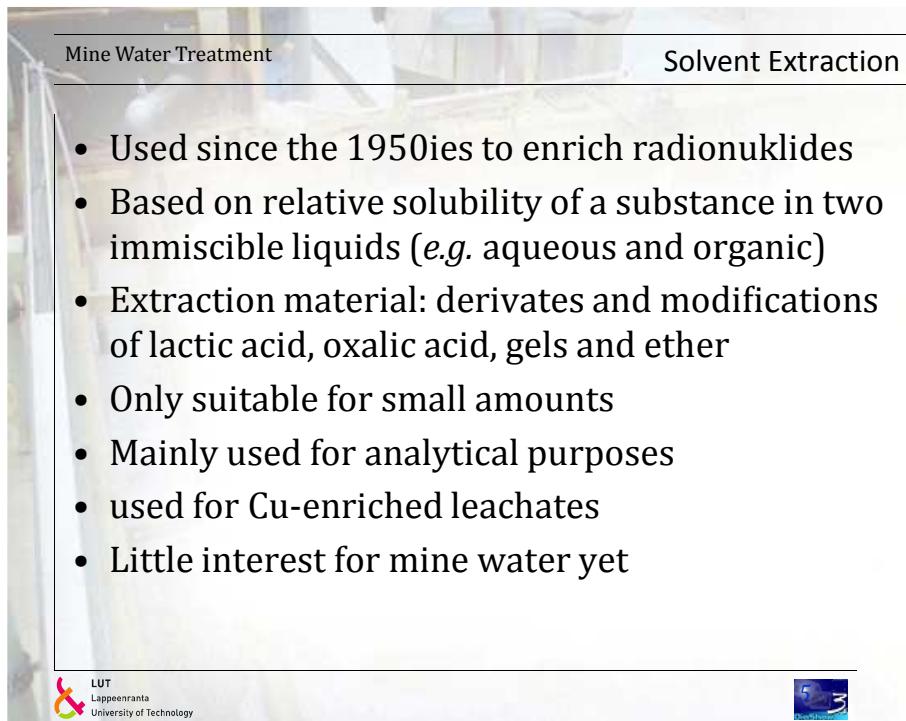
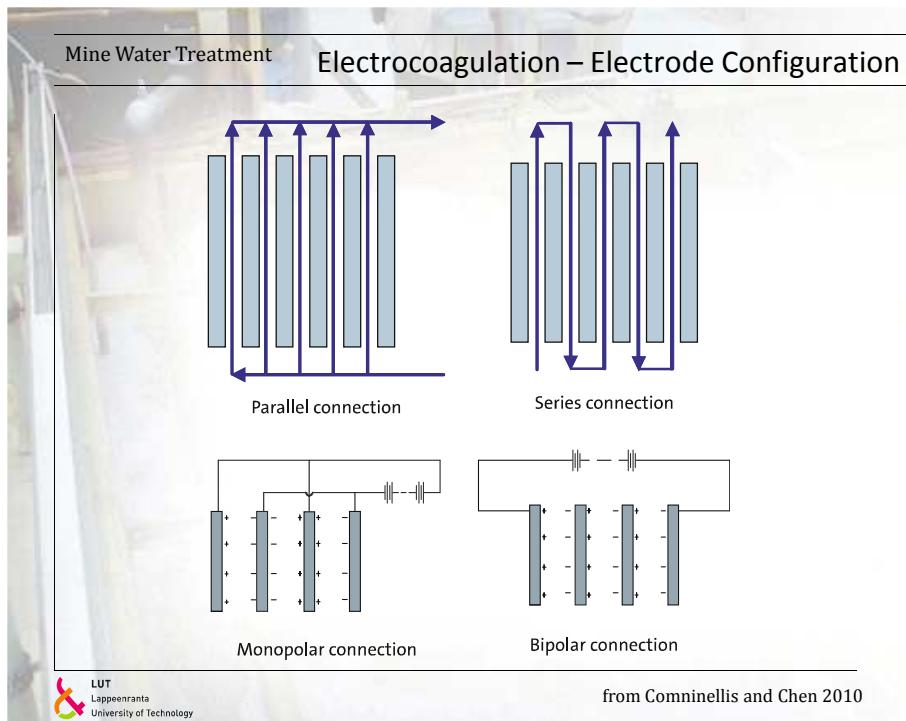
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Mine Water Treatment

Electrocoagulation

- First use in 1889 in London, UK
- 1946 first large scale plant for drinking water treatment
- At this time high energy demand, large investment costs
- Research mainly in US and USSR in the past 6 decades
- First mine water tests in 1972
- Electrochemical reactions on cathode and anode modify physicochemical parameters or release metal ions for (co-)precipitation





Mine Water Treatment Passive Treatment Methods

“A water treatment system that utilises naturally available energy sources such as topographical gradient, microbial metabolic energy, photosynthesis and chemical energy and requires regular but infrequent maintenance to operate successfully over its design life.”



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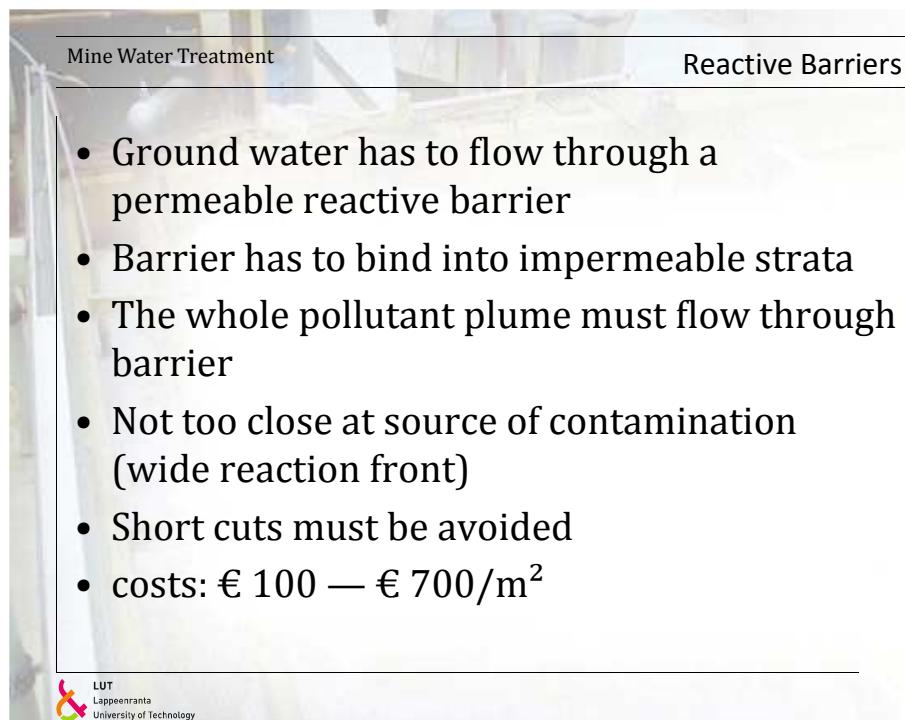
Pulses, Coetser, Heath & Muhlbauer 2004

Mine Water Treatment Passive Treatment Methods

- Reactive barrier/wall (“funnel-and-gate”)
- Anoxic limestone drains
- Aerobic constructed wetlands
- Anaerobic constructed wetlands
- SAPS (RAPS)
Successive Alkalinity Producing Systems
- VFL Vertical Flow Reactors
- Settlement lagoons



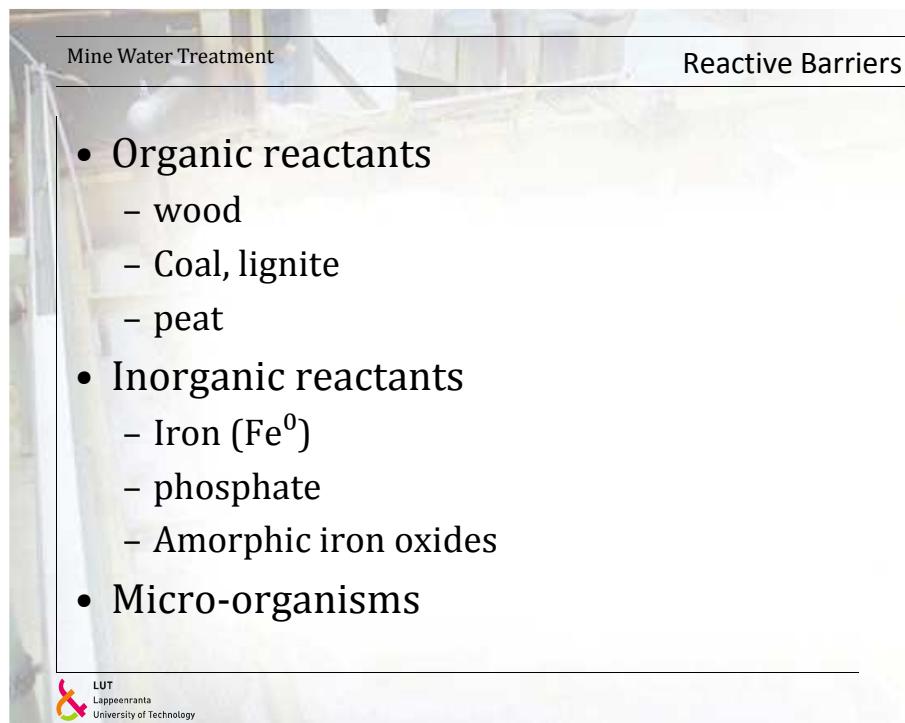
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Mine Water Treatment Reactive Barriers

- Ground water has to flow through a permeable reactive barrier
- Barrier has to bind into impermeable strata
- The whole pollutant plume must flow through barrier
- Not too close at source of contamination (wide reaction front)
- Short cuts must be avoided
- costs: € 100 — € 700/m²

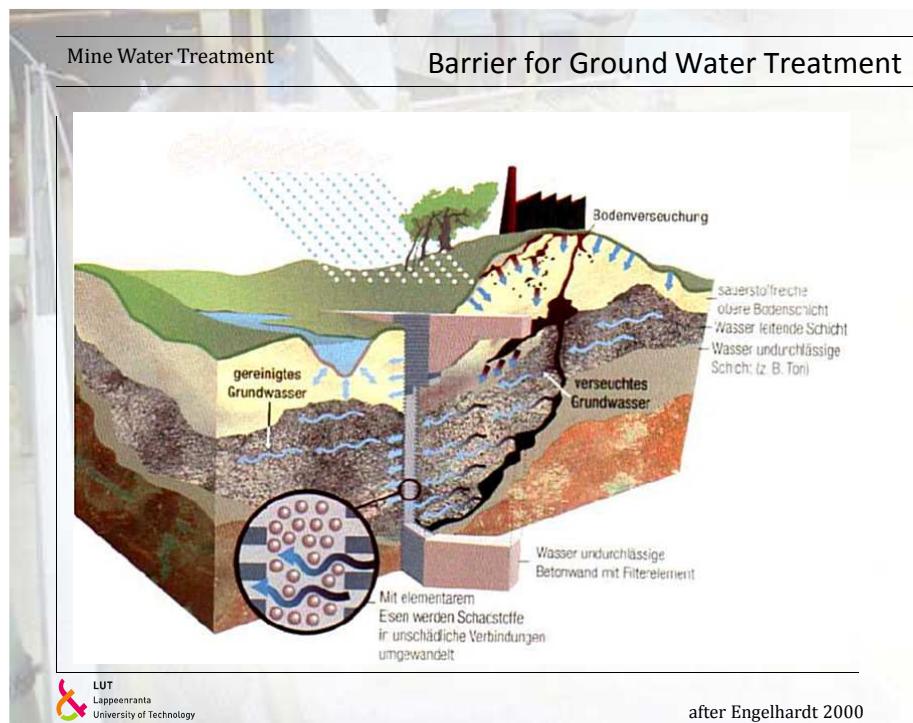
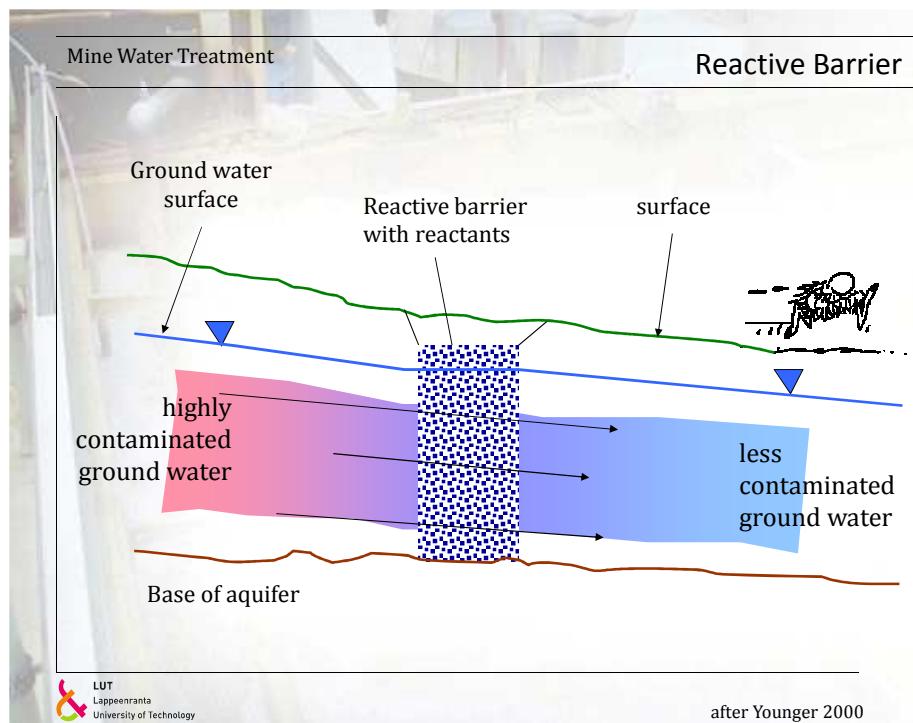
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Mine Water Treatment Reactive Barriers

- Organic reactants
 - wood
 - Coal, lignite
 - peat
- Inorganic reactants
 - Iron (Fe⁰)
 - phosphate
 - Amorphic iron oxides
- Micro-organisms

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Mine Water Treatment

Reactive Barrier: Construction Pitfalls

- Hydrogeological situation not taken into account → failure of reactive barrier

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after Kansy 2000

Mine Water Treatment

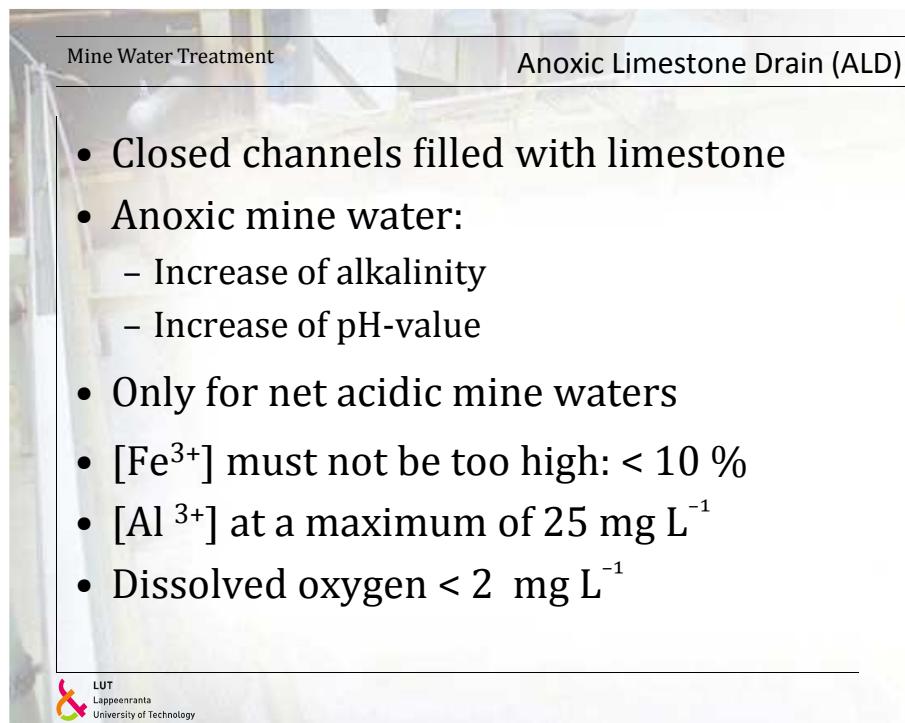
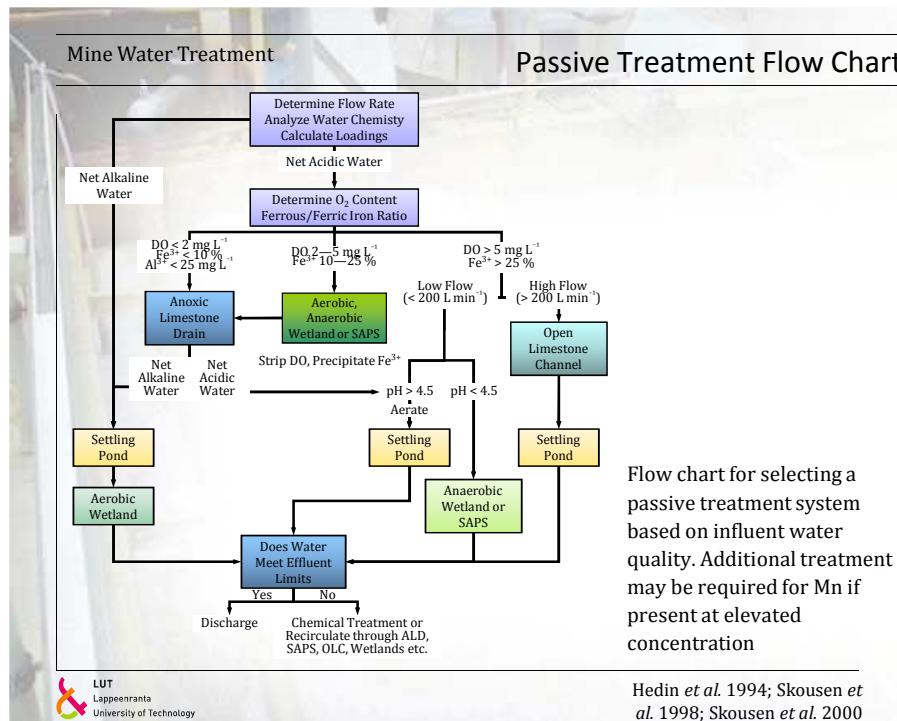
Uranium Mine Fry Canyon, Utah

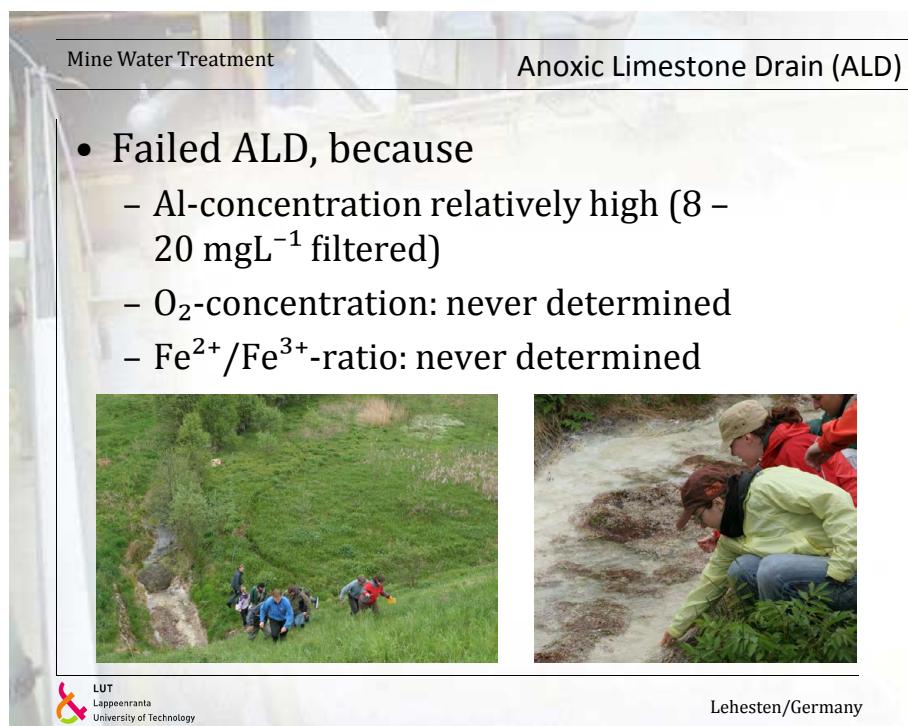
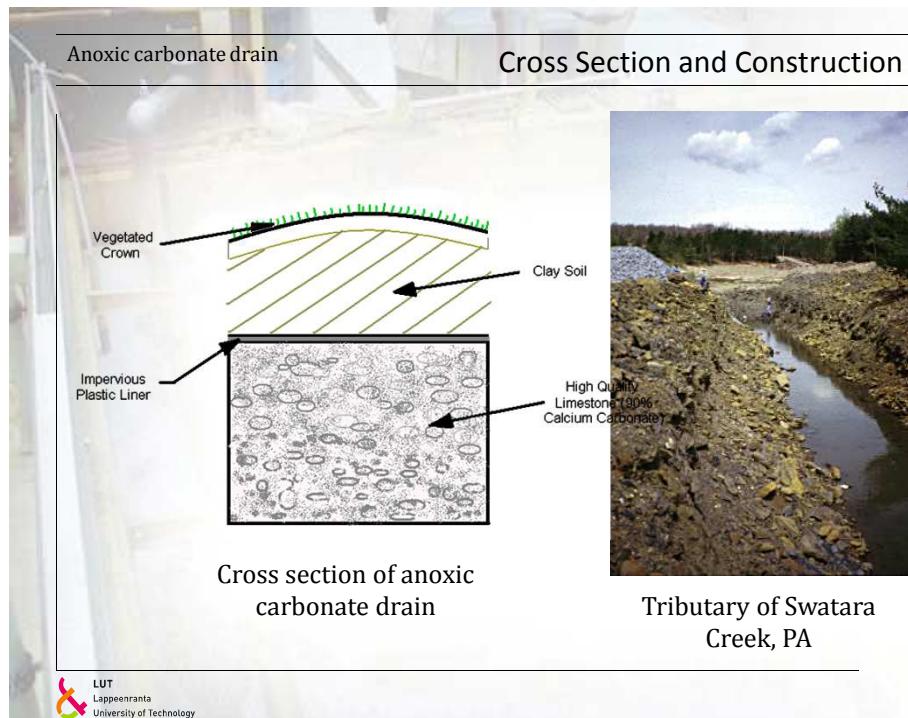
Filling of reactive barrier with reactive material

Completed reactive barrier before soil covering

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from USGS ("Fry Canyon Reactive Barrier Installation")





Anoxic carbonate drain Calculation of Carbonate needed ($\frac{t}{2}$)

$$(1) M_y = Q \cdot [Aci] \cdot 5.2596 \cdot 10^{-4}$$

$[\{t/a\} = \{L \text{ min}^{-1}\} \cdot \{\text{mg L}^{-1} \text{ CaCO}_3\} \cdot \{t \cdot \text{min} \cdot \text{mg}^{-1} \cdot a^{-1}\}]$

$$(2) M_s = t \cdot M_y$$

$[\{t\} = \{a\} \cdot \{t/a\}]$

$$(3) M_k = M_s \cdot p_k^{-1} \cdot 100 \%$$

$[\{t\} = \{t\} \cdot \{1\}]$

$$(4) M_{kt} = M_k \cdot l_k^{-1} \cdot 100 \%$$

$[\{t\} = \{t\} \cdot \{1\}]$

M_y : annual quantity of acid
 M_s : mass of acid over lifetime of drain
 M_k : mass of carbonates to neutralize acid
 M_{kt} : mass of carbonates to effect neutralisation

Q : water flow; $[Aci]$: acidity; t : lifetime of carbonate drain;
 p_k : CaCO_3 -purity of limestone; l_k : dissolution rate of limestone

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Anoxic carbonate drain Calculation of Carbonate needed ($\frac{t}{2}$)

“ $\pi \cdot \delta^2$ ”-rule

Residence time: 14 hours

Pore volume limestone: 50 %

lifetime: 15 years

Necessary carbonate volume:
 $\frac{1}{50\%} \cdot \text{volume mine water} \cdot 14 \text{ hours}$

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Passive Treatment	Aerobic Wetlands
	<ul style="list-style-type: none">• pH of mine water <i>circum neutral</i> (> 6.5)• Water net alkaline• Shallow water systems (15–50 cm)• Wetland plants (<i>Typha</i>, <i>Phragmites</i>, <i>Juncus</i>) to reduce water velocity• Fe-removal rates: $10\text{--}20 \text{ g} \cdot \text{m}^{-2} \cdot \text{d}^{-1}$

The figure illustrates the cross-section of an aerobic wetland. A vertical scale bar on the left indicates a height of 15—50 cm, with arrows pointing up and down. The cross-section shows a soil profile with a blue layer representing water or saturated soil. Several green plants with yellowish-green flower spikes (Typha) are rooted in the soil. Other green plants with smaller, more rounded flower spikes (Phragmites and Juncus) are also visible above the water level.

Aerobic Wetlands

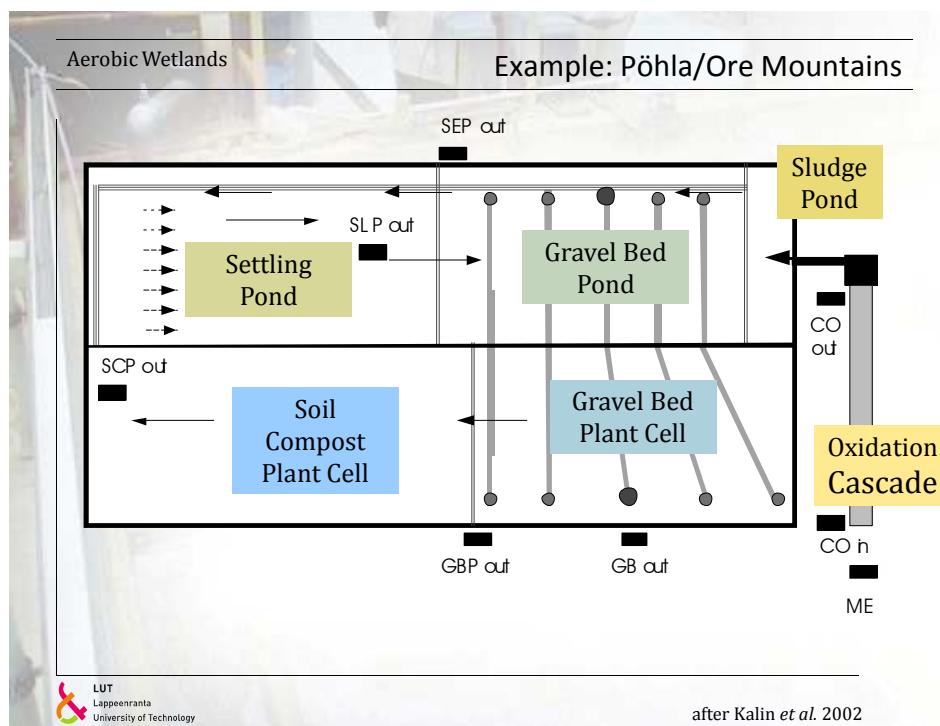
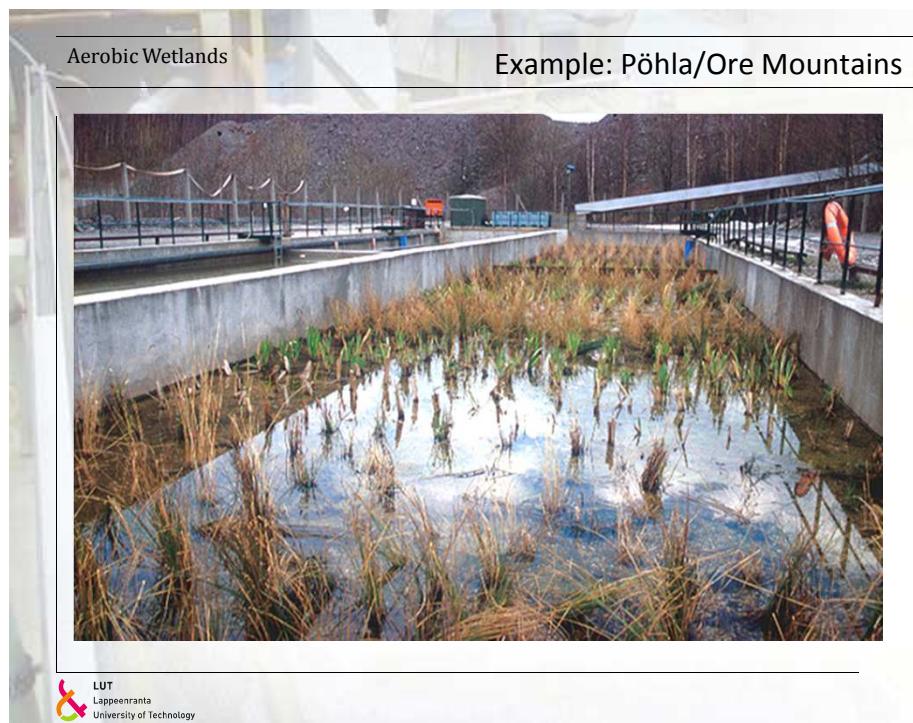
Cross Section and Plants

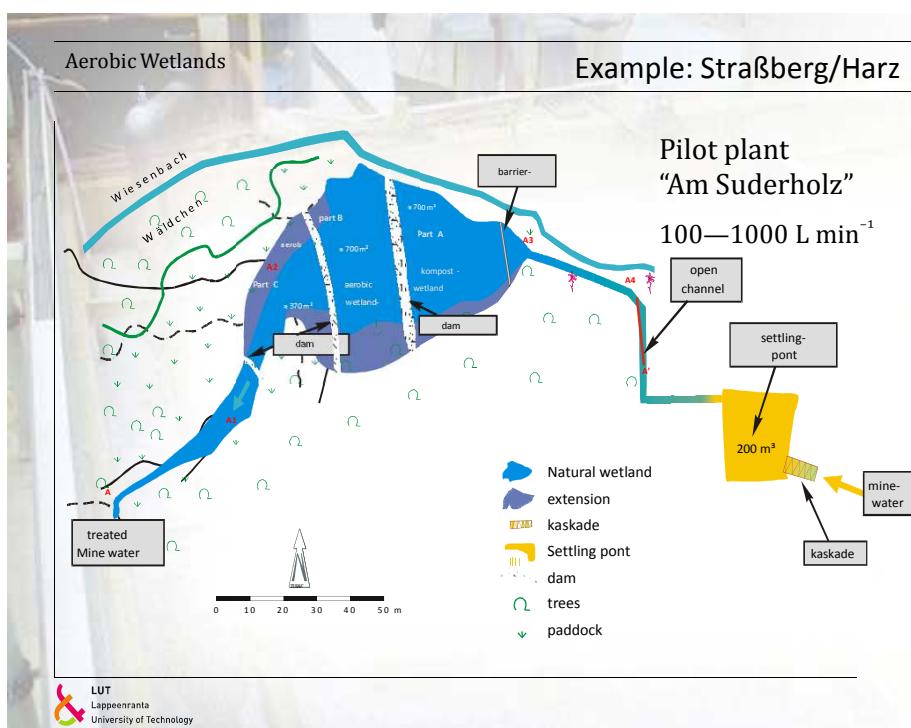
15 — 50 cm

Typha

Phragmites

Juncus

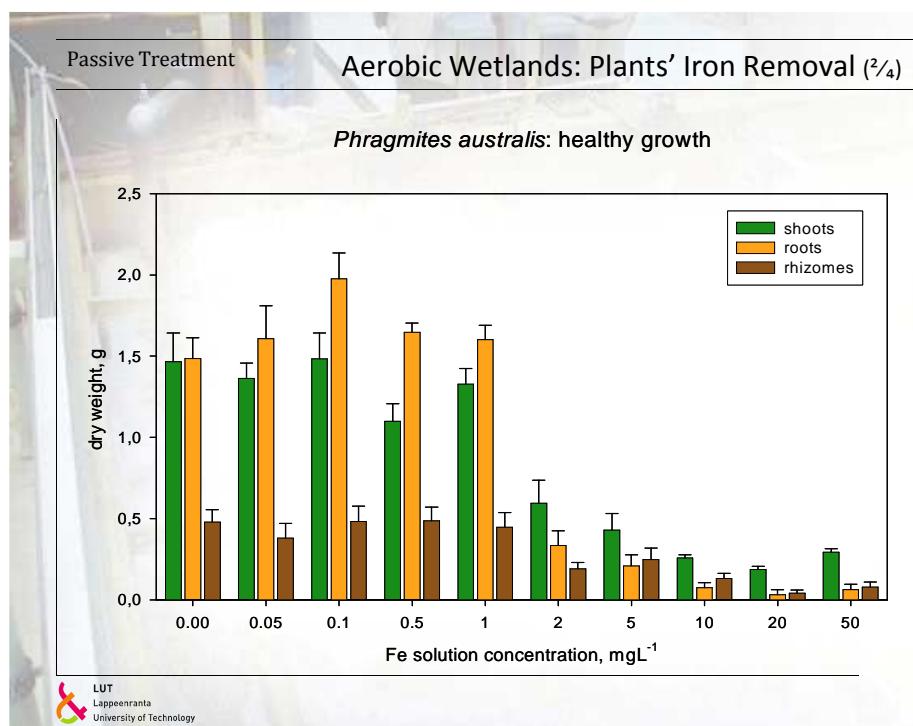


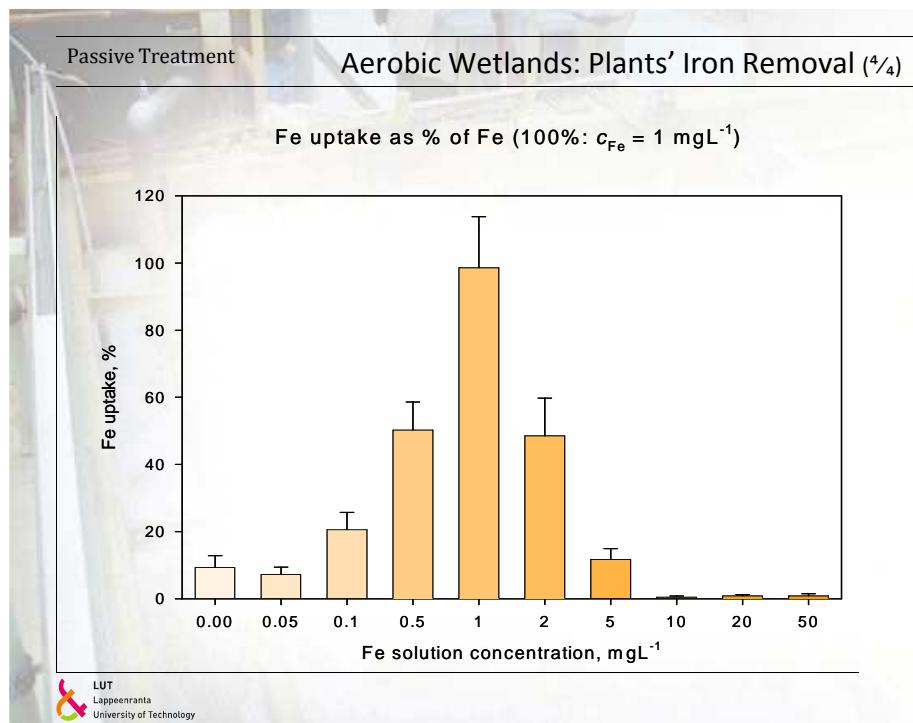
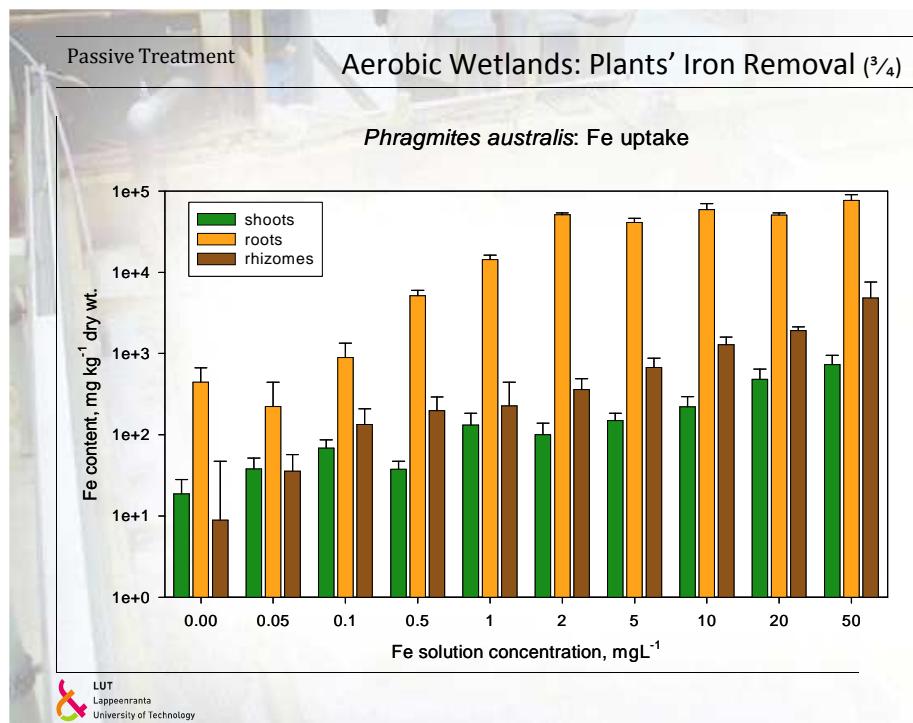


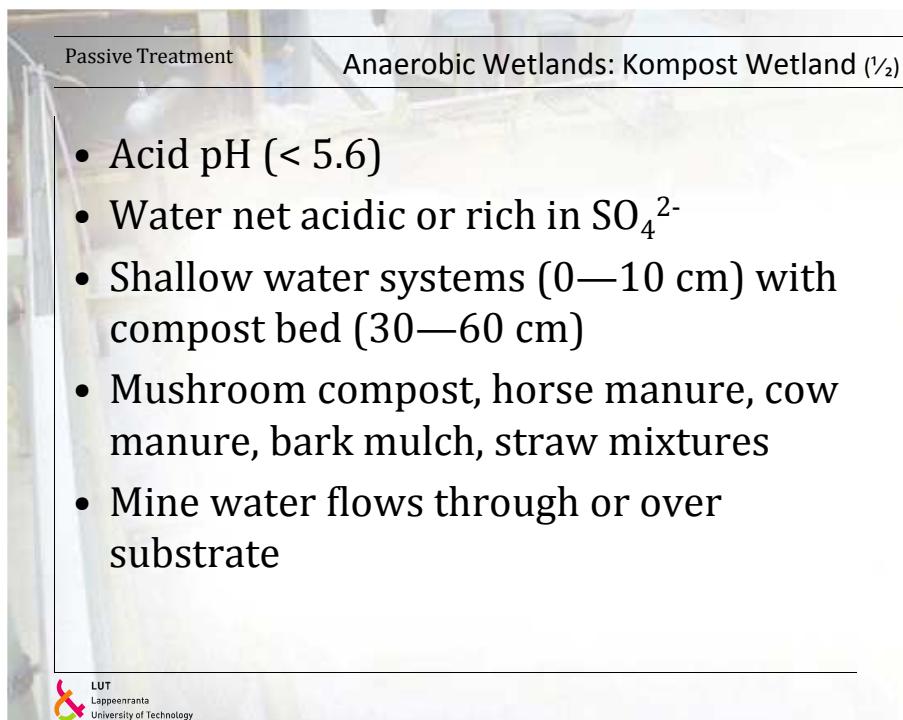
Passive Treatment Aerobic Wetlands: Plants' Iron Removal (1/4)

- Case study: *Phragmites australis*
- Seeds taken from uncontaminated site
- Seedlings of uniform size selected (5 for each treatment)
- 27 days growth, then $\text{FeSO}_4 \cdot 7\text{H}_2\text{O}$ added and another 64 days growth
- Plants harvested, divided into roots, rhizomes and shoots and dried at 40°C for 2 days

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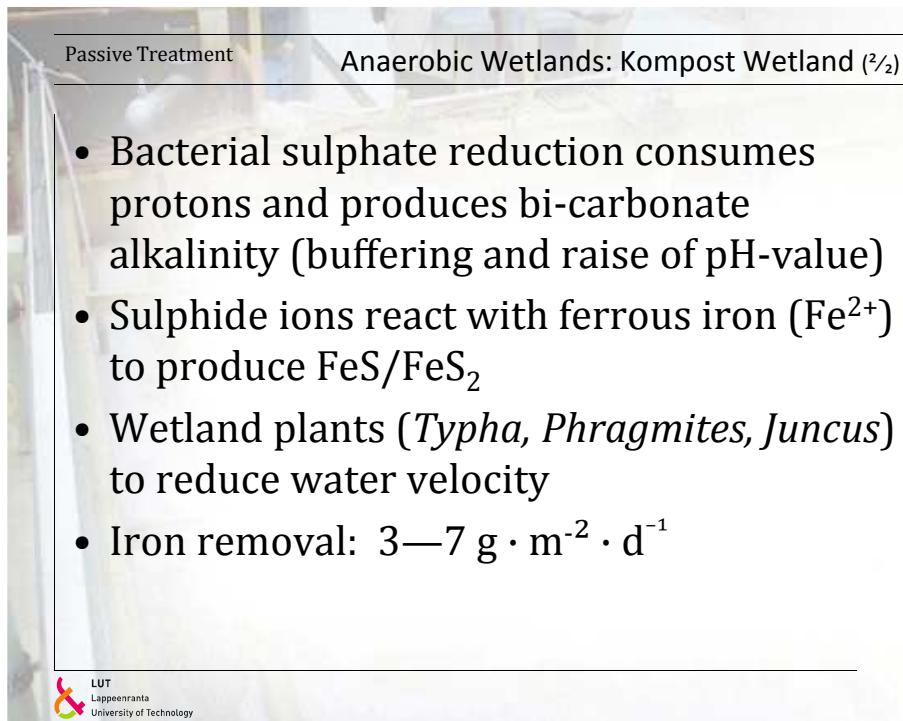




Passive Treatment Anaerobic Wetlands: Kompost Wetland (½)

- Acid pH (< 5.6)
- Water net acidic or rich in SO_4^{2-}
- Shallow water systems (0—10 cm) with compost bed (30—60 cm)
- Mushroom compost, horse manure, cow manure, bark mulch, straw mixtures
- Mine water flows through or over substrate

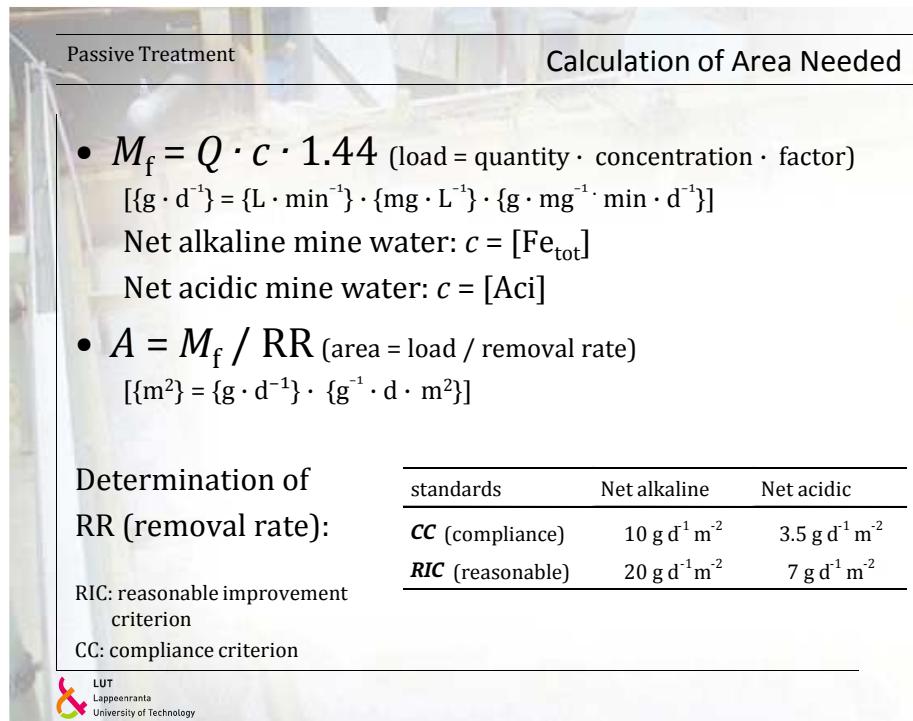
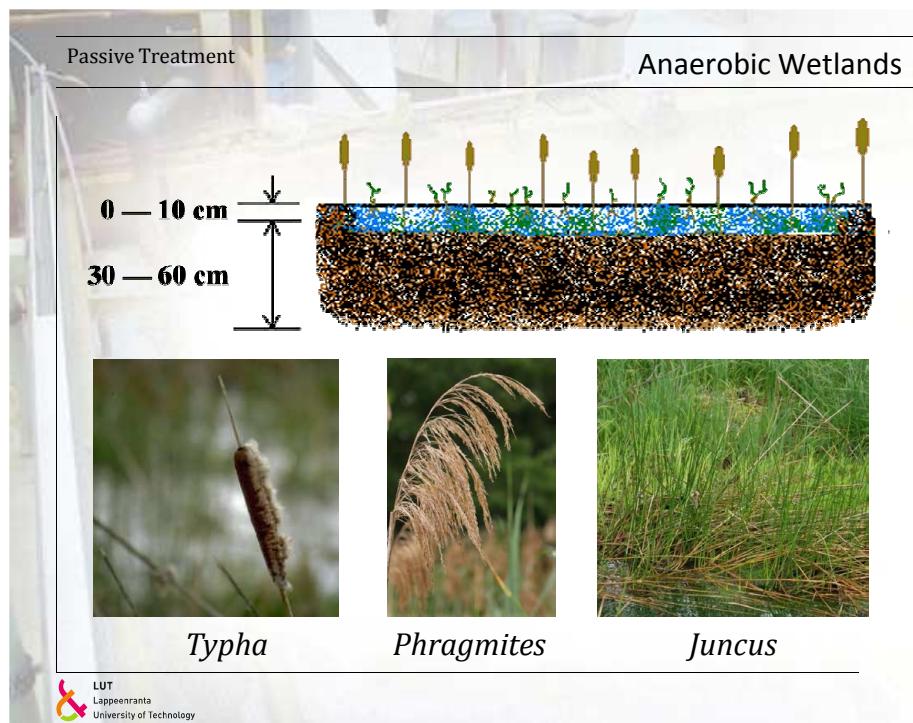
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Passive Treatment Anaerobic Wetlands: Kompost Wetland (½)

- Bacterial sulphate reduction consumes protons and produces bi-carbonate alkalinity (buffering and raise of pH-value)
- Sulphide ions react with ferrous iron (Fe^{2+}) to produce FeS/FeS_2
- Wetland plants (*Typha*, *Phragmites*, *Juncus*) to reduce water velocity
- Iron removal: $3—7 \text{ g} \cdot \text{m}^{-2} \cdot \text{d}^{-1}$

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Passive Treatment		Calculation of Area Needed: Gernrode/Harz	
Flow rate	16.2 L s^{-1}	$Q =$, L min^{-1}
Calcium	1122 mg L^{-1}	$[\text{Fe}_{\text{tot}}] =$, mg L^{-1}
Magnesium	100 mg L^{-1}	$[\text{Aci}] =$, mg L^{-1}
Sodium	333 mg L^{-1}	$M_{\text{f-Aci}} =$, g d^{-1}
Potassium	16 mg L^{-1}	$M_{\text{f-Fe}} =$, g d^{-1}
Iron	10.7 mg L^{-1}	$A_{\text{RIC-Aci}} =$, m^2
Manganese	4.3 mg L^{-1}	$A_{\text{CC-Aci}} =$, m^2
Zinc	144 $\mu\text{g L}^{-1}$	$A_{\text{RIC-Fe}} =$, m^2
Copper	28 $\mu\text{g L}^{-1}$	$A_{\text{CC-Fe}} =$, m^2
Alkalinity	8.1 mg L^{-1}		
Acidity	75.9 mg L^{-1}		
Sulphate	72 mg L^{-1}		
Chloride	1759 mg L^{-1}		
pH	5.6 -		
Temperature	11.2 $^{\circ}\text{C}$		
Redox	197 mV		
el. Conductivity	4,856 $\mu\text{S cm}^{-1}$		

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Passive Treatment		Calculation of Area Needed: Gernrode/Harz	
$Q =$	972 , L min^{-1}		
$[\text{Fe}_{\text{tot}}] =$	7.7 , mg L^{-1}		
$[\text{Aci}] =$	67.7 , mg L^{-1}		
$M_{\text{f-Aci}} =$	106236 , g d^{-1}		
$M_{\text{f-Fe}} =$	14977 , g d^{-1}		
$A_{\text{RIC-Aci}} =$	15177 , m^2		
$A_{\text{CC-Aci}} =$	30353 , m^2		
$A_{\text{RIC-Fe}} =$	749 , m^2		
$A_{\text{CC-Fe}} =$	1498 , m^2		

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Passive Treatment SAPS: Successive Alkalinity Producing Systems

- Combination of anoxic limestone drains (ALD) and anaerobic wetlands
- Water flows gravity driven downward through the anoxic wetland: compost and carbonate
- Hydraulic gradient at least 1.5 m, better 2.5 m
- Lifetime 15 — 20 years

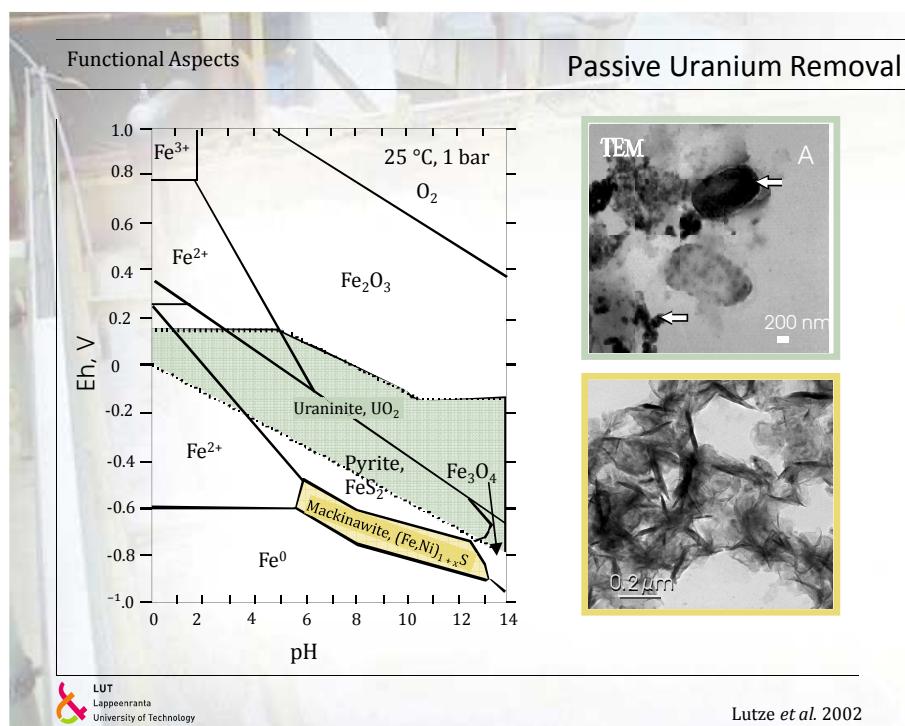
SAPS: Systems Cross Section and Scheme

Functional Aspects

Passive Uranium Removal

- Precipitation under reducting conditions
 - at the sulphate reduction zone
 - as Uraninite
- Sorption
 - Plants (e.g. roots)
 - Iron-hydroxide as co-precipitate
 - Biological processes involved
- Plant uptake
 - Low in the case of uranium

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VFRs – Vertical Flow Reactors

- Simple construction
- Alkaline conditions
- Acid conditions with low iron
- Bacterial processes involved – details not studied yet

raw mine water in

overflow

treated mine water out

ochre layer
11.5 cm unreactive <10 gravel bed
11.5 cm unreactive 30/30 stone bed

Florence 2014

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Settling Lagoons

- Simple construction
- Possible, wherever a fast precipitation occurs
- Acidity must not be too high

The diagram shows a trapezoidal settling lagoon. On the left, an 'Inflow' arrow points into the lagoon from a pipe. On the right, an 'Outflow' arrow points out of the lagoon through another pipe. The bottom of the lagoon has a triangular outlet structure with a vertical pipe and a valve symbol. The top edge of the lagoon is slightly irregular.

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Tar Creek Superfund Task Force 2000

Mine Water Treatment Strategic insights into leading technology

- Education and Training
 - Well educated operators
 - Aware of potential environmental impacts
 - Know how process operates
 - Are allowed to make own decisions

A man wearing a cap and glasses is seen from the side, looking at a computer monitor. The monitor displays a complex industrial control interface with various gauges, charts, and status indicators. In the background, other equipment and monitors are visible in the control room.

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Mine Water Treatment Strategic insights into leading technology

- Mine Water Management
 - Recycle
 - Reuse
 - Aquifer Storage and Recovery
 - Surface Storage
 - Expert Systems

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Mine Water Treatment Strategic insights into leading technology

- Membrane Techniques
 - Ultrafiltration
 - Reverse Osmosis
 - Chemical Pre-treatment

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Mine Water Treatment Strategic insights into leading technology

- Ion Exchange (used since 1969 for mine water)
 - GYP-CIX® (Bowell 2000: Berkeley Pit, Montana)
 - BIO-Fix (Bennett et al 1991: lab tests)
 - Zeolites (different authors and applications)

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itrcweb.org, Soudan Mine | iontechinc.com, Adit 93 Kremitkovtsi, Bulgaria | iontechinc.com Assarel-Medet, Bulgaria

Mine Water Treatment Strategic insights into leading technology

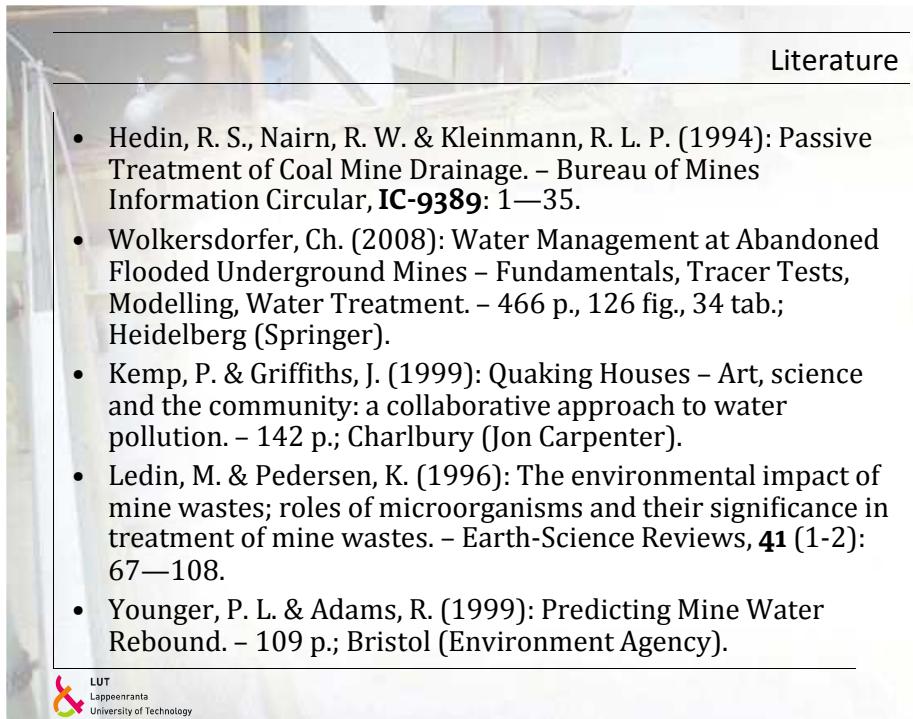
- Hybrid ICE Freeze Crystallization Technology
 - German – South African development

Symbol List

- INDUSTRIAL WASTE WATER
- REFRIGERANT LOOP
- DISTILLED WATER
- CHEMICAL RECOVERY
- FLUID TEMPERATURE
- HEAT EXCHANGER

e.g. Reddy & Lewis 2010

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