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From Ground Water to Mine Water

Environmental Hydrogeology in Mining

Introduction, Historical Background

Prof. Dr. Christian Wolkersdorfer

Industrial Research Chair in Mine Water Remediation & Management

From Ground Water to Mine Water

Contents

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Introduction

Subjects involved

- 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

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Introduction

Mine Water: The Good and the Ugly

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Introduction

History

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

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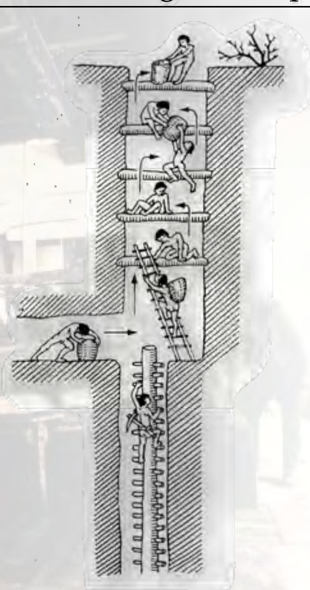
History

Dewatering Techniques

- Bailing
  - Manuel bucket or sack water-raising



from Rebrik 1987

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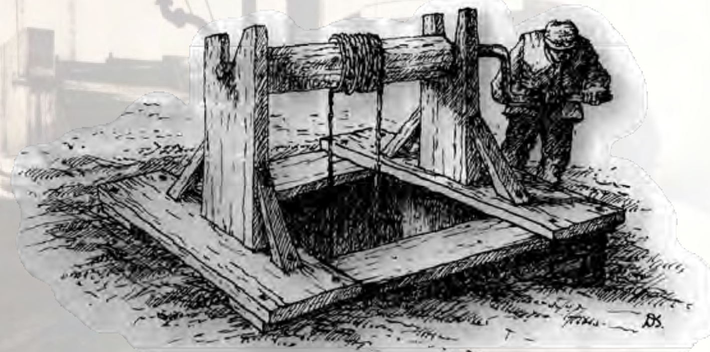
History

Dewatering Techniques

- Whinches
  - Manuel bucket or sack water-raising



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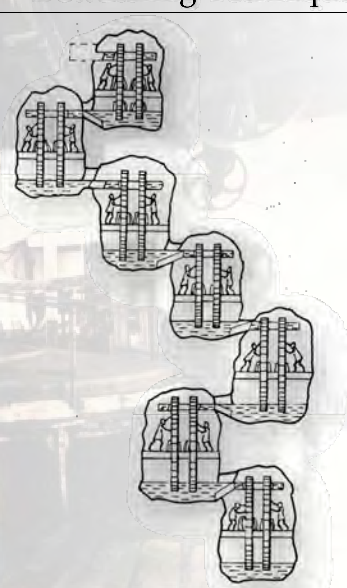
Cowman & Reilly 1988

History

Dewatering Techniques

- Man powered Water wheels
  - Egypt
  - Man power



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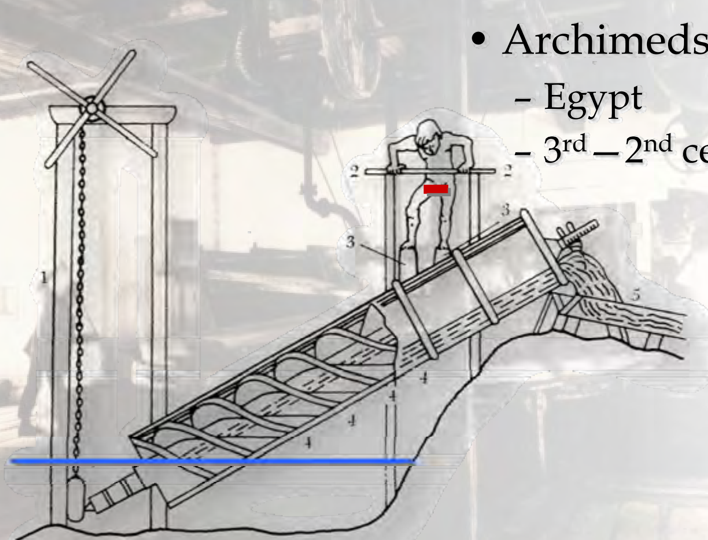
from Rebrik 1987

History

Dewatering Techniques



- Archimeds' screw
  - Egypt
  - 3^{rd} – 2^{nd} cent. BC

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from Rebrik 1987

History

Dewatering Techniques

- Bulgenkunst (bucket sprocket)
  - Germany
  - 14^{th} century

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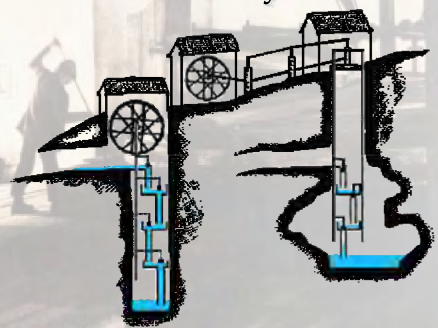
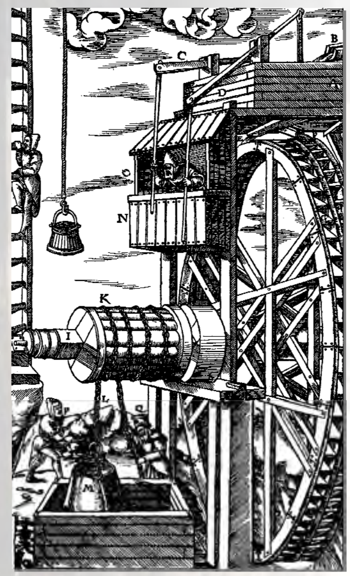
from Agricola 1555

History

Dewatering Techniques

- Water wheel
  - Germany
  - Rammelsberg
  - 15th century





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from Agricola 1555

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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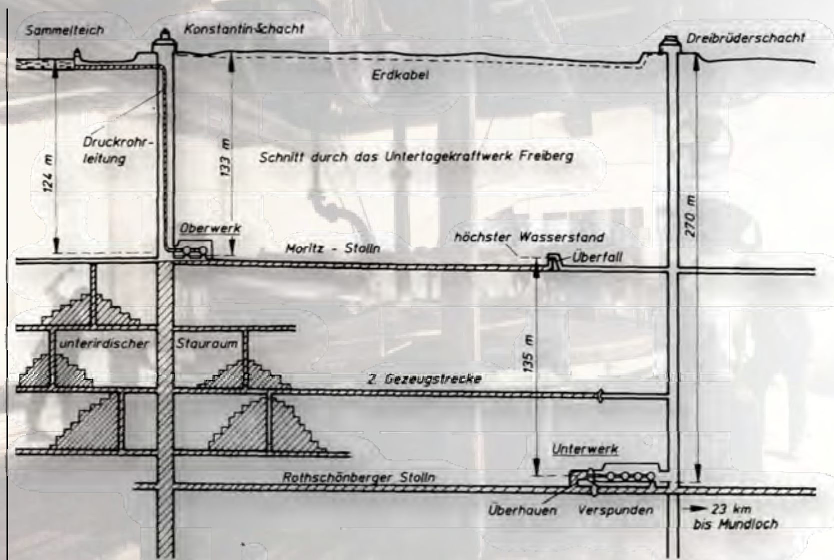
Production of Energy

Ore Mountains: Freiberg/Saxony



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from Jobst *et al*. 1994

Production of Energy

Ore Mountains: Freiberg/Saxony

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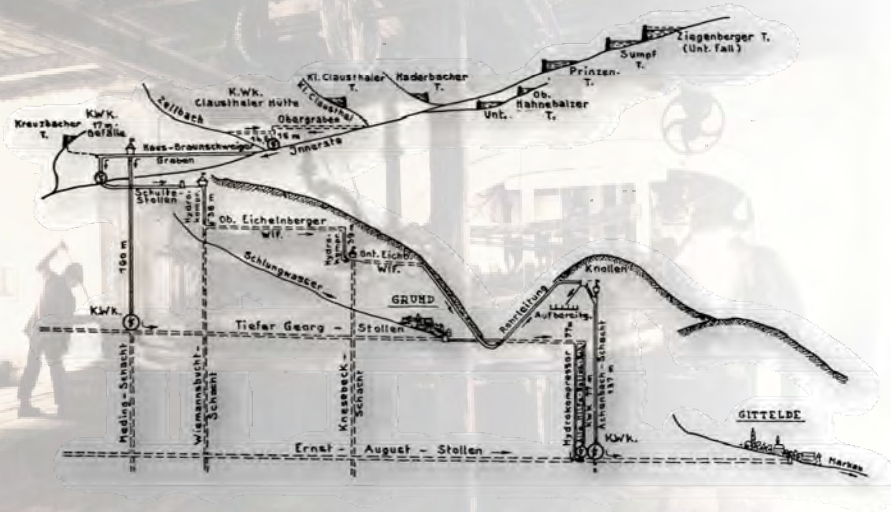
Weyer 2002

Production of Energy

Harz Mountains: Innerste Water System



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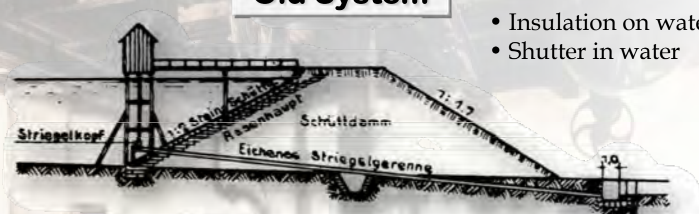
from Haase 1985

Production of Energy

Harz Mountains: Dam Constructions

Old System

- Insulation on water side
- Shutter in water



New System

- Insulation within dam
- Shutter in dam

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from Haase 1985

Acidic or polluted mine water

Ore Processing

- Ore cleaning
- Separation

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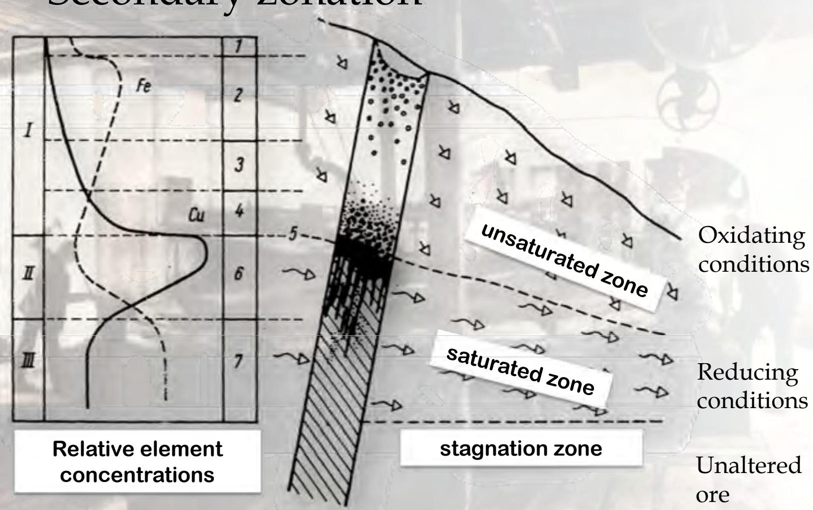
from Agricola 1555

Acidic or polluted mine water

Genesis of Ore Deposits

- Secondary zonation



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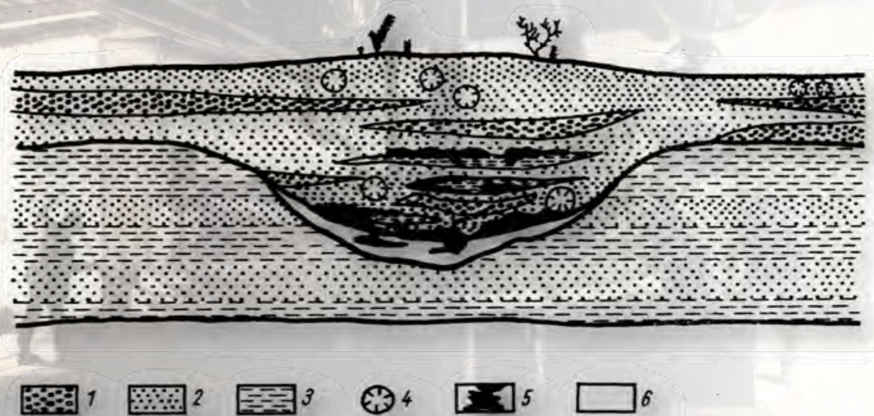
Baumann *et al.* 1979

Acidic or polluted mine water

Genesis of Ore Deposits

- Uranium: Roll Front Deposit



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Baumann *et al.* 1979

Acidic or polluted mine water

Reasons for Mine Closure

- „Four things ruin a mine“

War

Deseases

Inflation

Listlessness

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from Lässl 1556

History

Literature

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- 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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From Ground Water to Mine Water

Environmental Hydrogeology in Mining

Mining Methods, Technical Terms

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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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From Ground Water to Mine Water

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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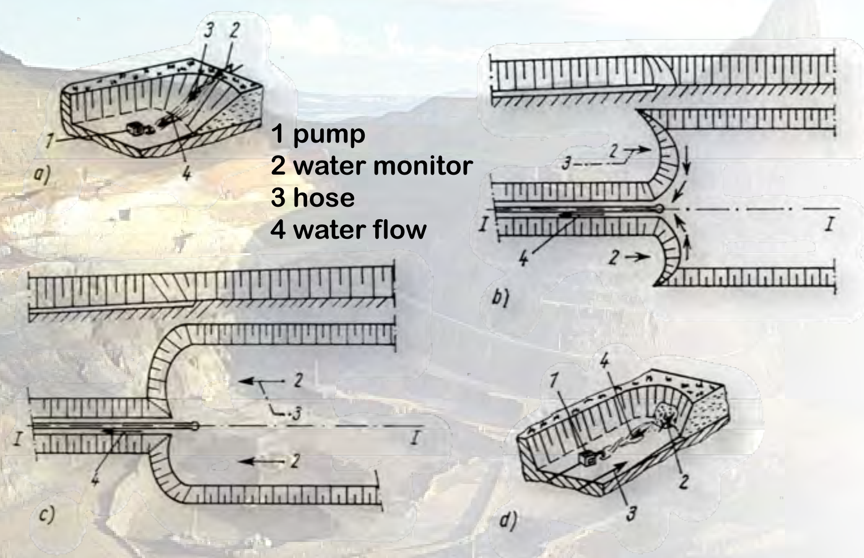
Mining Methods

Hydrominig



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from Strzodka *et al.* 1979

Mining Methods

Hydrominig

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Tin mining Cornwall, UK

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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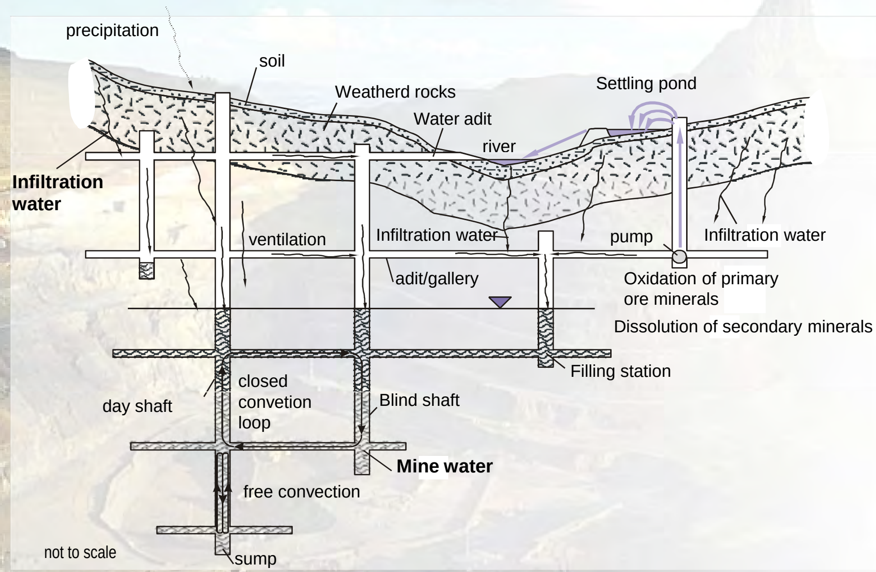
Mining Methods

Scheme of flooded Underground mine



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from Wolkersdorfer 1996

Mining Methods

Mine Outlay: historic lead-zinc-mine Tyrol

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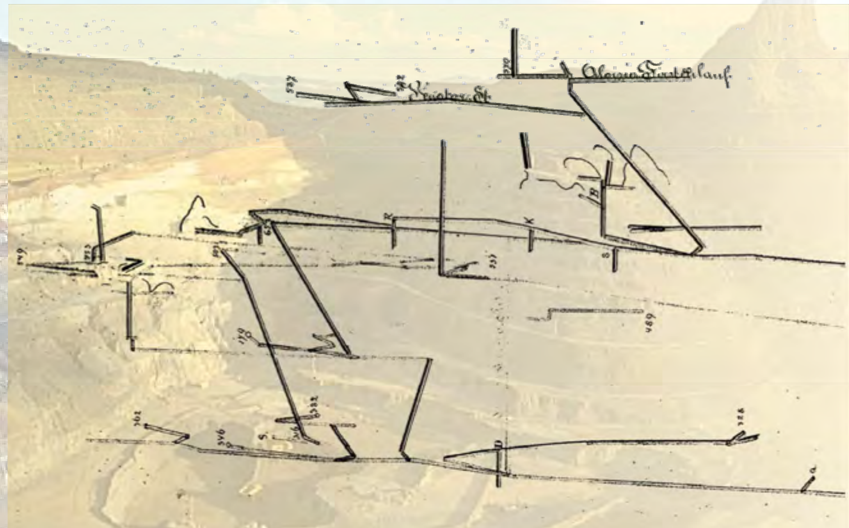
from BH Innsbruck 1880

Mining Methods

Mine Outlay: historic lead-zinc-mine Tyrol



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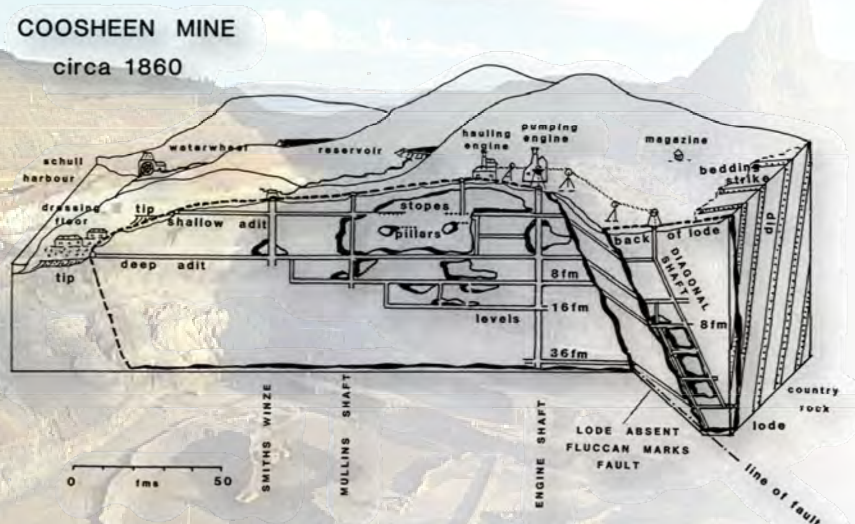
from BH Innsbruck 1880

Mining Methods

Scheme of deep underground mine



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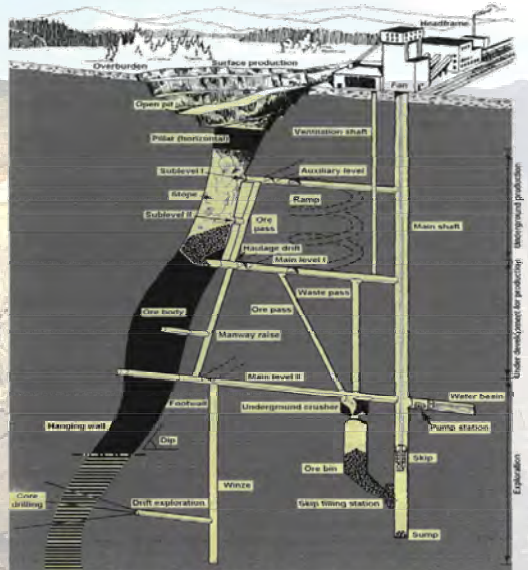
Cowman & Reilly 1988

Mining Methods

Scheme of deep underground mine



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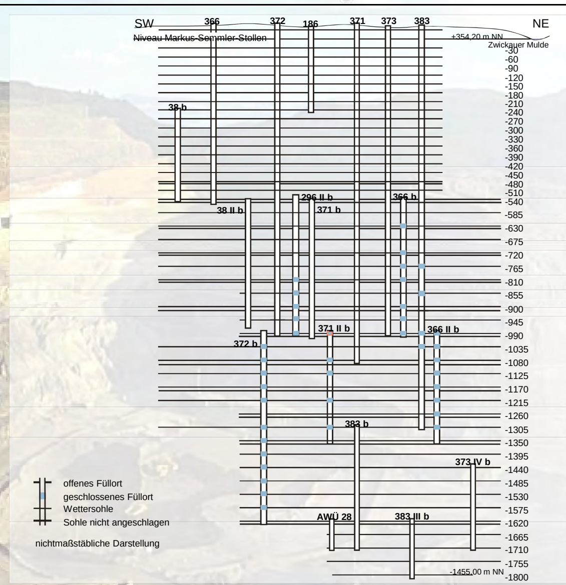
Gertsch & Bullock 1998

Mining Methods

Example: German uranium mine



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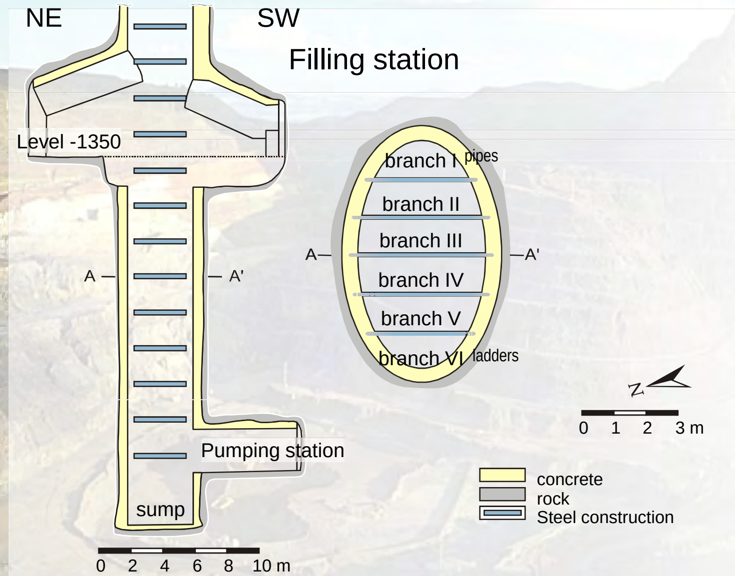
from Wolkersdorfer 1996

Mining Methods

Typical filling station and shaft



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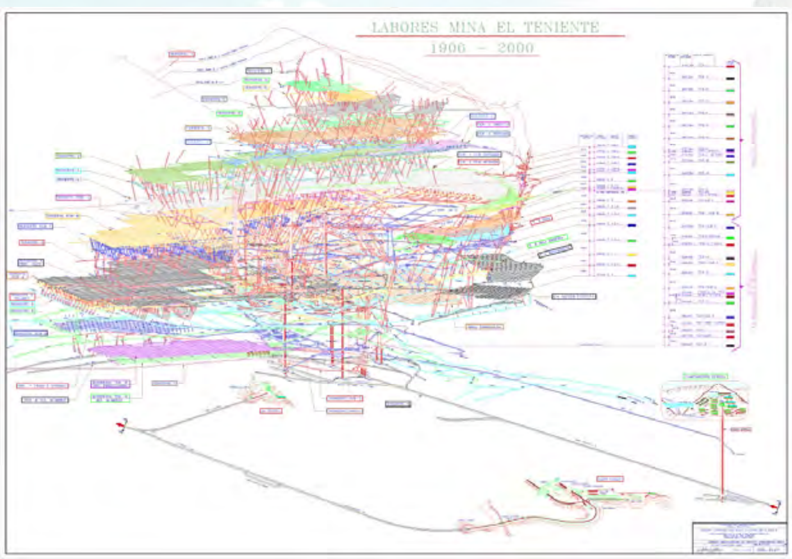
from Wolkersdorfer 1996

Mining Methods

Sewell – El Teniente Chile (1906 – 2000)



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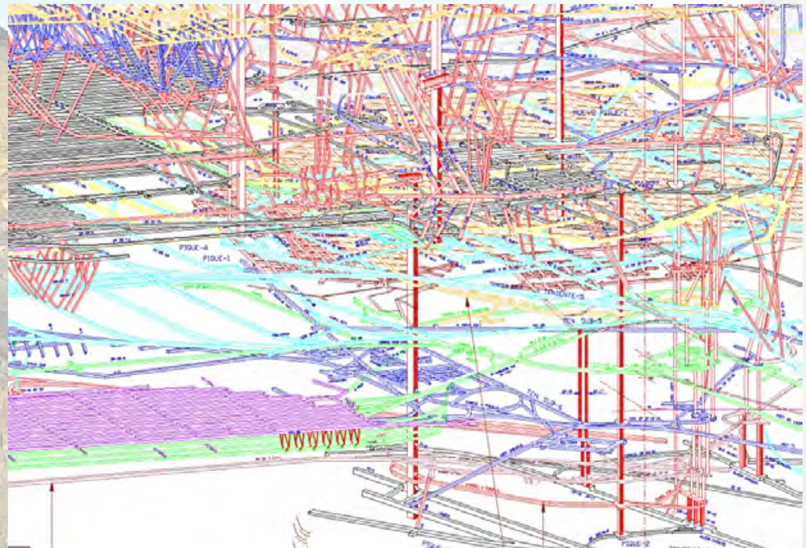
World's largest copper mine: ≈ 2000 km of workings

Mining Methods

Sewell – El Teniente Chile (1906 – 2000)



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World's largest copper mine: ≈ 2000 km of workings

Mining Methods

Underground mining

- Shafts and galleries must guarantee:
  - Man haulage (Skips, trackless haulage, mine railway)
  - Material haulage
  - Row 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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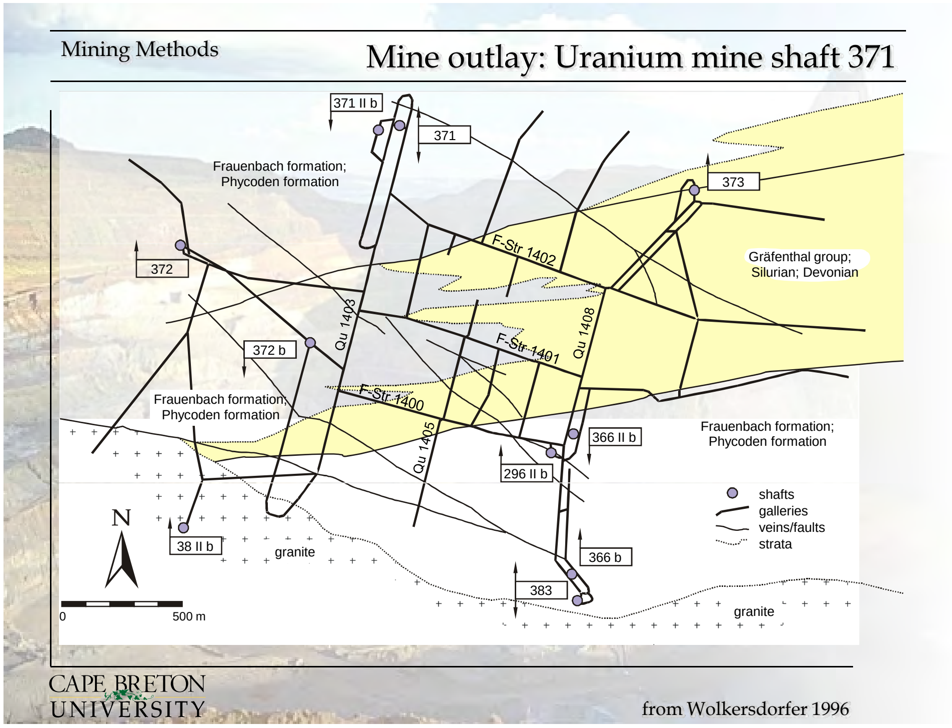
Mining Methods
Mine outlay: Uranium mine shaft 371
371 II b
371
373
372
372 b
Frauenbach formation; Phycoden formation
Gräfenthal group; Silurian; Devonian
F-Str 1402
F-Str 1401
F-Str 1400
Qu 1403
Qu 1408
Qu 1405
366 II b
296 II b
38 II b
366 b
383
granite
N
0
500 m
shafts
galleries
veins/faults
strata
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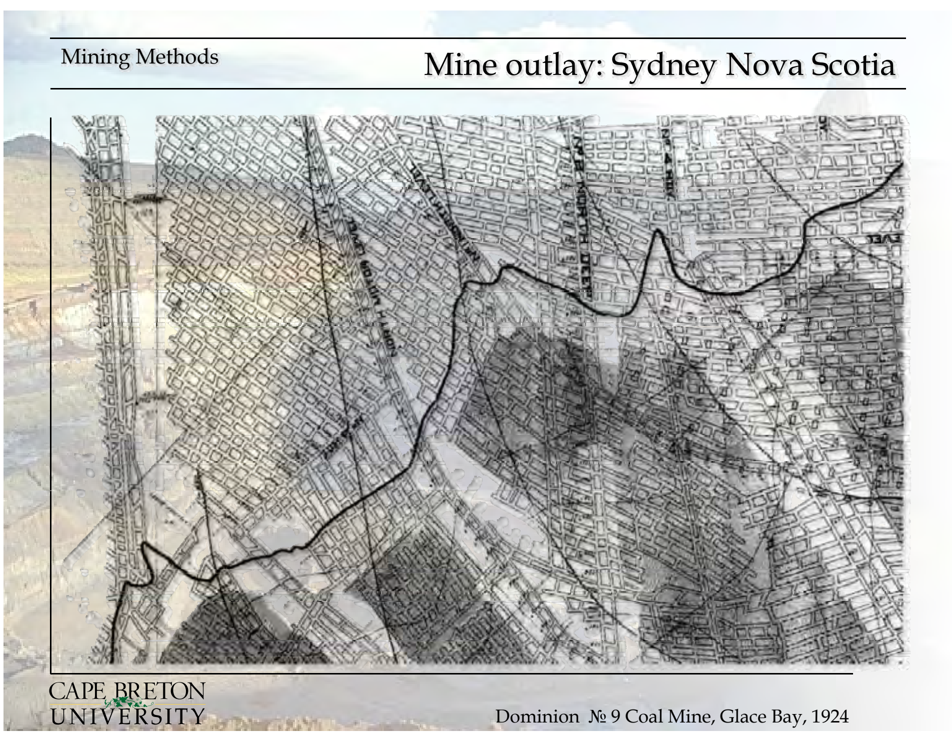
from Wolkersdorfer 1996


Mining Methods
Mine outlay: Sydney Nova Scotia
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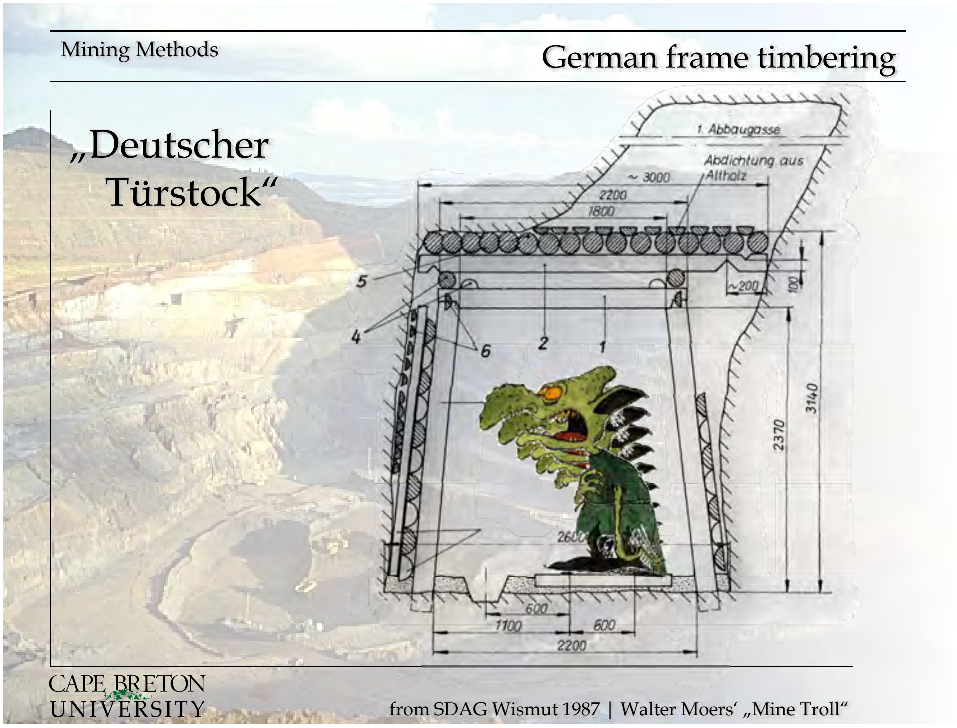
Dominion № 9 Coal Mine, Glace Bay, 1924


Mining Methods
German frame timbering
„Deutscher Türstock“
1. Abbaugasse
Abdichtung aus Altholz
~ 3000
2200
1800
~200
100
3140
2370
2600
600
1100
600
2200
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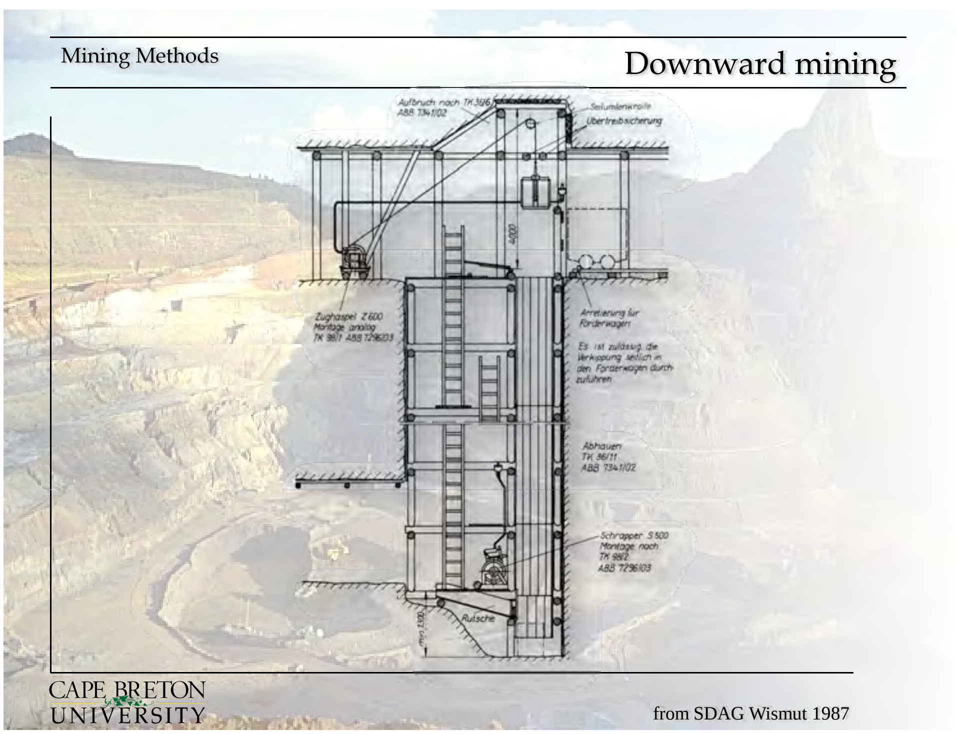
from SDAG Wismut 1987 | Walter Moers‘ „Mine Troll“


Mining Methods
Downward mining
Rutsche
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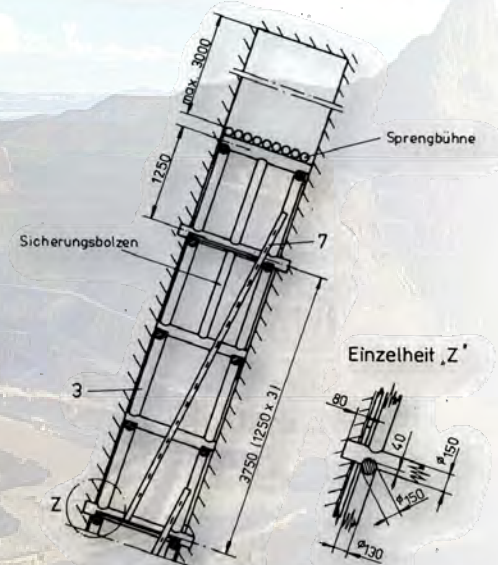
from SDAG Wismut 1987

Mining Methods

Cross/shaft timbering

„Bolzenschrot-zimmerung“

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



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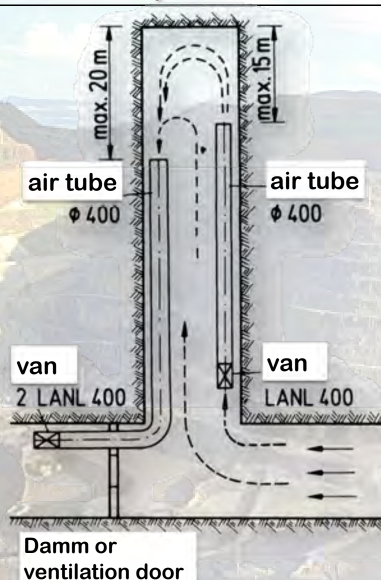
from SDAG Wismut 1987

Mining Methods

Auxillary Ventilation at Advancing Face



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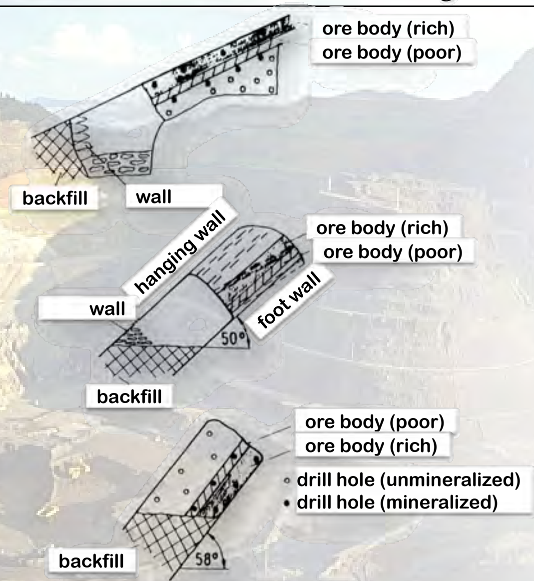
from Jobst et al. 1994

Mining Methods

Old Freiberg Cut-and-Fill



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from Jobst et al. 1994

Mining Methods

Underground Mining (1/2)

- Longwall methods
  - longwall mining, cross-cut mining
- Stoping methods
  - Shrinkage stoping
  - cut-and-fill mining
  - cross working (cross-cut with filling)
  - sub level stoping (currently most popular)
- Pillar methods
  - room-and-pillar
  - room-and-pillar caving
  - cross working

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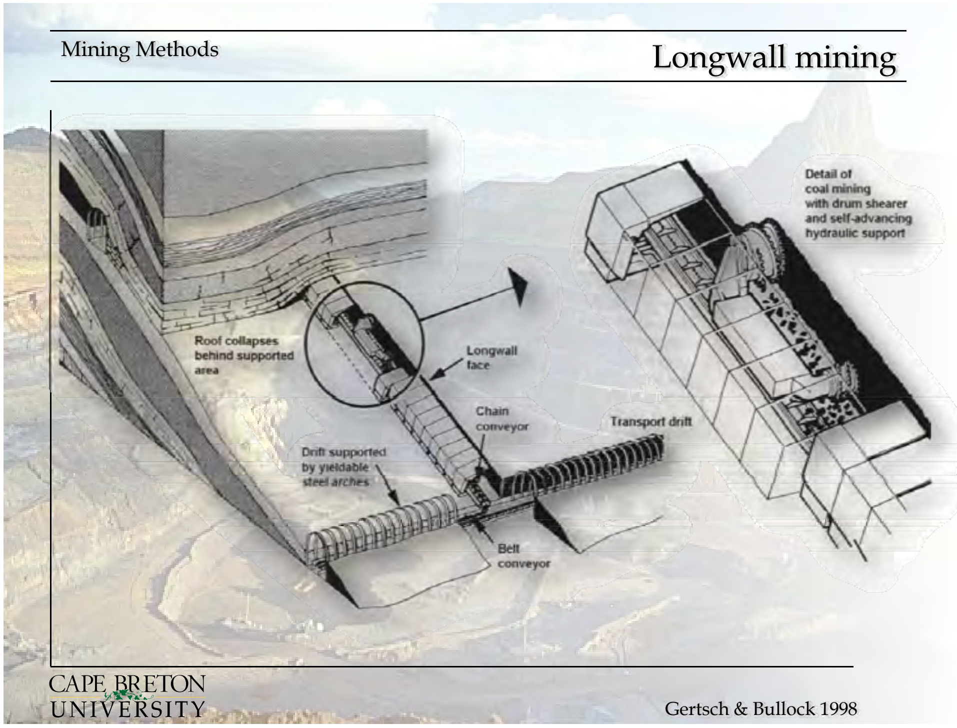
Mining Methods
Longwall mining
Detail of coal mining with drum shearer and self-advancing hydraulic support
Roof collapses behind supported area
Longwall face
Chain conveyor
Transport drift
Drift supported by yieldable steel arches
Belt conveyor
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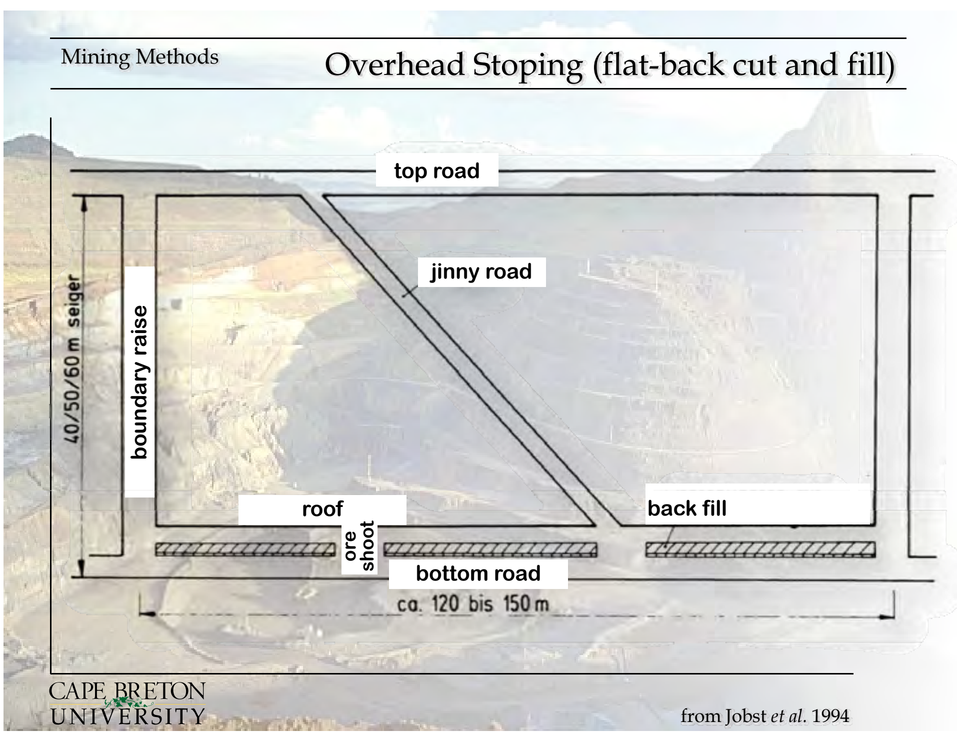
Gertsch & Bullock 1998


Mining Methods
Overhead Stoping (flat-back cut and fill)
top road
jinny road
40/50/60 m seiger
boundary raise
roof
ore shoot
back fill
bottom road
ca. 120 bis 150 m
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from Jobst et al. 1994

Mining Methods

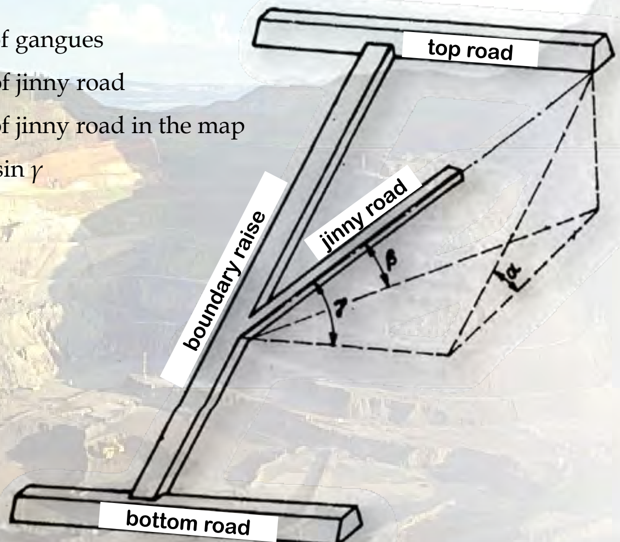
Dip Angle of Jinny Road

α = dip angle of gangues

β = dip angle of jinny road

γ = dip angle of jinny road in the map

$\sin \beta = \sin \alpha \times \sin \gamma$



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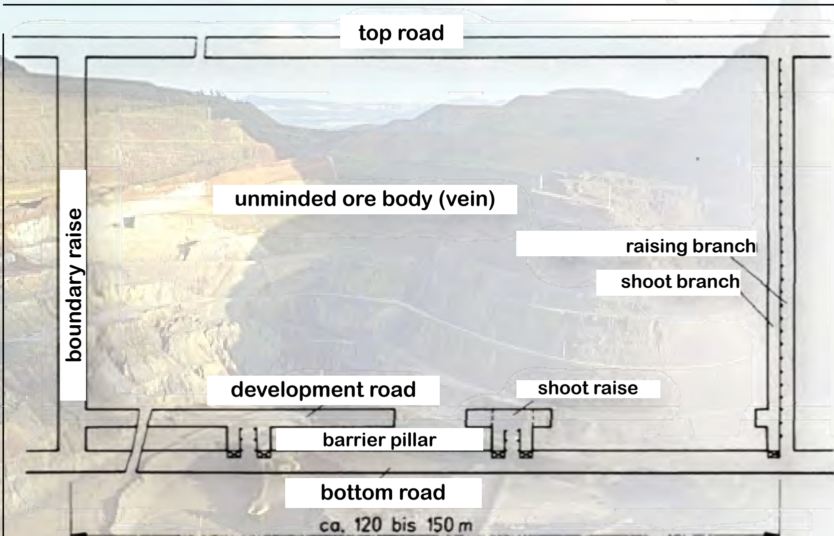
from SDAG Wismut 1987

Mining Methods

Stope Overhead



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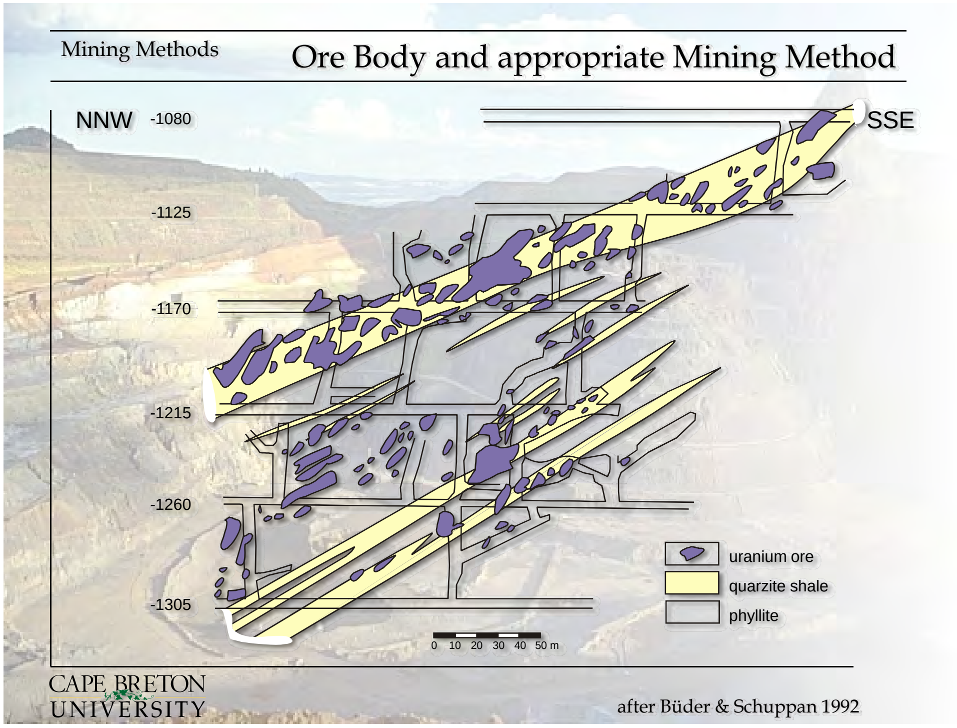
from Jobst *et al.* 1994


Mining Methods
Ore Body and appropriate Mining Method
NNW
SSE
-1080
-1125
-1170
-1215
-1260
-1305
uranium ore
quartzite shale
phyllite
0 10 20 30 40 50 m
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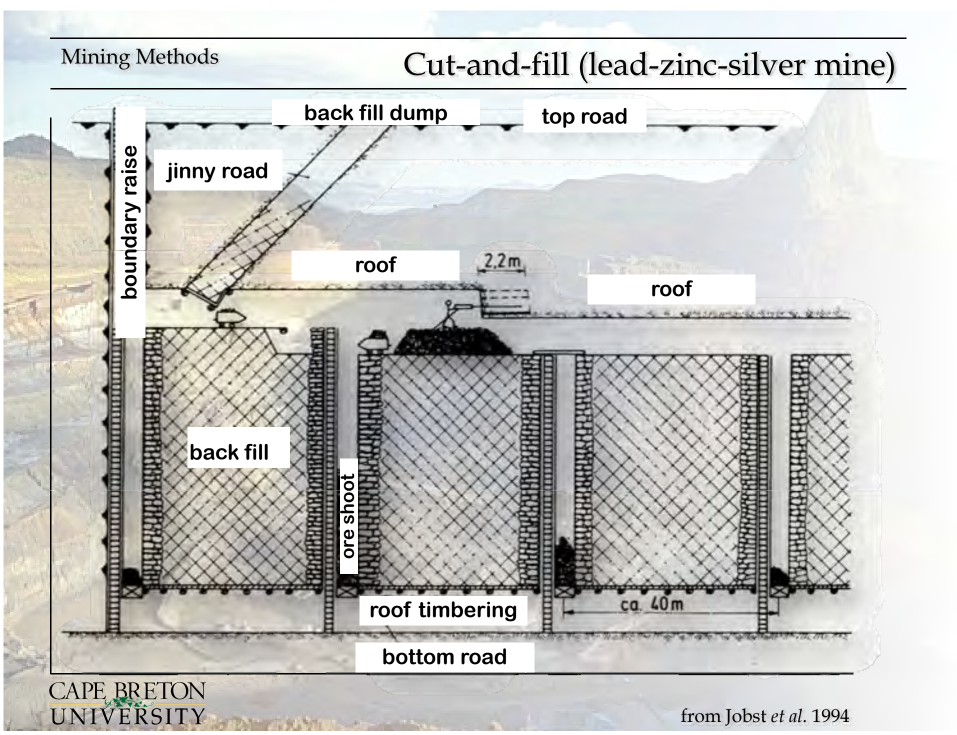
after Büder & Schuppan 1992


Mining Methods
Cut-and-fill (lead-zinc-silver mine)
back fill dump
top road
boundary raise
jinny road
roof
2,2 m
roof
back fill
ore shoot
roof timbering
ca. 40 m
bottom road
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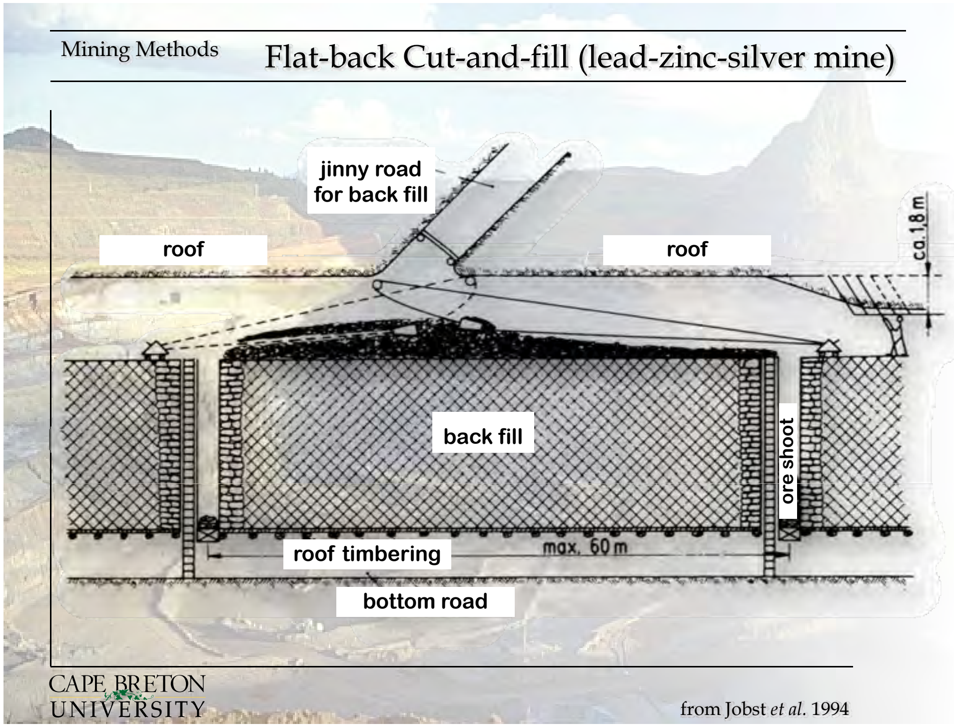
from Jobst et al. 1994


Mining Methods
Flat-back Cut-and-fill (lead-zinc-silver mine)
jinny road
for back fill
roof
roof
ca. 1,8 m
back fill
ore shoot
roof timbering
max. 60 m
bottom road
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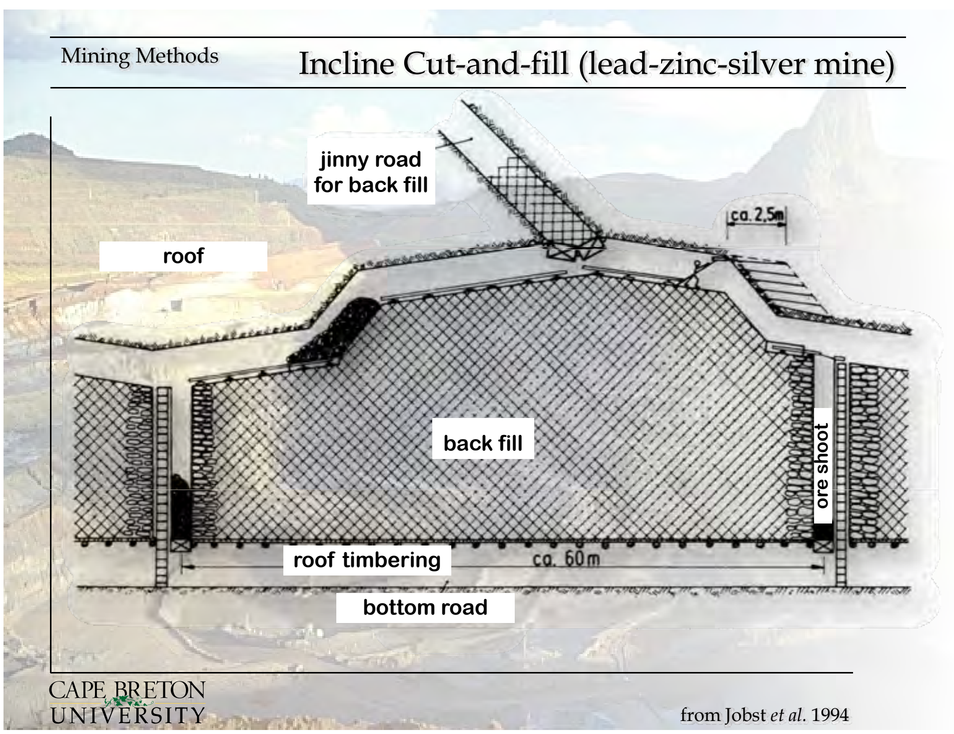
from Jobst et al. 1994


Mining Methods
Incline Cut-and-fill (lead-zinc-silver mine)
jinny road
for back fill
ca. 2,5m
roof
back fill
ore shoot
roof timbering
ca. 60 m
bottom road
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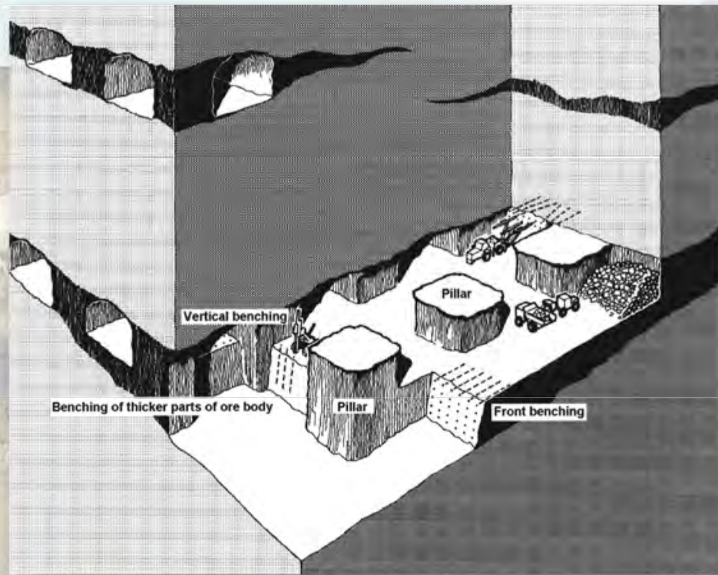
from Jobst et al. 1994

Mining Methods

Room and Pillar



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Gertsch & Bullock 1998

Mining Methods

Underground Mining (2/2)

- Mining Methods using stopes
  - Bell pit mining (ancient method)
  - shrinkage stoping
  - room-and-pillar
  - sublevel stoping
  - sublevel caving
- Mining Methods using pillars or panels
  - Pillar mining
  - block caving

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Mining Methods

Copper Mining in the Bronce Age

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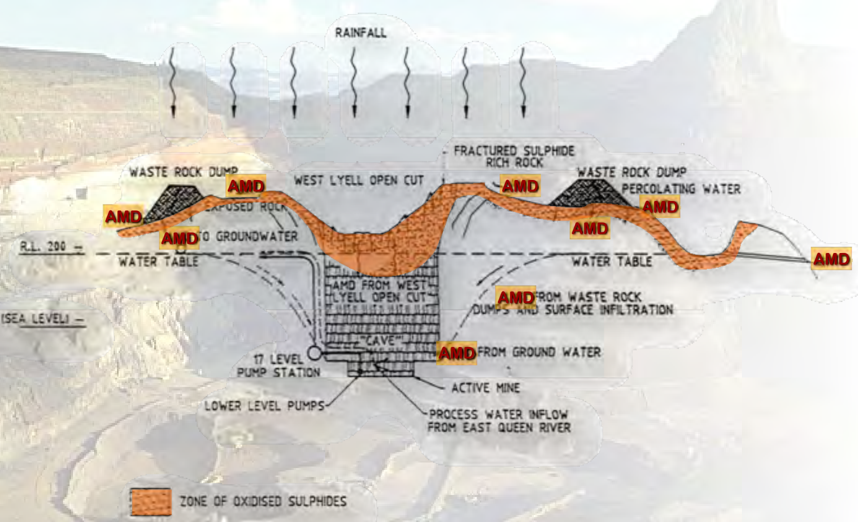
Steuer & Zimmermann 1993

Mining Methods

Sublevel Caving and Acid Mine Drainage



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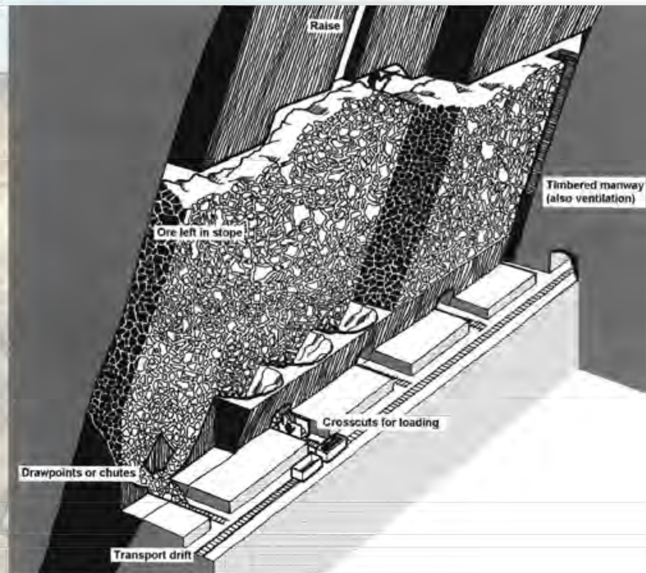
from Thompson & Brett Pty. Ltd. 1995

Mining Methods

Raise and Shrinkage



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Gertsch & Bullock 1998

Mining Methods

Open Pit Mining

- More than 80 % of worldwide mines
  - e.g. iron, copper, coal, gold, uranium
- Large areas needed
  - many 10-thousands of square meters
  - farmland or forests are used
- Overburden
  - Dumps, stock piles
- Good hydraulic control of open pit
  - Mine water pumps around the mine and before mining starts

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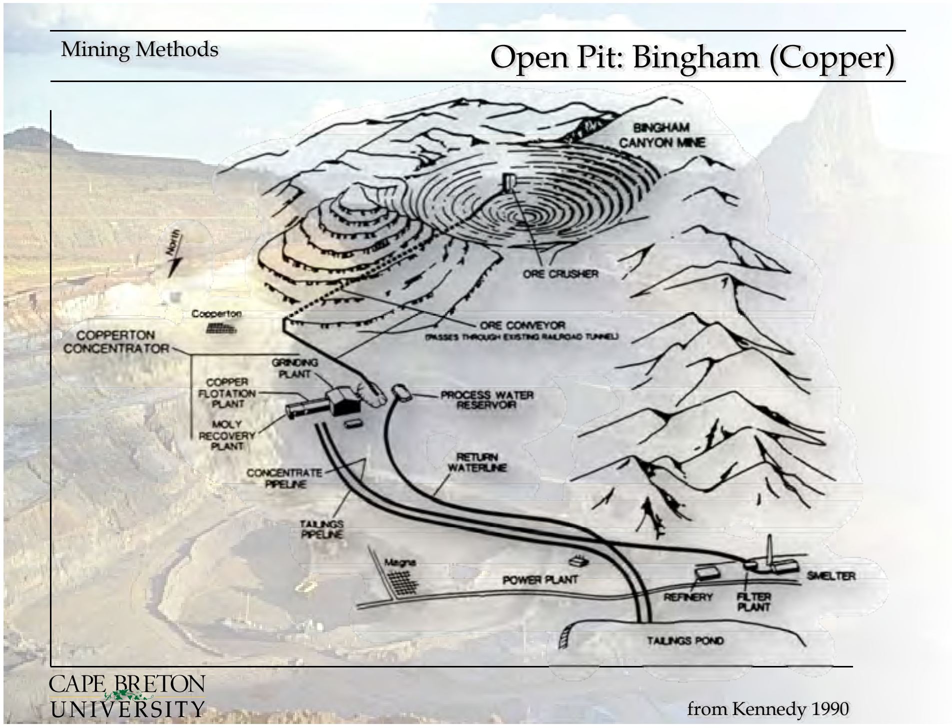
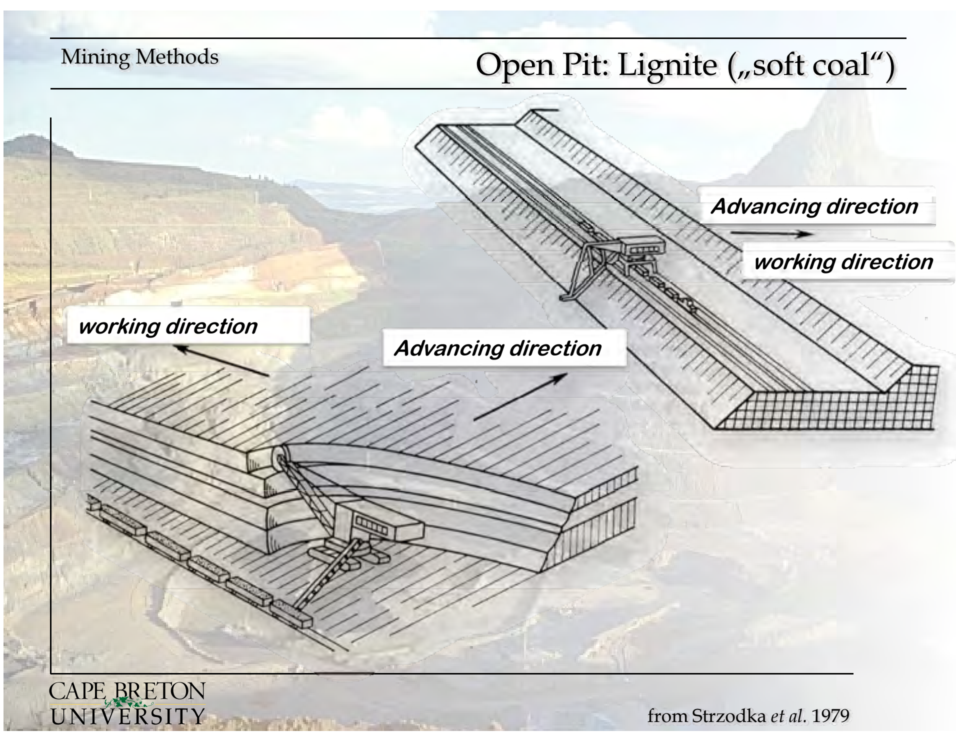

Mining Methods
Open Pit: Bingham (Copper)
BINGHAM CANYON MINE
North
ORE CRUSHER
Copperton
ORE CONVEYOR
(PASSES THROUGH EXISTING RAILROAD TUNNEL)
COPPERTON CONCENTRATOR
GRINDING PLANT
COPPER FLOTATION PLANT
MOLY RECOVERY PLANT
PROCESS WATER RESERVOIR
RETURN WATERLINE
CONCENTRATE PIPELINE
TAILINGS PIPELINE
Magna
POWER PLANT
REFINERY
FILTER PLANT
SMELTER
TAILINGS POND
CAPE BRETON UNIVERSITY
from Kennedy 1990


Mining Methods
Open Pit: Lignite („soft coal“)
Advancing direction
working direction
working direction
Advancing direction
CAPE BRETON UNIVERSITY
from Strzodka et al. 1979

Mining Methods

Types of Backfill („Goaf treatment“)

- Rock filling
  - Manual packing, flow stowing
- Pneumatic packing
  - 1924 Gewerkschaft „Deutschland“ Oelsnitz
- Slinger stowing (mechanical stowing)
- Hydraulic filling
  - 1907 Bleicherode
- Dummy road packing (hardly used nowadays)
- Backfill ratio 0.4 – 0.7 (usually 0.55 – 0.6)

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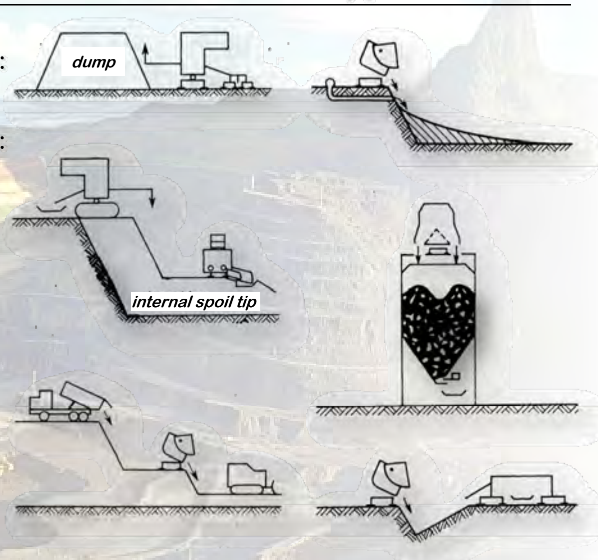
Mining Methods

Types of Backfill

- 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

- 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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From Ground Water to Mine Water

Environmental Hydrogeology in Mining

Water and Water Inrushes

Prof. Dr. Christian Wolkersdorfer

Industrial Research Chair in Mine Water Remediation & Management

Contents

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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 water
  - Dust suppression, cooling water

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Water and Water Inrushes

Where does the Water flow?

- Voids: adits, shafts, raises, stopes
- Loosening zone around voids
- Fissures, faults, ore veins
- Bedding planes, cleavage planes
- Microfractures in the rock
- Rock matrix
- Depth dependence
  - new mineworks deeper than about 140 m are unlikely to encounter major feeders

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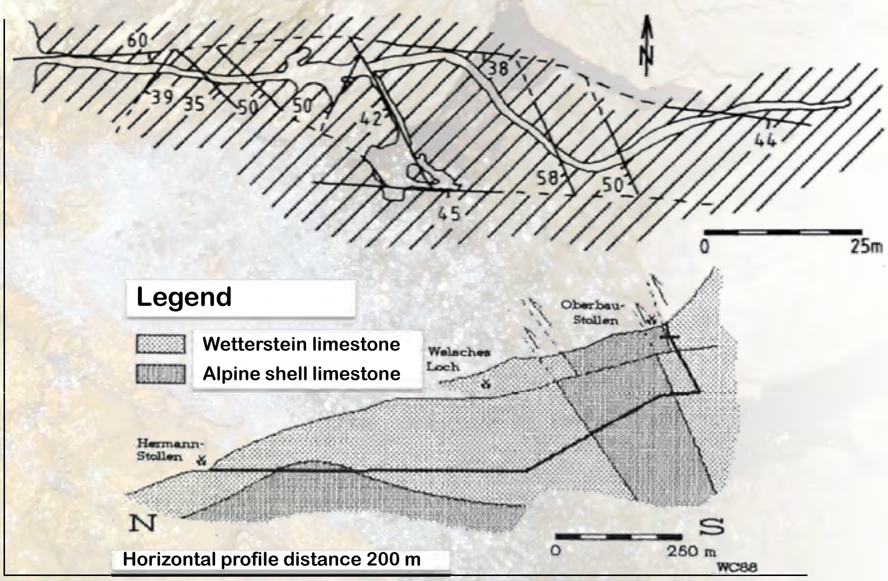
Infiltration water

Lithology, Faults Dependence



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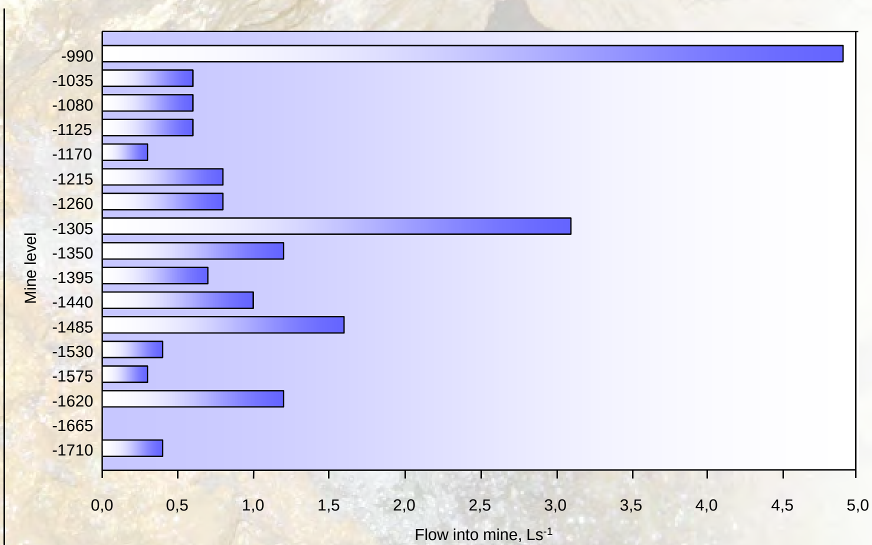
Wolkersdorfer 1989

Infiltration water

Depth dependence



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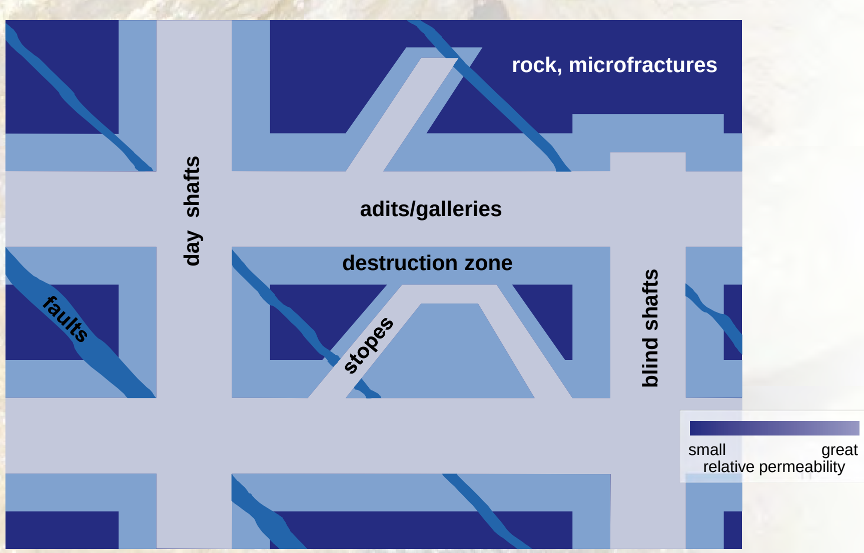
Wolkersdorfer 1996

Infiltration water

Relative Permeability



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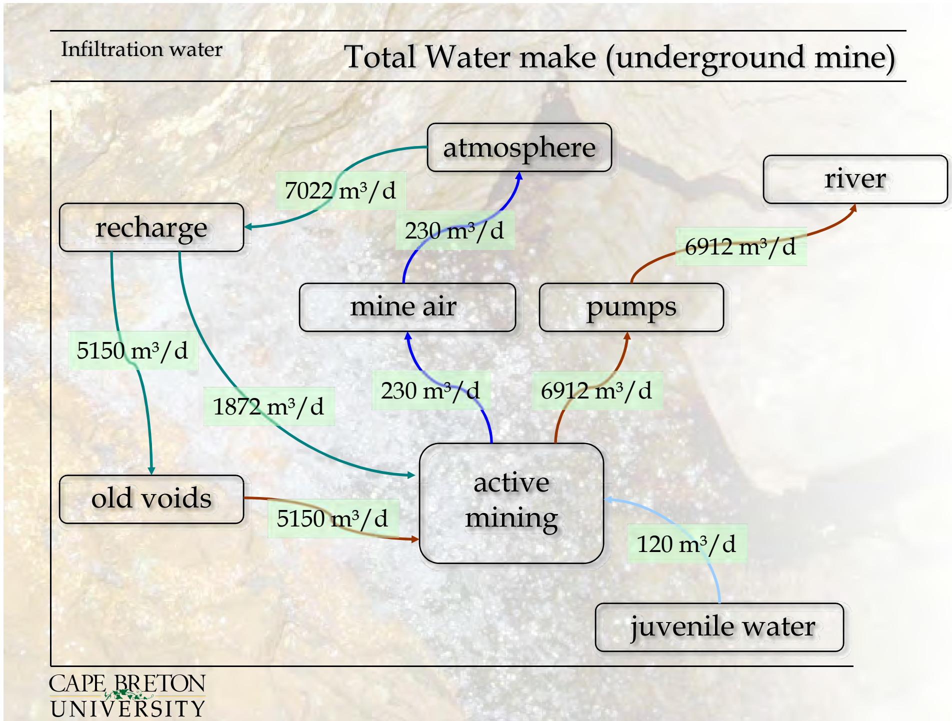
Wolkersdorfer 1996


Infiltration water
Total Water make (underground mine)
atmosphere
river
7022 m³/d
recharge
230 m³/d
6912 m³/d
mine air
pumps
5150 m³/d
230 m³/d
6912 m³/d
1872 m³/d
active mining
old voids
5150 m³/d
120 m³/d
juvenile water
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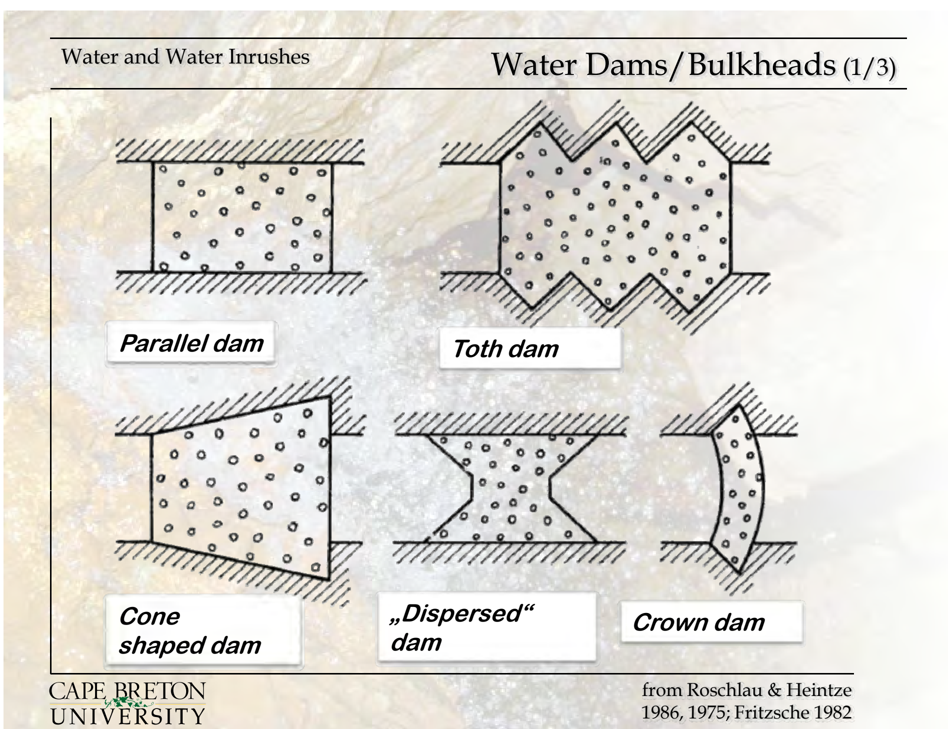
Water and Water Inrushes
Water Dams/Bulkheads (1/3)
Parallel dam
Toth dam
Cone shaped dam
„Dispersed“ dam
Crown dam
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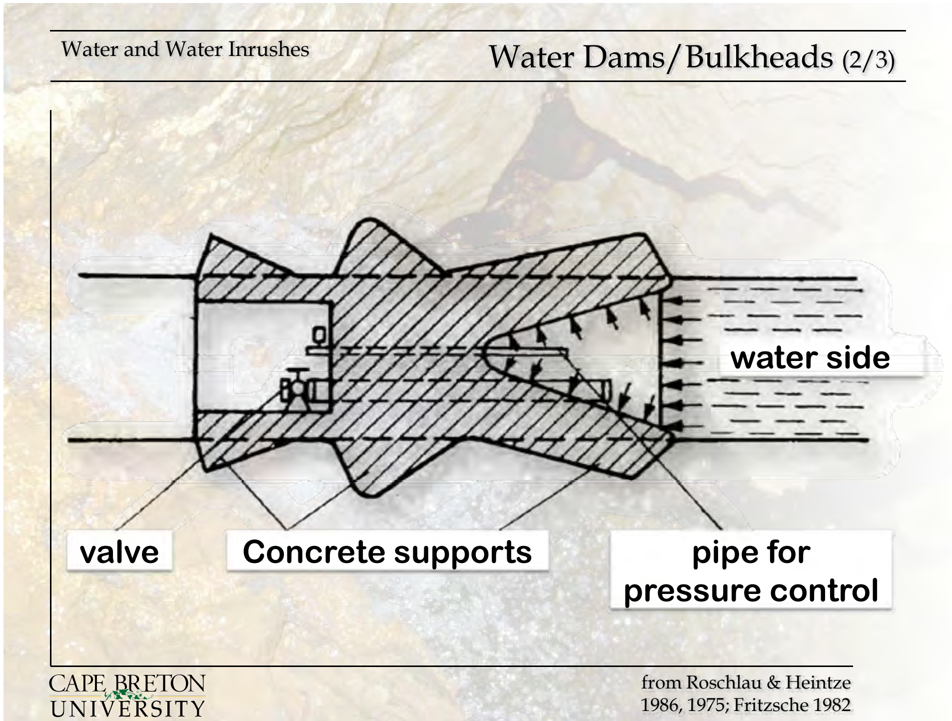
from Roschlau & Heintze 1986, 1975; Fritzsche 1982


Water and Water Inrushes
Water Dams/Bulkheads (2/3)
water side
valve
Concrete supports
pipe for pressure control
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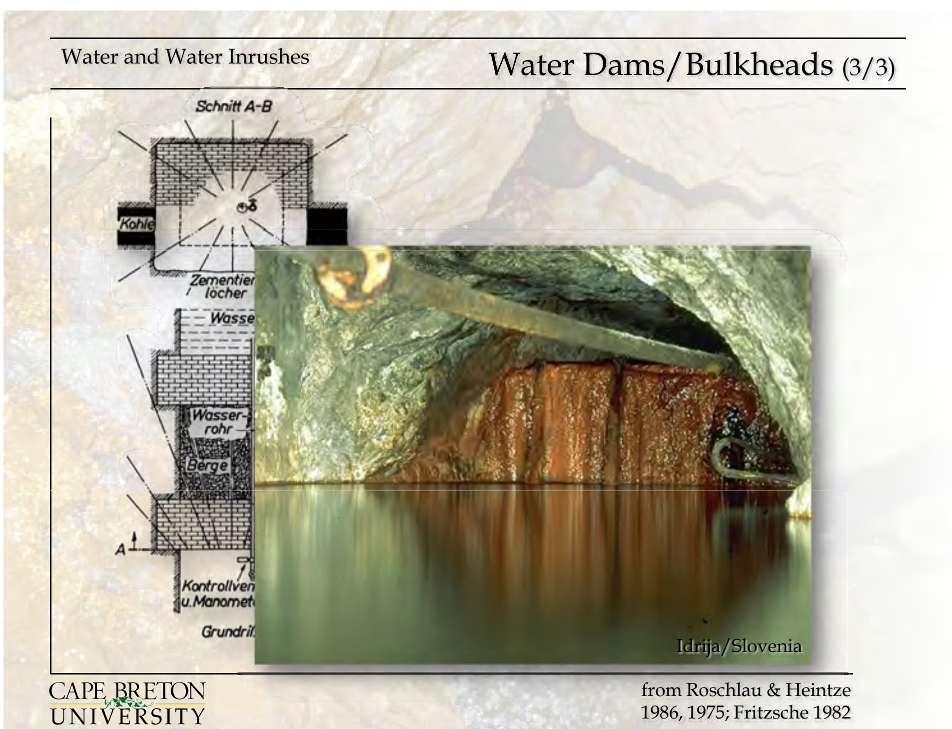
from Roschlau & Heintze 1986, 1975; Fritzsche 1982


Water and Water Inrushes
Water Dams/Bulkheads (3/3)
Schnitt A-B
Kohle
Wasser-rohr
Berge
A
Idrija/Slovenia
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from Roschlau & Heintze 1986, 1975; Fritzsche 1982

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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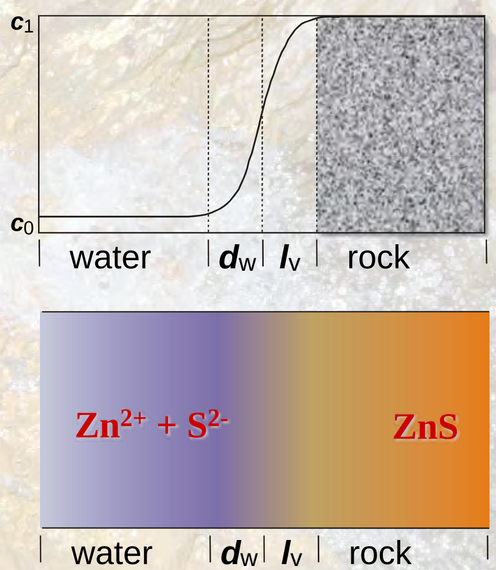
Infiltration water

Concentration gradient



d_w: diffusion zone

l_v: weathering zone

$$K_{ZnS} = \frac{[Zn^{2+}] \cdot [S^{2-}]}{[ZnS]}$$

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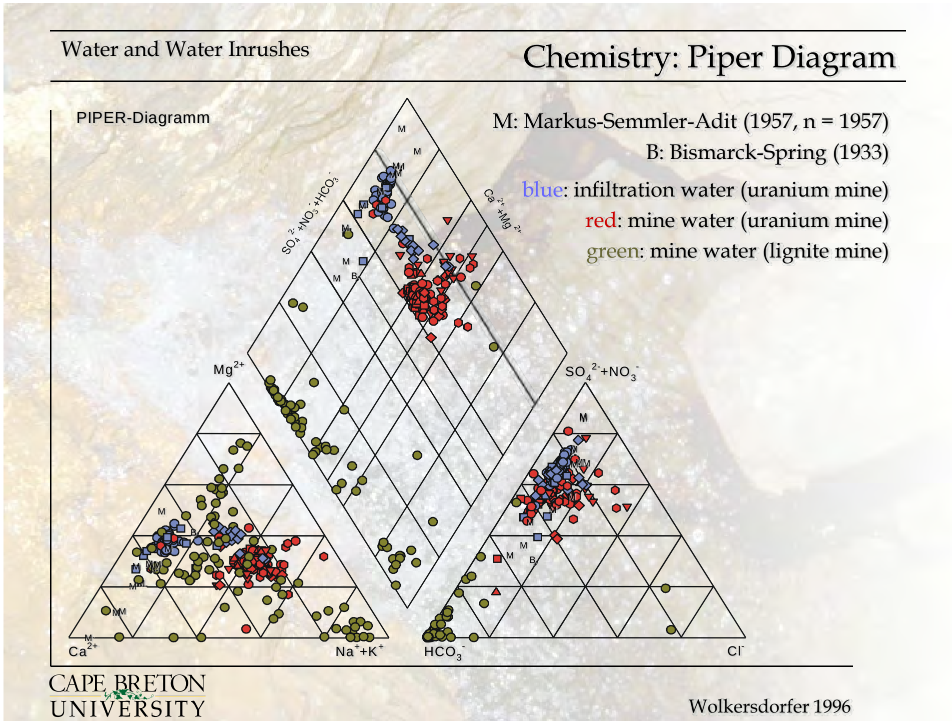
Wolkersdorfer 1996


Water and Water Inrushes
Chemistry: Piper Diagram
PIPER-Diagramm
M: Markus-Semmler-Adit (1957, n = 1957)
B: Bismarck-Spring (1933)
blue: infiltration water (uranium mine)
red: mine water (uranium mine)
green: mine water (lignite mine)
Mg2+
Ca2+
Na++K+
HCO3-
Cl-
SO42-+NO3-
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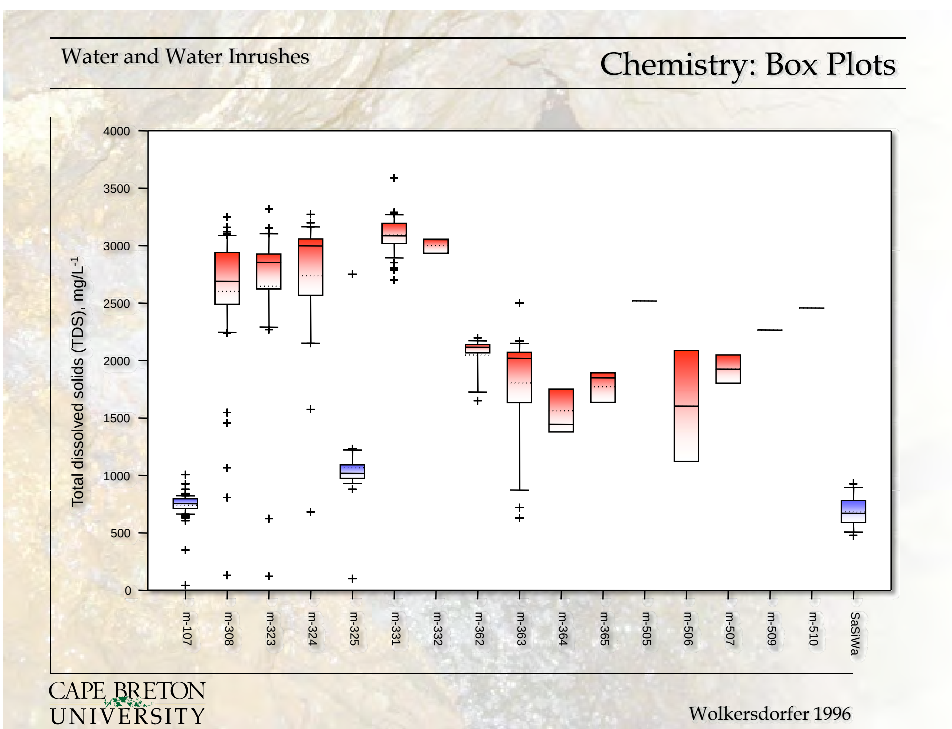
Wolkersdorfer 1996


Water and Water Inrushes
Chemistry: Box Plots
Total dissolved solids (TDS), mg/L-1
4000
3500
3000
2500
2000
1500
1000
500
0
m-107
m-308
m-323
m-324
m-325
m-331
m-332
m-362
m-363
m-364
m-365
m-505
m-506
m-507
m-509
m-510
SaStWa
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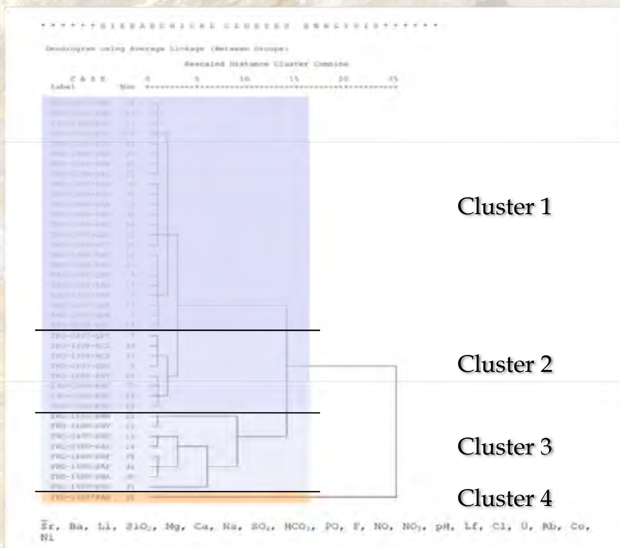
Water and Water Inrushes

Multivariate Statistics



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Water and Water Inrushes

Humidity in the mine air: an estimation

- Air flux (min/max: 10…1,300 m³/s; mean: 120…700 m³/s)
  - Q = 133 m³/s
- Temperature
  - θ = 26.7 °C
- Relative humidity
  - η = 80%
- Volume of Water in Steam (100%, 26.7 °C, 1000 hPa)
  - V = 25 mL/m³
- Daily water make in the mine air
  - $V_w = Q \cdot \eta \cdot V \cdot 0.0864 = 229.8$ m³/d

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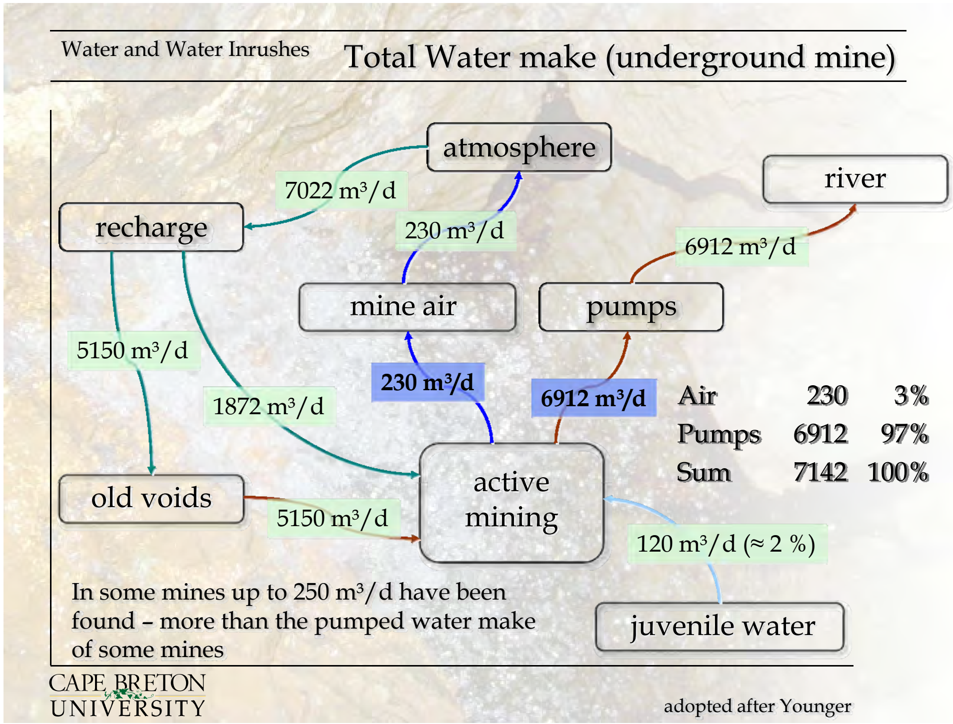

Water and Water Inrushes

Types of water inflows

- Constant Feeders
  - Fractures
  - Fissures,
  - Bedding planes
- Short-lived Feeders
  - Karstic features
- Droppers
  - Bedding planes,
  - Fissures
- SAUL's rule (empirical rule)
  - 20...40% of the annual precipitation seep into the mine

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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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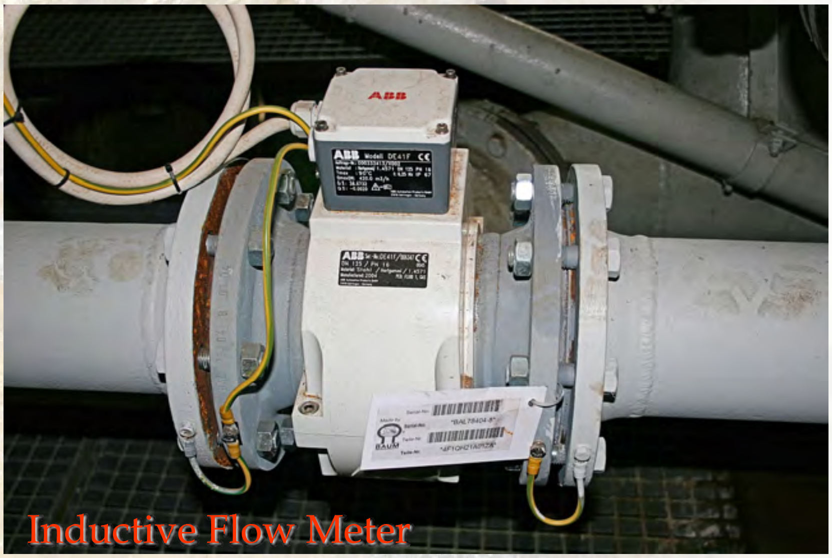
Water and Water Inrushes

Measuring of water flows



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Water and Water Inrushes

Measuring of water flows

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Water and Water Inrushes

Measuring of water flows

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Water and Water Inrushes

Calculation of water inflows (1/3)

- Mining area: A = 30 km²
- Precipitation 1950—1990: N = 825 mm/a
- Mean surface flow: a_o = 38.7%
- Mean evaporation: V_E = 630 mm/a
- Mean temperature: θ = 8.5 °C
- Evapotranspiration ET:

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

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Water and Water Inrushes

Calculation of water inflows (2/3)

- $V_N = A \cdot N =$ $\cdot 10^6$ m³/a
- $V_A = V_N \cdot a_o =$ $\cdot 10^6$ m³/a
- $ET_{reel} =$ mm/a
- $V_{ETreel} =$ $\cdot 10^6$ m³/a
- $V_{sick} = V_N - V_A - V_{ETreel} =$ $\cdot 10^6$ m³/a
- Total water make: $V_{pump} =$ 7…10 $\cdot 10^6$ m³/a
- From droppers: $V_{drops} =$ 0.6 $\cdot 10^6$ m³/a
- SAUL's rule: $\cdot 10^6$ m³/a

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Water and Water Inrushes

Calculation of water inflows (3/3)

- $V_N = A \cdot N =$ 24.75 $\cdot 10^6$ m³/a
- $V_A = V_N \cdot a_o =$ 9.58 $\cdot 10^6$ m³/a
- $ET_{reel} =$ 461 mm/a
- $V_{ETreel} =$ 13.8 $\cdot 10^6$ m³/a
- $V_{sick} = V_N - V_A - V_{ETreel} =$ 1.37 $\cdot 10^6$ m³/a
- V_{pump} (measured) = 7…10 $\cdot 10^6$ m³/a
- V_{drops} (measured) = 0.6 $\cdot 10^6$ m³/a
- SAUL's rule: 5…10 $\cdot 10^6$ m³/a

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Water and Water Inrushes

Literature

- 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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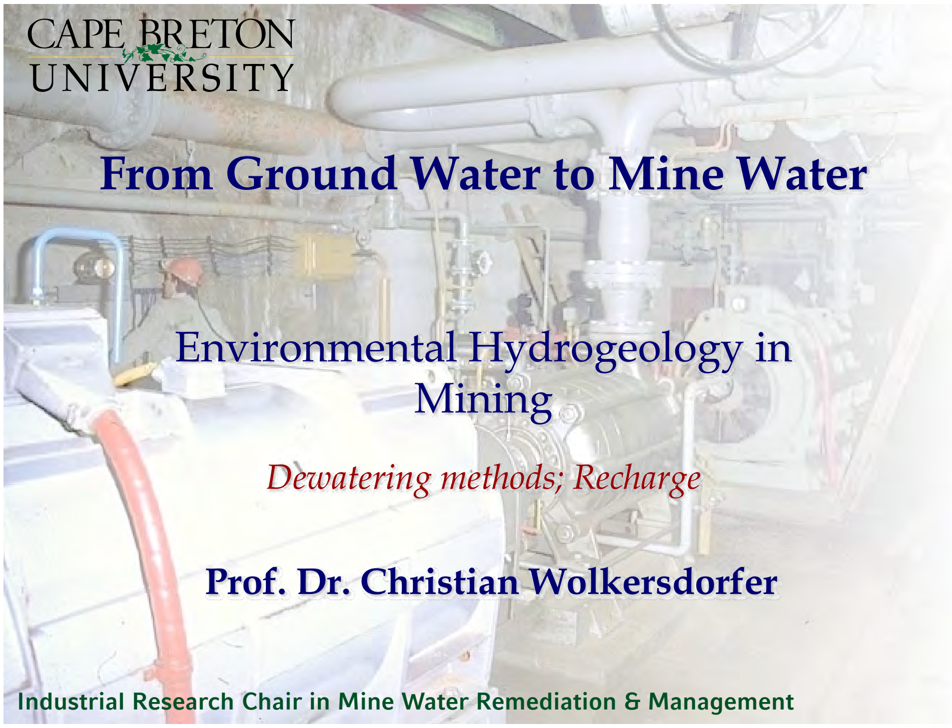
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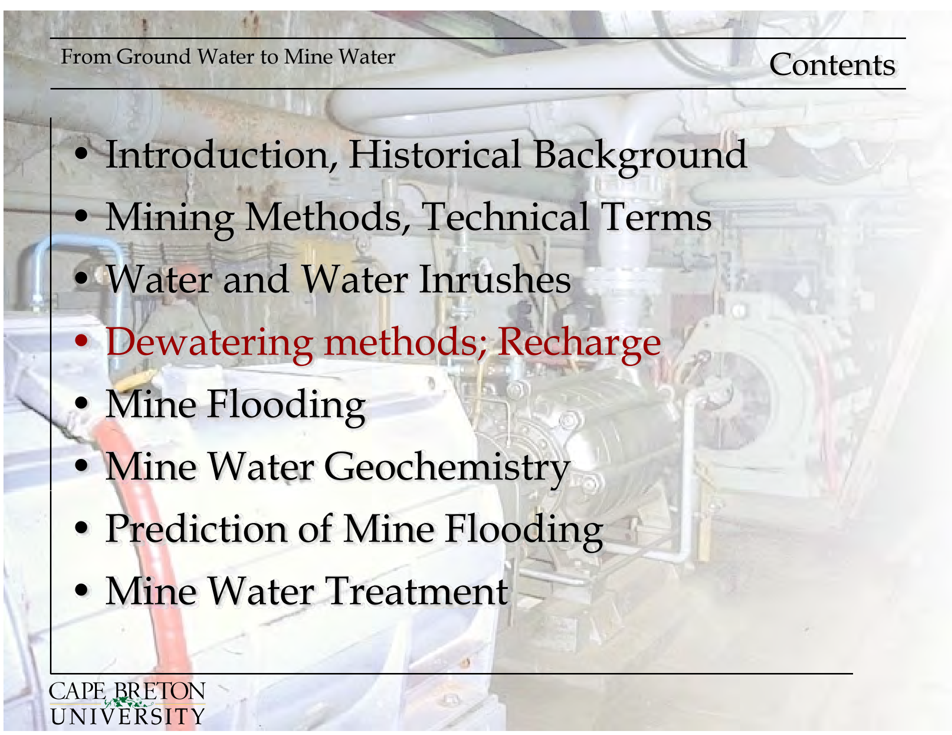
From Ground Water to Mine Water
Environmental Hydrogeology in Mining
Dewatering methods; Recharge
Prof. Dr. Christian Wolkersdorfer
Industrial Research Chair in Mine Water Remediation & Management


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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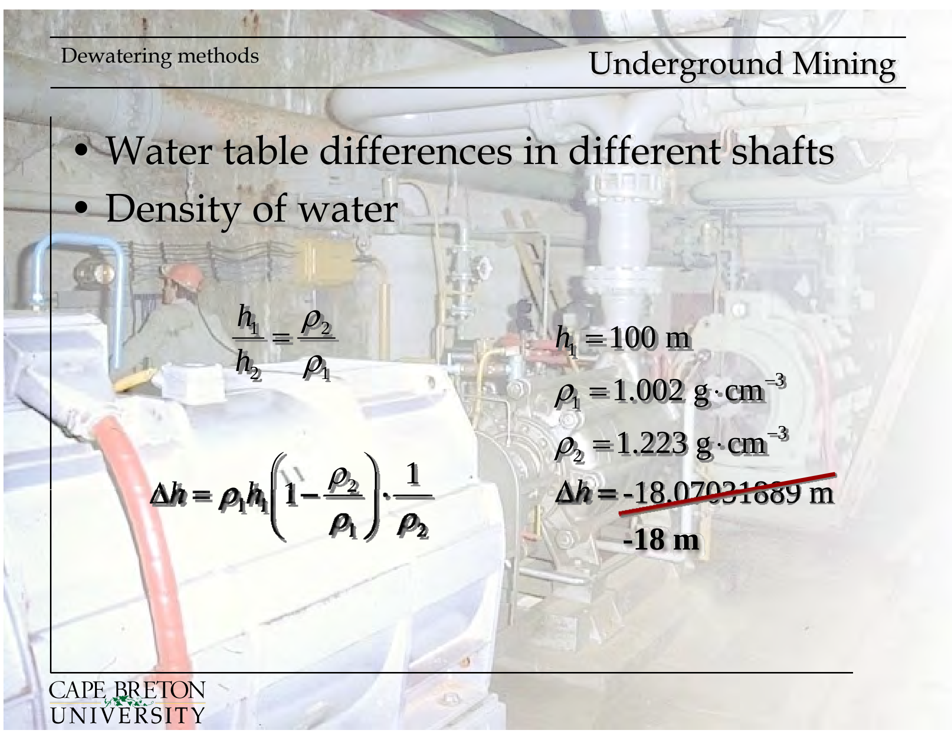
Dewatering methods
Underground Mining
• Water table differences in different shafts
• Density of water
$\frac{h_1}{h_2} = \frac{\rho_2}{\rho_1}$
$\Delta h = \rho_1 h_1 \left(1 - \frac{\rho_2}{\rho_1}\right) \cdot \frac{1}{\rho_2}$
$h_1 = 100$ m
$\rho_1 = 1.002\ g \cdot cm^{-3}$
$\rho_2 = 1.223\ g \cdot cm^{-3}$
$\Delta h =$ -18.07031889 m
-18 m
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Dewatering methods

Open cast mining

- Filter wells
- Disposal well, Inverted well
- Vaccum drainage
- Horizontal drains
- Sealing walls (grout walls)
  - 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

- Ruhr Area (hard coal)
  - 1957 30 76.9 $\cdot 10^6$ m^3 a^{-1} ca. 1500 km^2
  - 1982 3 48.6 $\cdot 10^6$ m^3 a^{-1}
- Ibbenbüren (hard coal)
  - 1979 4 14.0 $\cdot 10^6$ m^3 a^{-1} 15 km^2
- Lusatia/Saxony (lignite; draw down: 150—200 m)
  - 1990 7000 1.2 $\cdot 10^9$ m^3 a^{-1} 2500 km^2
- Rhine Area (lignite; draw down: 500 m)
  - 1985 1250 1.0 $\cdot 10^9$ m^3 a^{-1} 2900 km^2

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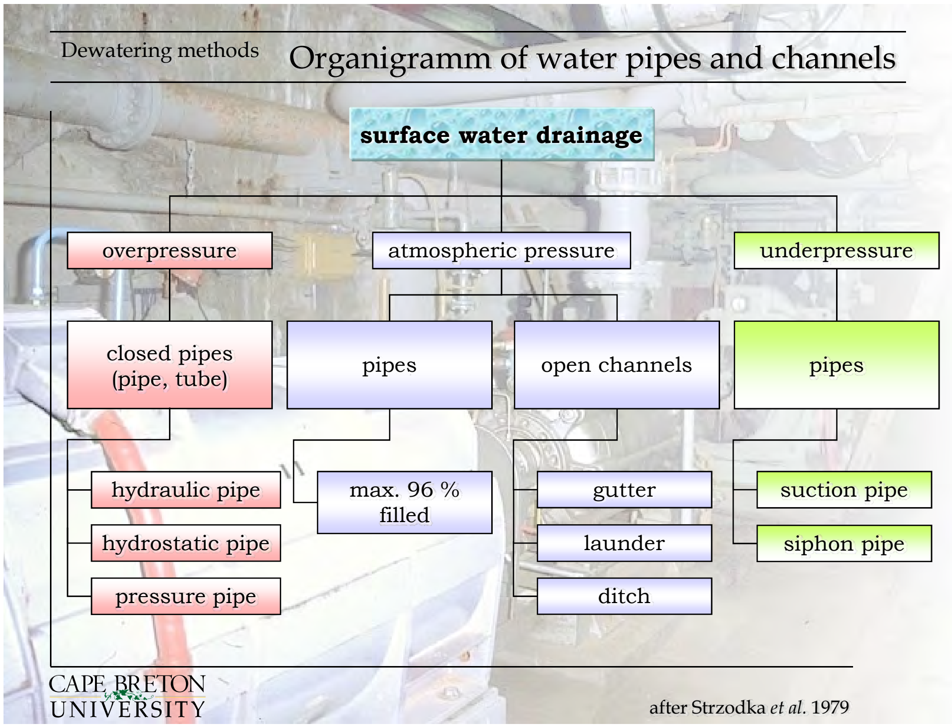
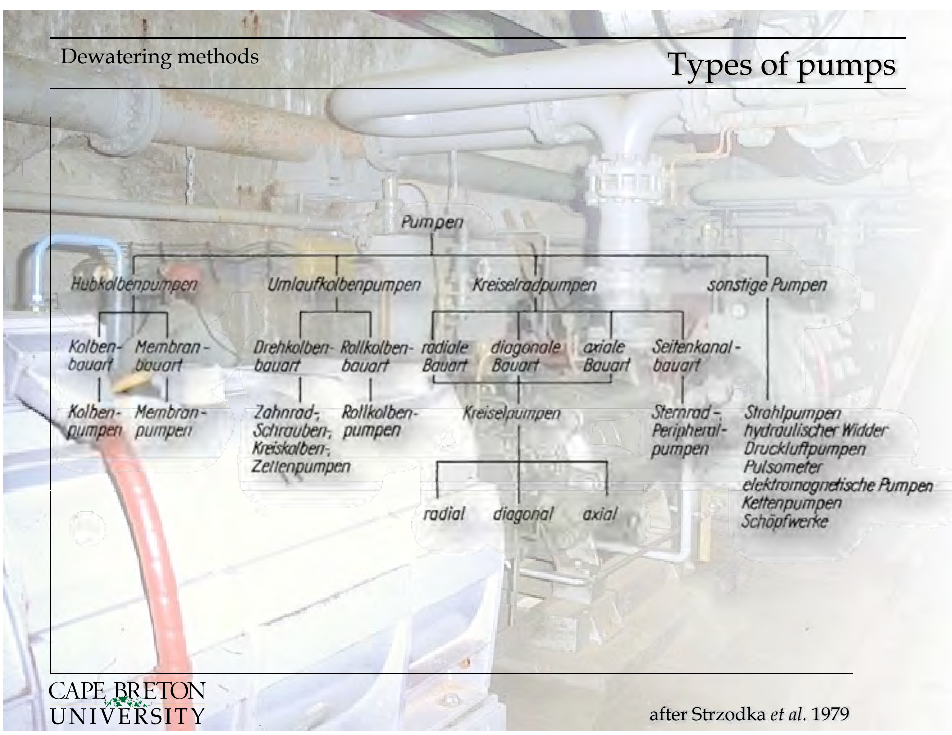
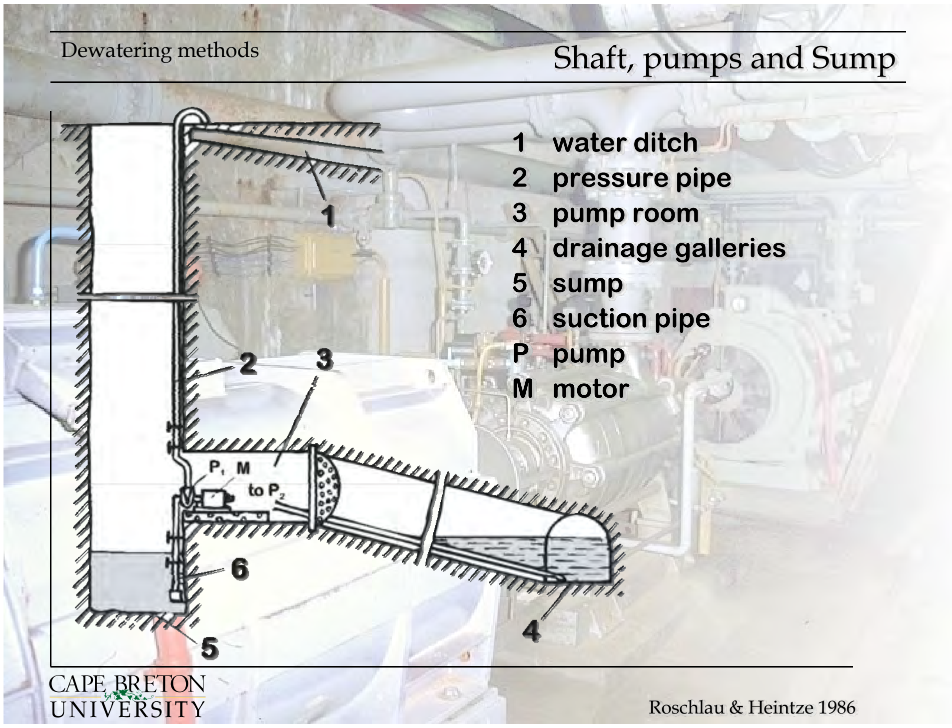

Dewatering methods
Organigramm of water pipes and channels
surface water drainage
overpressure
atmospheric pressure
underpressure
closed pipes (pipe, tube)
pipes
open channels
pipes
hydraulic pipe
hydrostatic pipe
pressure pipe
max. 96 % filled
gutter
launder
ditch
suction pipe
siphon pipe
CAPE BRETON UNIVERSITY
after Strzodka et al. 1979


Dewatering methods
Types of pumps
Pumpen
Hubkolbenpumpen
Umlaufkolbenpumpen
Kreiselradpumpen
sonstige Pumpen
Kolben-bauart
Membran-bauart
Drehkolben-bauart
Rollkolben-bauart
radiale Bauart
diagonale Bauart
axiale Bauart
Seitenkanal-bauart
Kolben-pumpen
Membran-pumpen
Zahnrad-, Schrauben-, Kreiskolben-, Zellenpumpen
Rollkolben-pumpen
Kreiselpumpen
Sternrad-, Peripheral-pumpen
Strahlpumpen
hydraulischer Widder
Druckluftpumpen
Pulsometer
elektromagnetische Pumpen
Kettenpumpen
Schöpfwerke
radial
diagonal
axial
CAPE BRETON UNIVERSITY
after Strzodka et al. 1979


Dewatering methods
Shaft, pumps and Sump
1 water ditch
2 pressure pipe
3 pump room
4 drainage galleries
5 sump
6 suction pipe
P pump
M motor
1
2
3
P₁ M
to P₂
6
5
4
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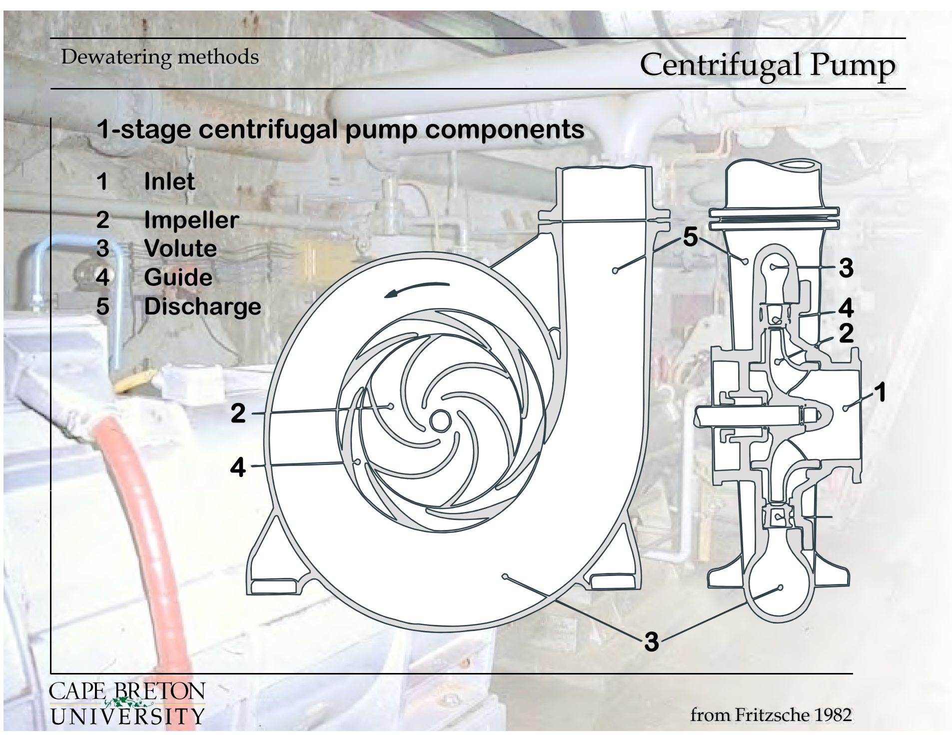
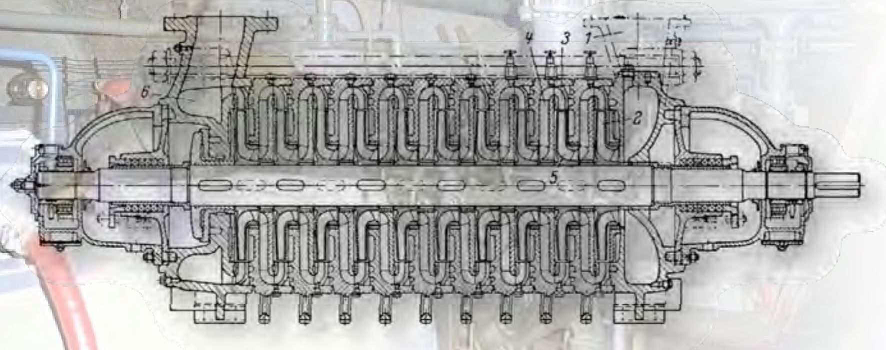
Roschlau & Heintze 1986


Dewatering methods
Centrifugal Pump
1-stage centrifugal pump components
1 Inlet
2 Impeller
3 Volute
4 Guide
5 Discharge
5
3
4
2
1
2
4
3
CAPE BRETON UNIVERSITY
from Fritzsche 1982

Dewatering methods

Centrifugal Pump



10-stage centrifugal pump

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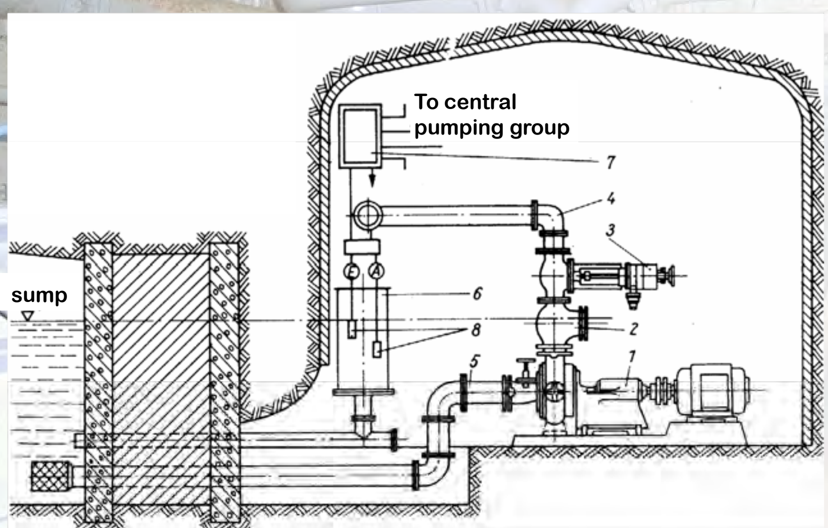
from Fritzsche 1982

Dewatering methods

Automatic Pumping Station



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from Fritzsche 1982

Dewatering methods

Underground pumping station

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from Böttcher *et al*. 1991

Dewatering methods

Underground pumping station

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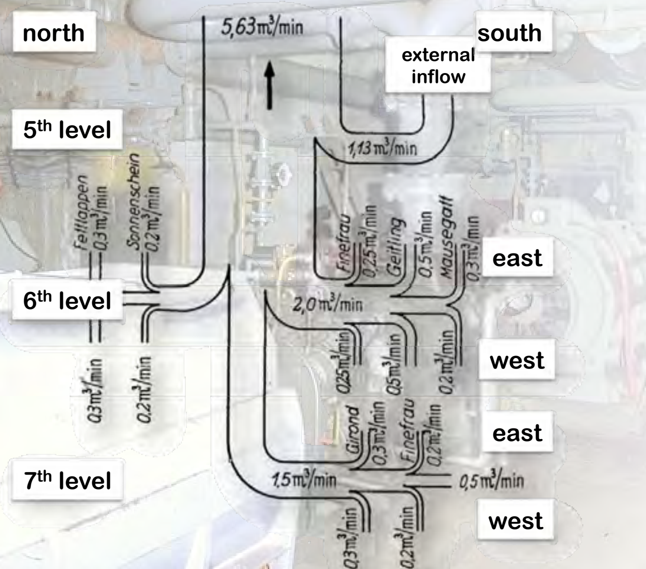
curtesy Rudnik Idrija

Dewatering methods

Underground water make



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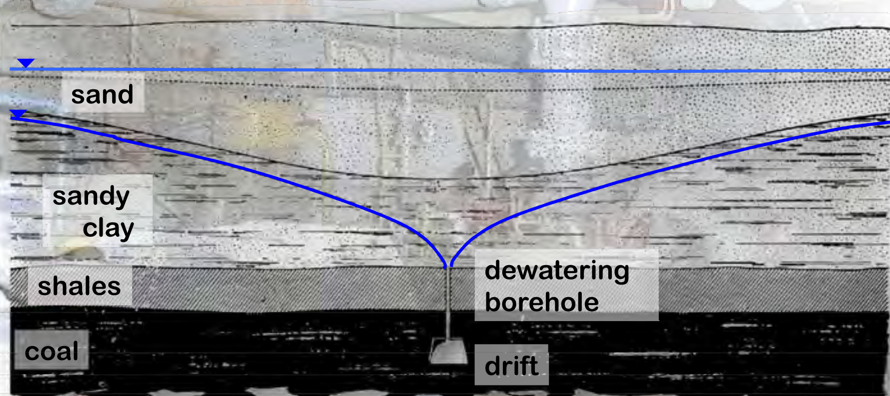
after Fritzsche 1982

Dewatering methods

Lowering of groundwater table



- loss of boyancy
  → subsidence of surface above mine

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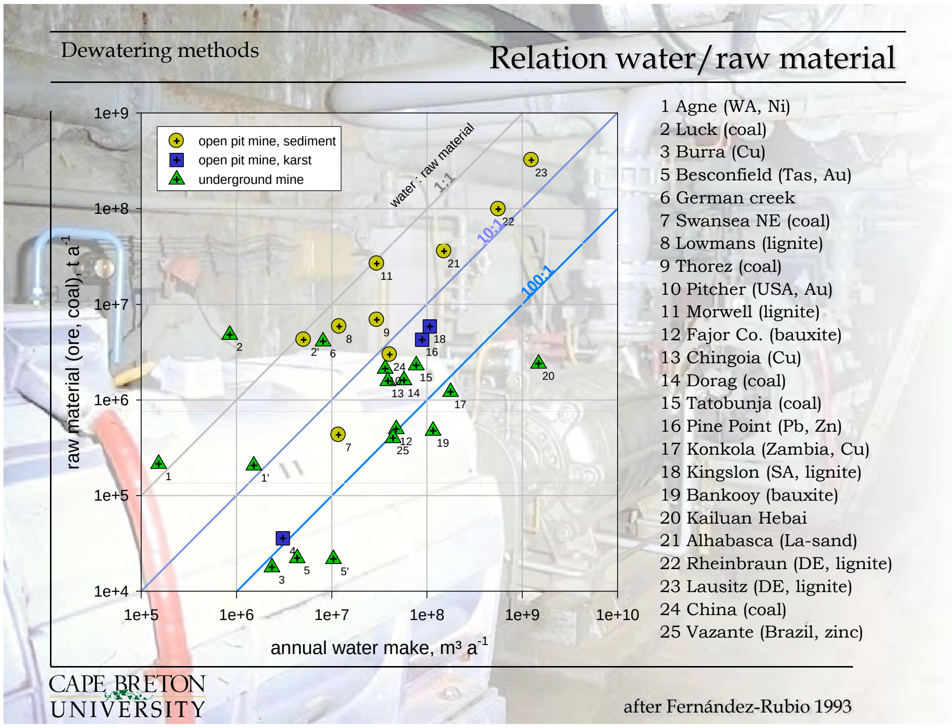
from Kegel 1950


Dewatering methods
Relation water/raw material
open pit mine, sediment
open pit mine, karst
underground mine
water : raw material
1:1
10:1
100:1
raw material (ore, coal), t a-1
annual water make, m³ a-1
1e+4
1e+5
1e+6
1e+7
1e+8
1e+9
1e+10
1 Agne (WA, Ni)
2 Luck (coal)
3 Burra (Cu)
5 Besconfield (Tas, Au)
6 German creek
7 Swansea NE (coal)
8 Lowmans (lignite)
9 Thorez (coal)
10 Pitcher (USA, Au)
11 Morwell (lignite)
12 Fajor Co. (bauxite)
13 Chingoia (Cu)
14 Dorag (coal)
15 Tatobunja (coal)
16 Pine Point (Pb, Zn)
17 Konkola (Zambia, Cu)
18 Kingslon (SA, lignite)
19 Bankooy (bauxite)
20 Kailuan Hebai
21 Alhabasca (La-sand)
22 Rheinbraun (DE, lignite)
23 Lausitz (DE, lignite)
24 China (coal)
25 Vazante (Brazil, zinc)
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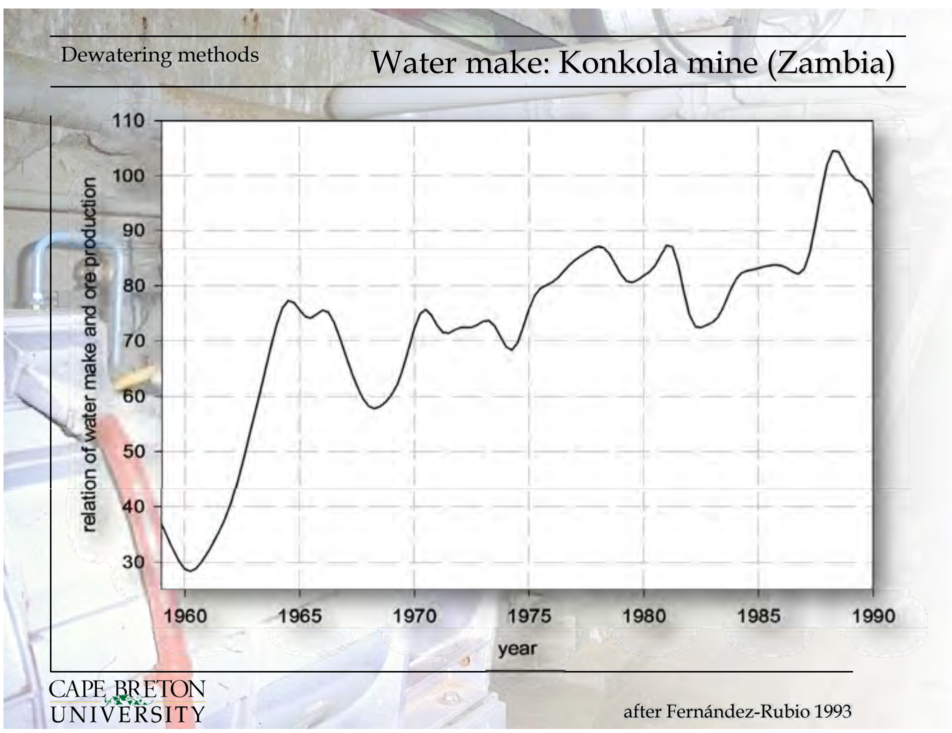
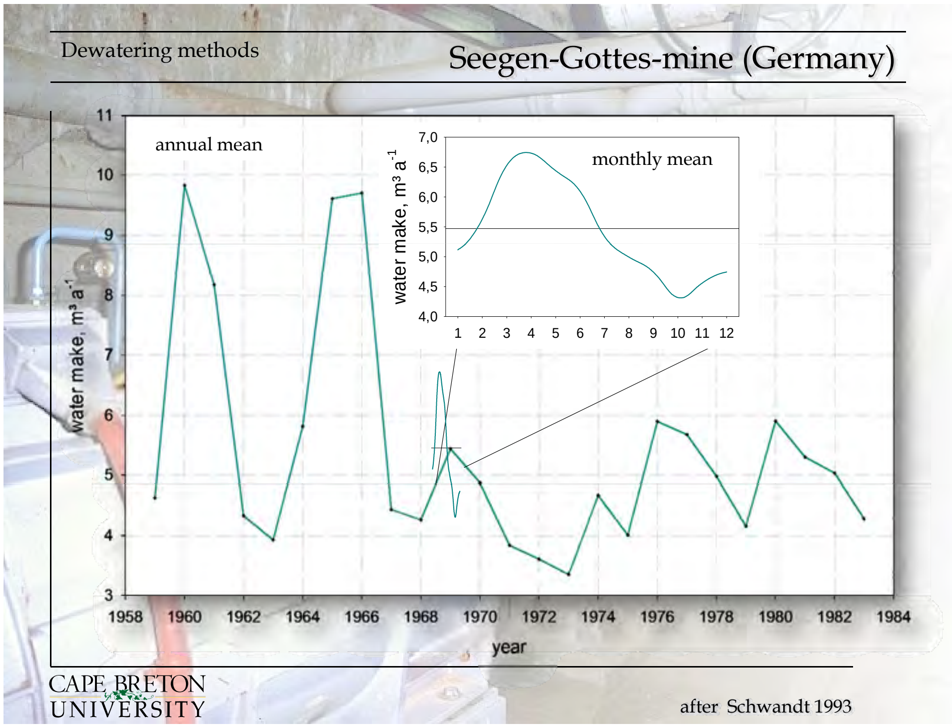
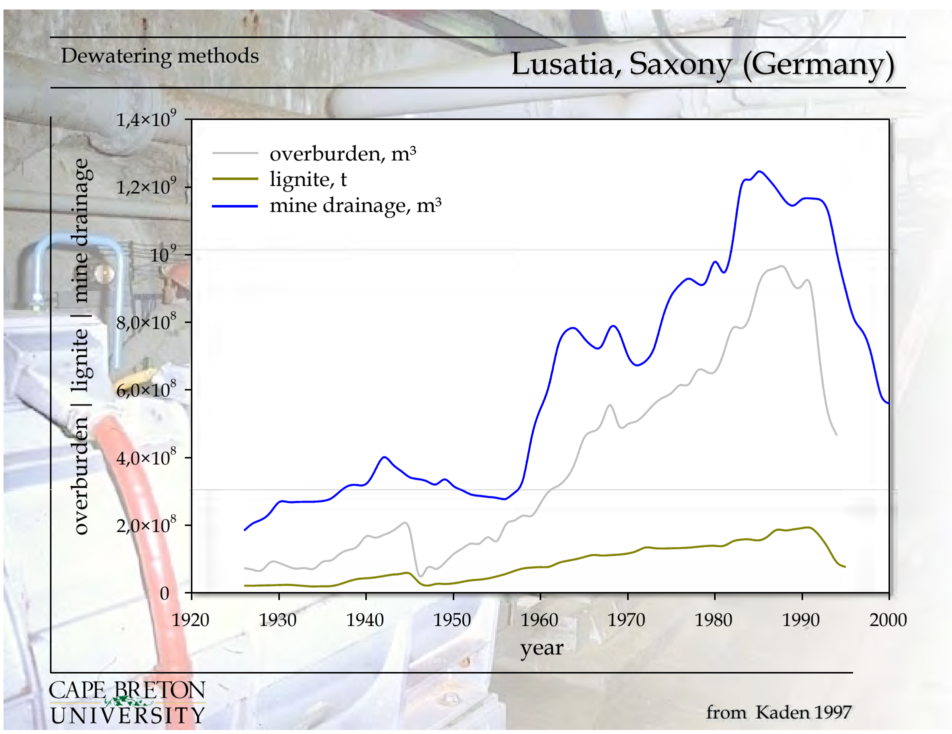
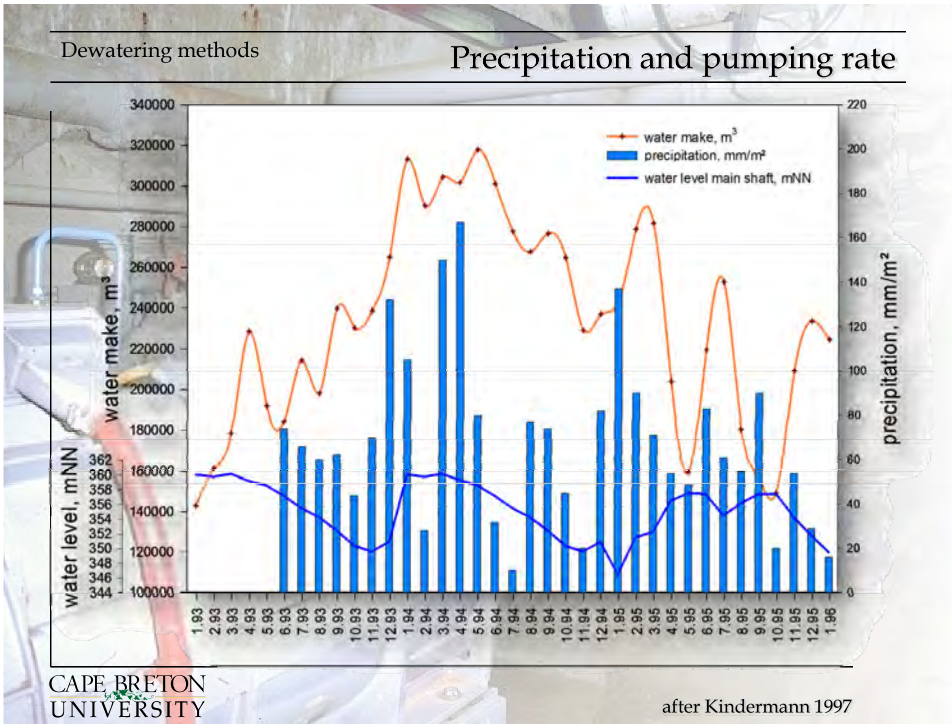
after Fernández-Rubio 1993


Dewatering methods
Water make: Konkola mine (Zambia)
relation of water make and ore production
year
30
40
50
60
70
80
90
100
110
1960
1965
1970
1975
1980
1985
1990
CAPE BRETON UNIVERSITY
after Fernández-Rubio 1993


Dewatering methods
Seegen-Gottes-mine (Germany)
annual mean
monthly mean
water make, m³ a⁻¹
year
CAPE BRETON UNIVERSITY
after Schwandt 1993


Dewatering methods
Lusatia, Saxony (Germany)
overburden, m³
lignite, t
mine drainage, m³
overburden | lignite | mine drainage
year
CAPE BRETON UNIVERSITY
from Kaden 1997


Dewatering methods
Precipitation and pumping rate
water make, m³
precipitation, mm/m²
water level main shaft, mNN
water make, m³
water level, mNN
precipitation, mm/m²
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after Kindermann 1997


Dewatering methods
Subsidence
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Roncourt/Lorraine 2005

Dewatering methods

Subsidence

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Roncourt/Lorraine 2005

Dewatering methods

Subsidence

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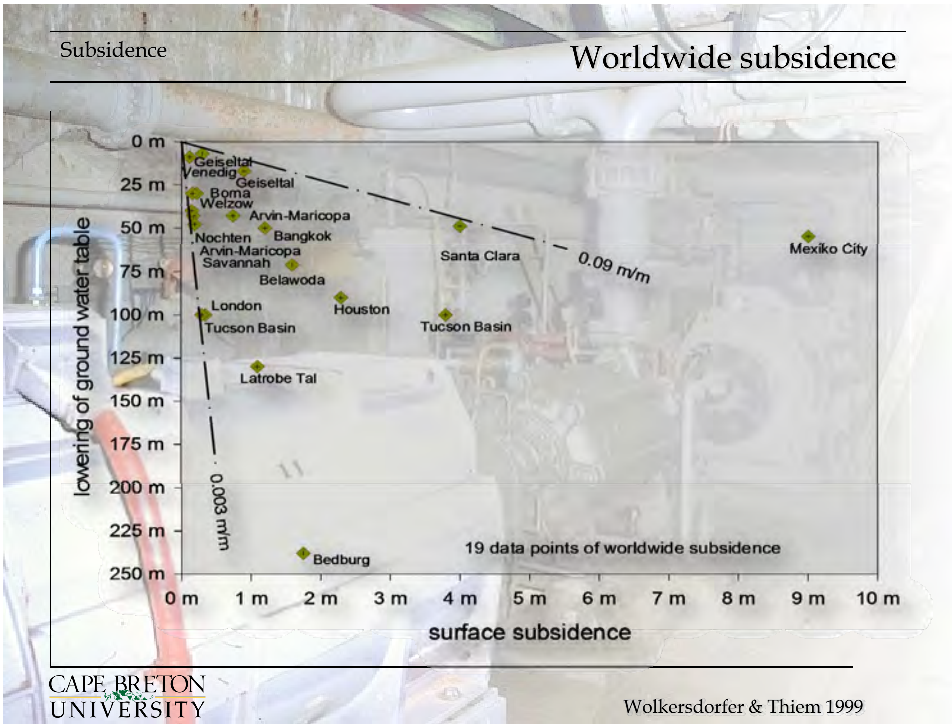
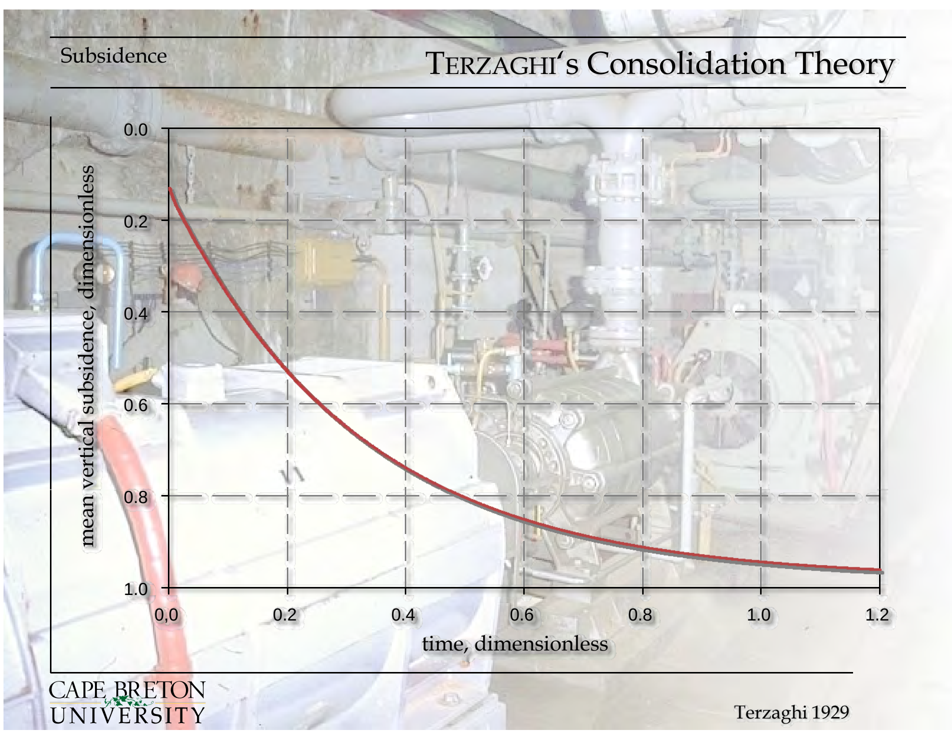
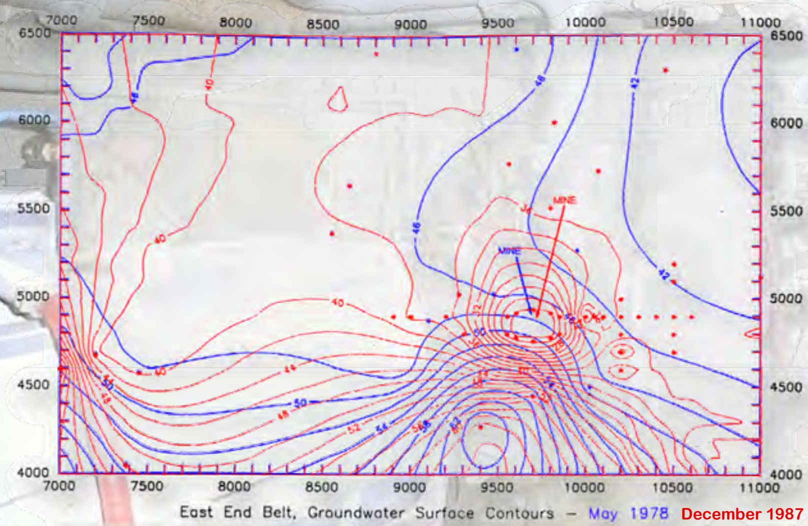
Roncourt/Lorraine 2005


Subsidence
Worldwide subsidence
0 m
25 m
50 m
75 m
100 m
125 m
150 m
175 m
200 m
225 m
250 m
lowering of ground water table
Geiseltal
Venedig
Geiseltal
Borna
Welzow
Arvin-Maricopa
Nochten
Bangkok
Arvin-Maricopa
Savannah
Belawoda
Santa Clara
0.09 m/m
Mexiko City
London
Tucson Basin
Houston
Tucson Basin
Latrobe Tal
0.003 m/m
Bedburg
19 data points of worldwide subsidence
0 m
1 m
2 m
3 m
4 m
5 m
6 m
7 m
8 m
9 m
10 m
surface subsidence
CAPE BRETON UNIVERSITY
Wolkersdorfer & Thiem 1999


Subsidence
TERZAGHI's Consolidation Theory
0.0
0.2
0.4
0.6
0.8
1.0
mean vertical subsidence, dimensionless
0,0
0.2
0.4
0.6
0.8
1.0
1.2
time, dimensionless
CAPE BRETON UNIVERSITY
Terzaghi 1929

Subsidence

Open cast mine: ground water withdrawal



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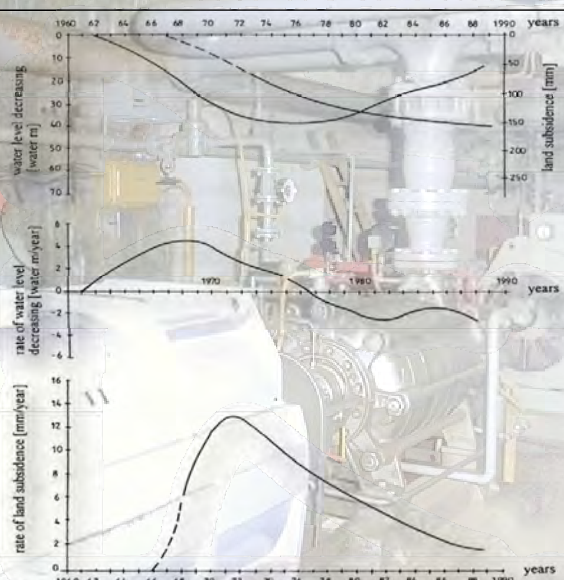
after Dudgeon 1994

Subsidence

Matraalia: Ground Water Withdrawal



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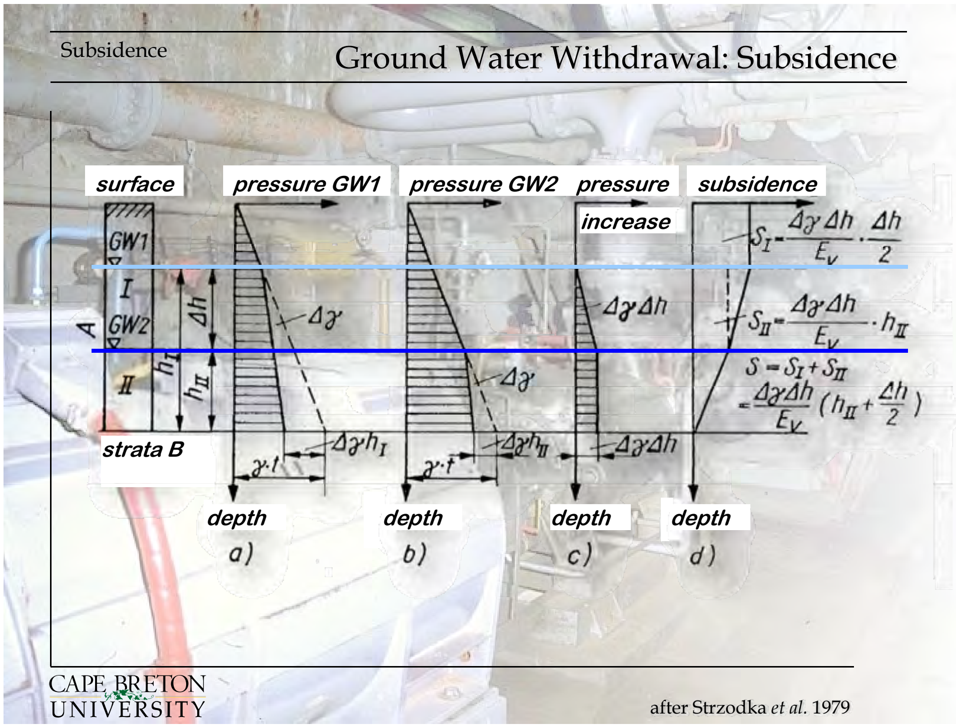
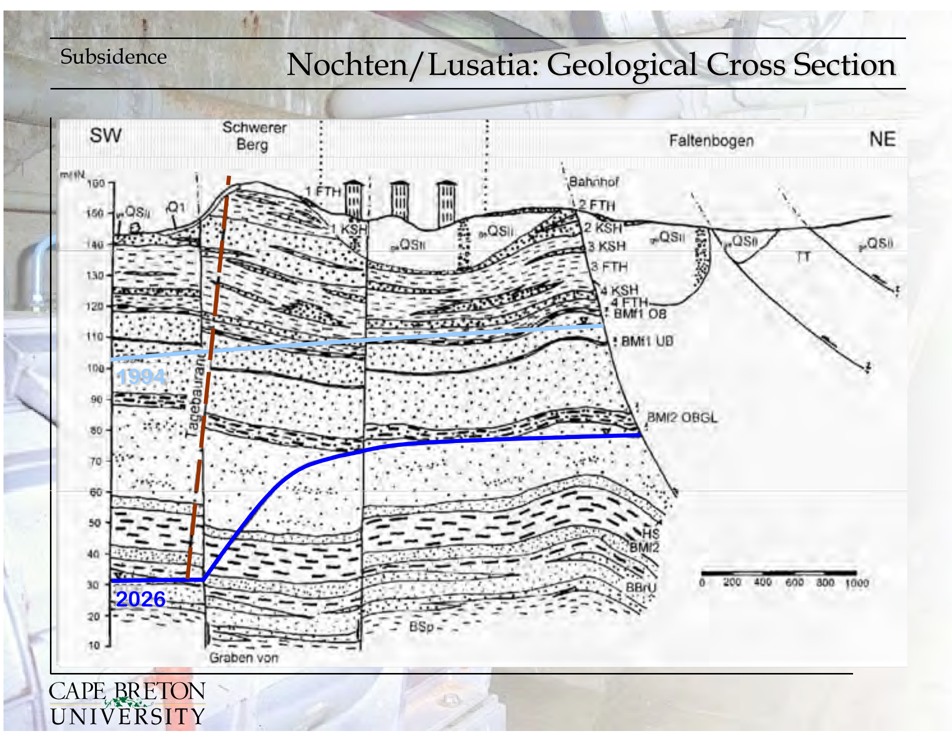
from Jambrik 1995


Subsidence
Ground Water Withdrawal: Subsidence
surface
pressure GW1
pressure GW2
pressure
increase
subsidence
GW1
GW2
strata B
depth
depth
depth
depth
a)
b)
c)
d)
CAPE BRETON UNIVERSITY
after Strzodka et al. 1979


Subsidence
Nochten/Lusatia: Geological Cross Section
SW
Schwerer Berg
Faltenbogen
NE
Bahnhof
1994
2026
Tagebaurand
Graben von
CAPE BRETON UNIVERSITY

Subsidence

Nochten/Lusatia: Soil Parameters

stratum	soil type	thickness *M*	compressibility E_s	porosity *n*
		m	MN/m²	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

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Subsidence

Nochten/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

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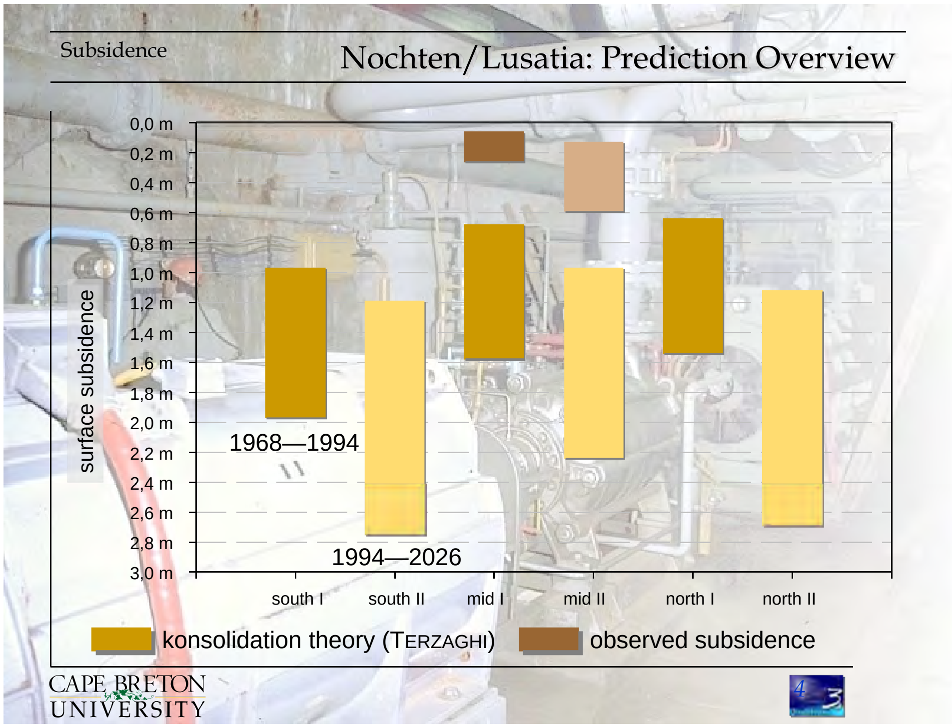
Subsidence
Nochten/Lusatia: Prediction Overview
surface subsidence
0,0 m
0,2 m
0,4 m
0,6 m
0,8 m
1,0 m
1,2 m
1,4 m
1,6 m
1,8 m
2,0 m
2,2 m
2,4 m
2,6 m
2,8 m
3,0 m
1968—1994
1994—2026
south I
south II
mid I
mid II
north I
north II
konsolidation theory (TERZAGHI)
observed subsidence
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From Ground Water to Mine Water

Environmental Hydrogeology in Mining

Mine Flooding

Prof. Dr. Christian Wolkersdorfer

Industrial Research Chair in Mine Water Remediation & Management

From Ground Water to Mine Water

Contents

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Accidently Mine Water Inrushes

- Mine water inundation
  - Adjacent mines (abandoned panels)
  - Hanging wall
    - Roßleben/Germany (1939): 51 m^3 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

- 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

- Monitoring system
- Controlled raise of mine water table
- Interference with raise of mine water table possible
- Active flooding (e.g. Hope/Germany)
- Passive flooding (Niederschlema/Germany)

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Mine Flooding

Uncontrolled Flooding

- Stop of mine water pumps
- No geotechnical monitoring system
- No chemical control
- Usually without monitoring system
- If mine budged is unclear
- No risk for people or buildings
- During war times or crisis

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Mine Flooding

Calculations

- Empirical
  - SAUL's rule
- Analytical
  - Turbulent flow
  - Lamiar flow
- Numerical
  - GRAM
  - SHETRAN
  - Monte Carlo
  - CFD

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Mine Flooding

Catastrophical mine water inundations

1815
1837
1883
1885
1895
1889
1891
1892
1898
1901
1908
1912
1917
1918
1923
1925
1927

1927	Carbonado Mine. Carbonado. Col		7
1950	Knockshinnoch Colliery, Ayrshire. Scot		13
1952	Holmes Slope, Forrestville, Pa.	A	5
1954	Newton Chickli Colliery, M.P, India		62
1958	Central Bowrah, Jharia, India		23
1959	River Slope. Port Griffith. Pa.	A	12
1960	Dhamua main , M.P., India		16
1970	Karanpura Colliery, Bihar, India		3
1973	Lofthouse Colliery. Northumberland, England.		7
1975	Silvewara Colliery, Nagpur, M.P., India		10
1975	Chasnala Colliery, Jharia, India		375
1977	Porter Tunnel Mine. Tover City. Pa	A	9
1978	Moss No. 3. Dante. Va.		4
1979	Mine No. 1. Poteau, Okla.		1
1981	Harlan No. 5. Grays Knob, Ky.		3
1983	Hurrilladih Colliery, Jharia, India		19
1985	Lykens No. o, Lykens. Pa.	A	1

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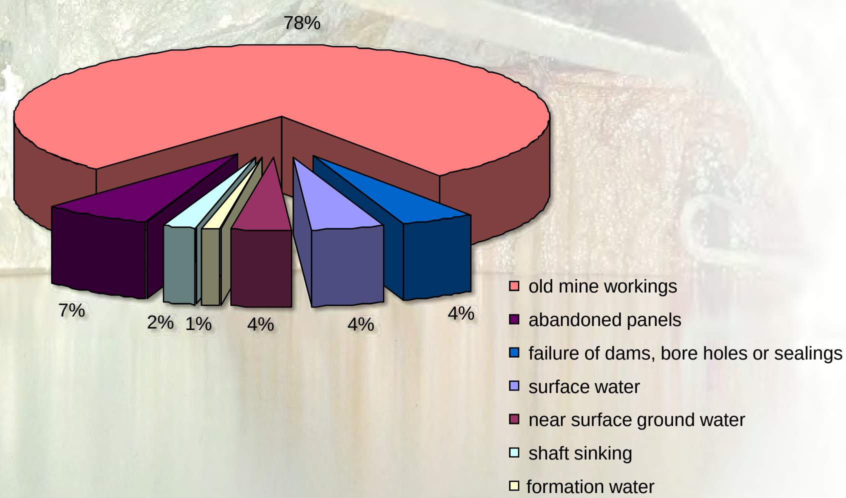
Vutukuri & Singh 1995

Mine Flooding

Reasons for mine inundation



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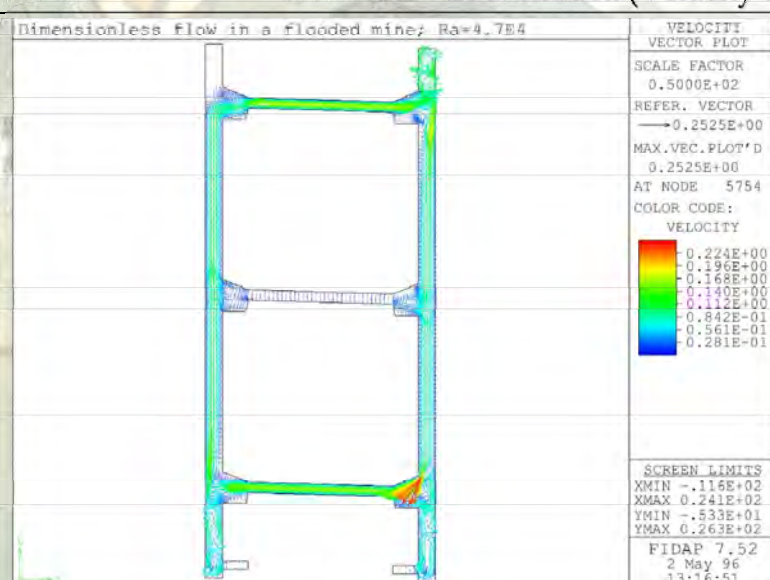
Job 1987;
Vutukuri & Singh 1995

Mine Flooding

CFD-Modell (Velocity Plot)



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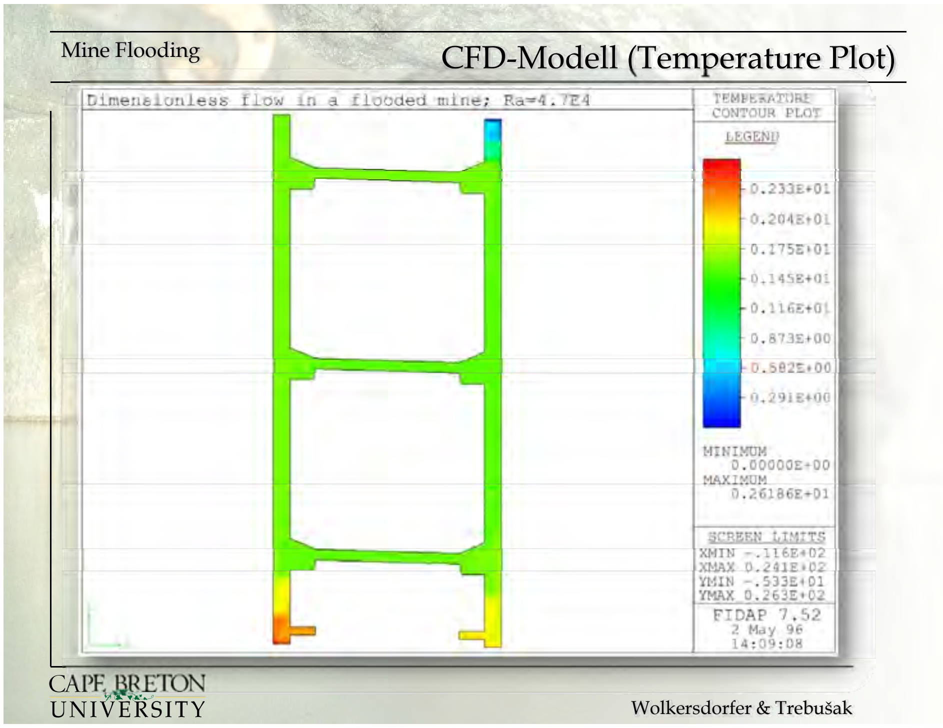
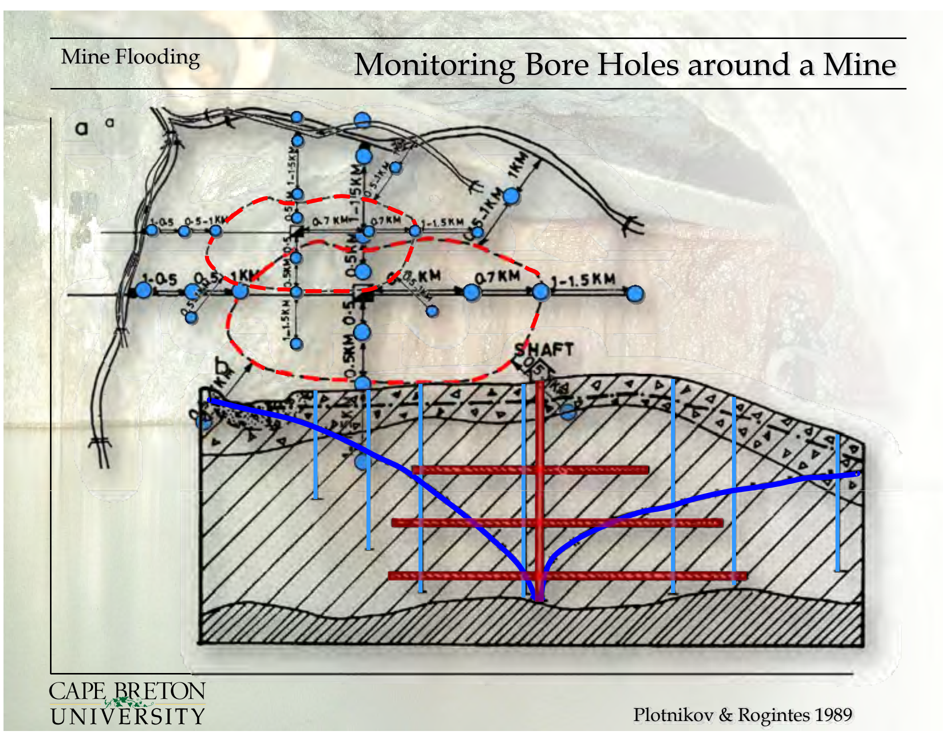
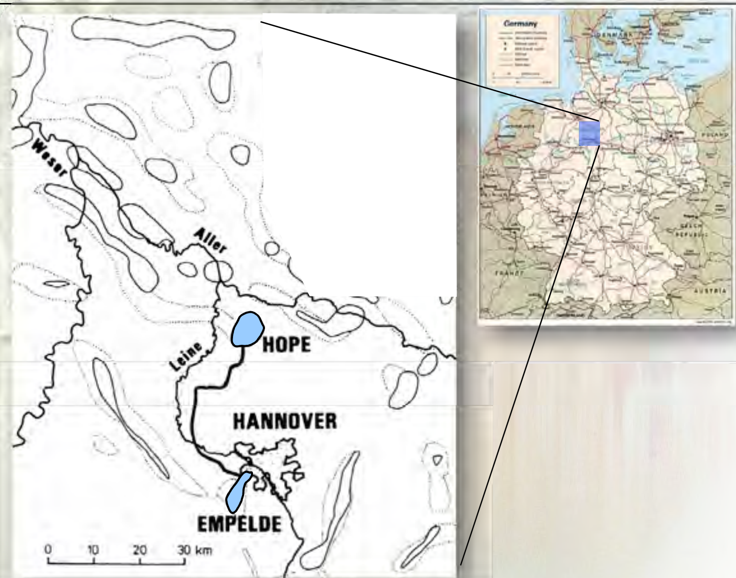
Wolkersdorfer & Trebušak


Mine Flooding
CFD-Modell (Temperature Plot)
Dimensionless flow in a flooded mine; Ra=4.7E4
TEMPERATURE CONTOUR PLOT
LEGEND
0.233E+01
0.204E+01
0.175E+01
0.145E+01
0.116E+01
0.873E+00
0.582E+00
0.291E+00
MINIMUM 0.00000E+00
MAXIMUM 0.26186E+01
SCREEN LIMITS
XMIN -.116E+02
XMAX 0.241E+02
YMIN -.533E+01
YMAX 0.263E+02
FIDAP 7.52
2 May 96
14:09:08
CAPE BRETON UNIVERSITY
Wolkersdorfer & Trebušak


Mine Flooding
Monitoring Bore Holes around a Mine
SHAFT
CAPE BRETON UNIVERSITY
Plotnikov & Rogintes 1989

Mine Flooding

Hope/Germany: Topography



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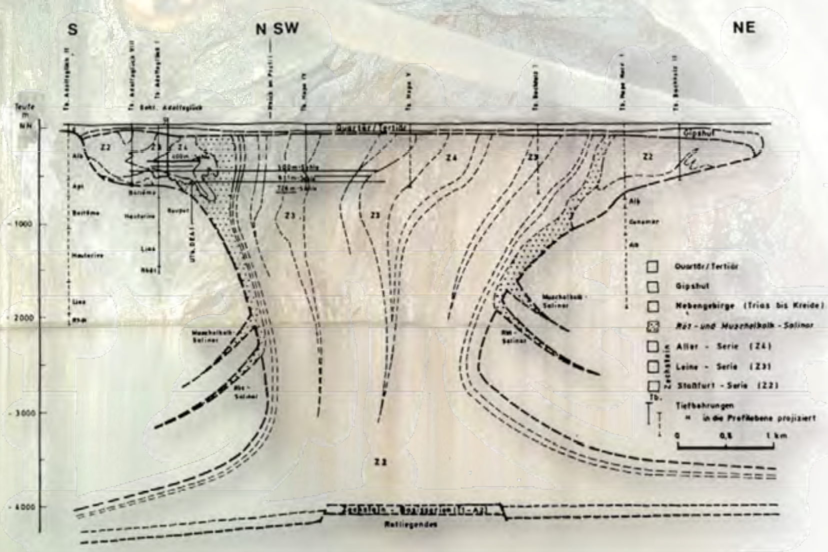
from GSF 1985

Mine Flooding

Hope/Germany: Geological Profile



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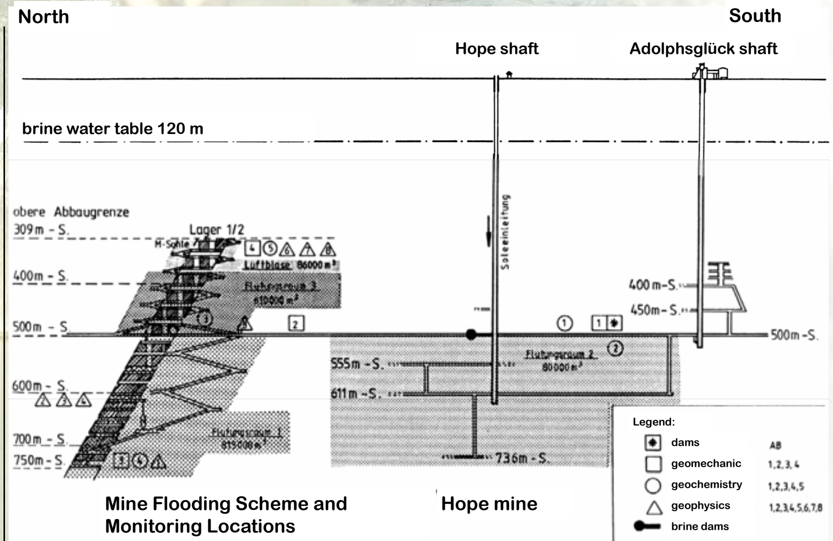
from GSF 1985

Mine Flooding

Hope/Germany: Flooding Scheme



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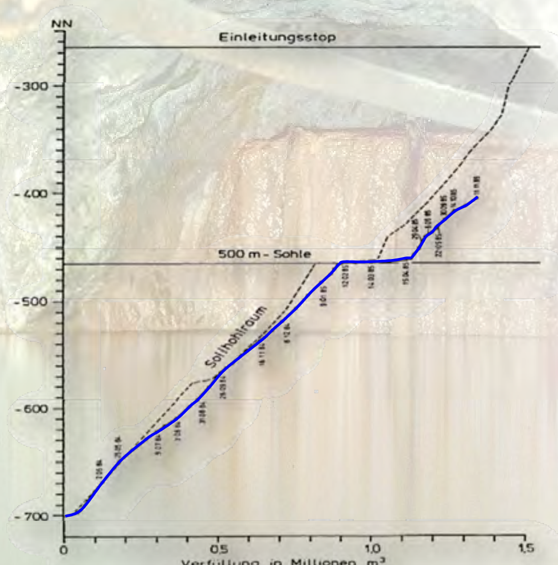
from Flach & Heick 1986

Mine Flooding

Hope/Germany: Raise of Mine Water Table

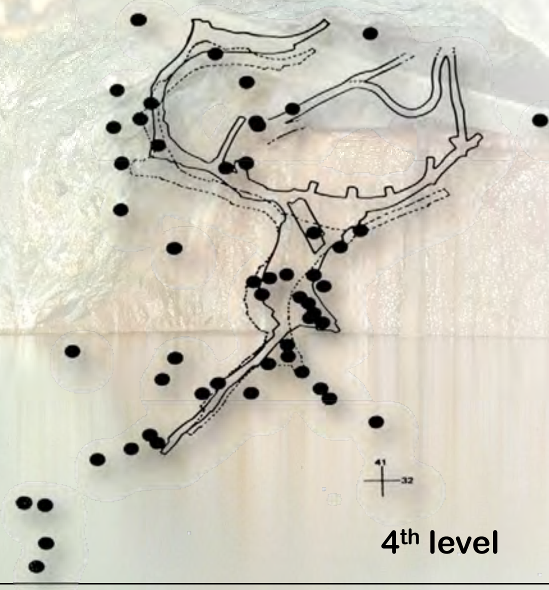


CAPE BRETON UNIVERSITY

from GSF 1986

Mine Flooding

Hope/Germany: Rockbursts

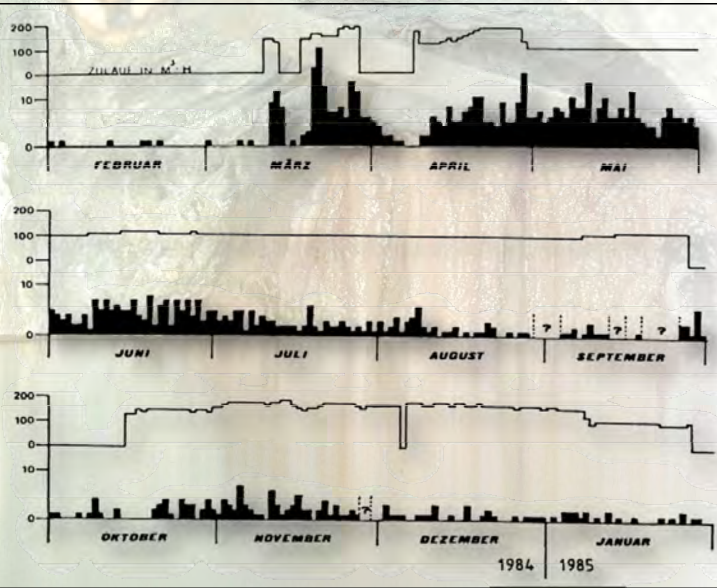


CAPE BRETON UNIVERSITY

from Flach & Heick 1986

Mine Flooding

Hope/Germany: Rock Bursts



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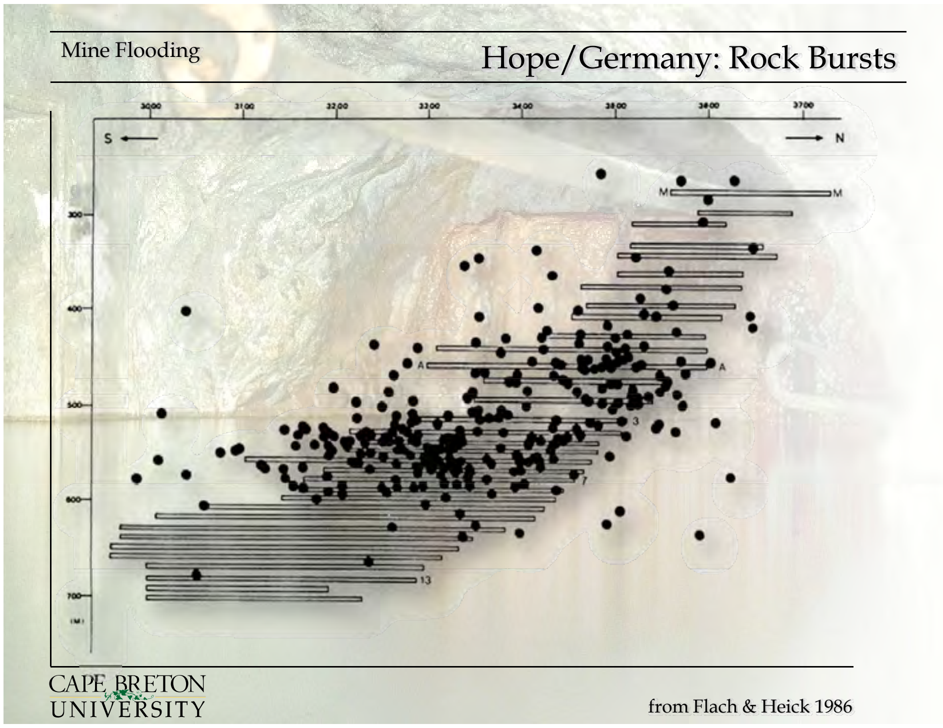
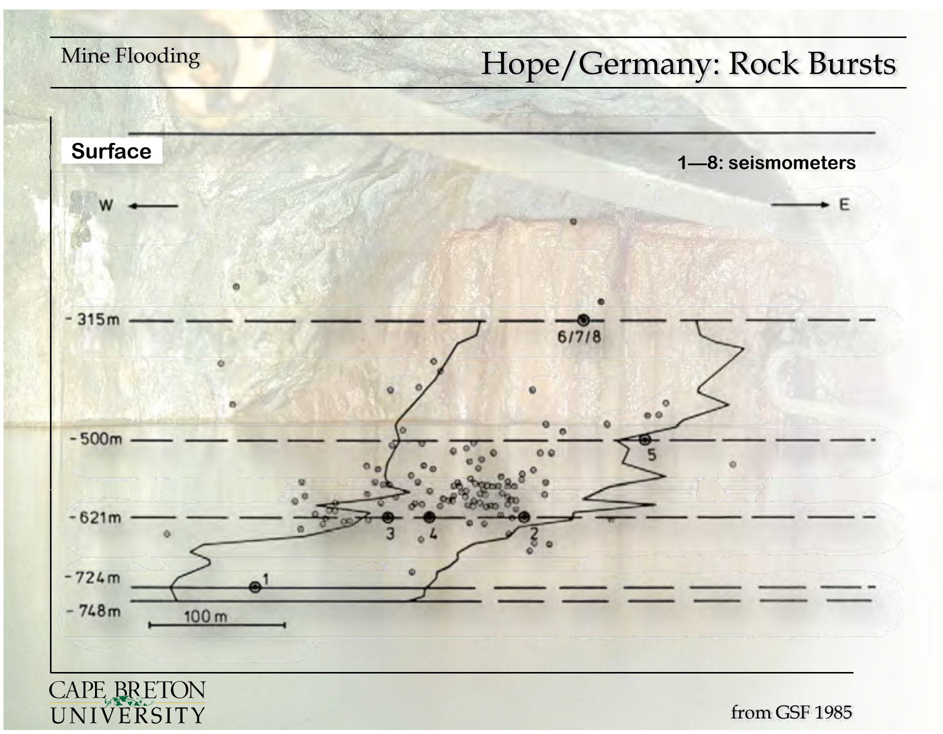
from Flach & Heick 1986


Mine Flooding
Hope/Germany: Rock Bursts
S
N
300
400
500
600
700
CAPE BRETON UNIVERSITY
from Flach & Heick 1986


Mine Flooding
Hope/Germany: Rock Bursts
Surface
1—8: seismometers
W
E
- 315m
6/7/8
- 500m
5
- 621m
3
4
2
- 724m
1
- 748m
100 m
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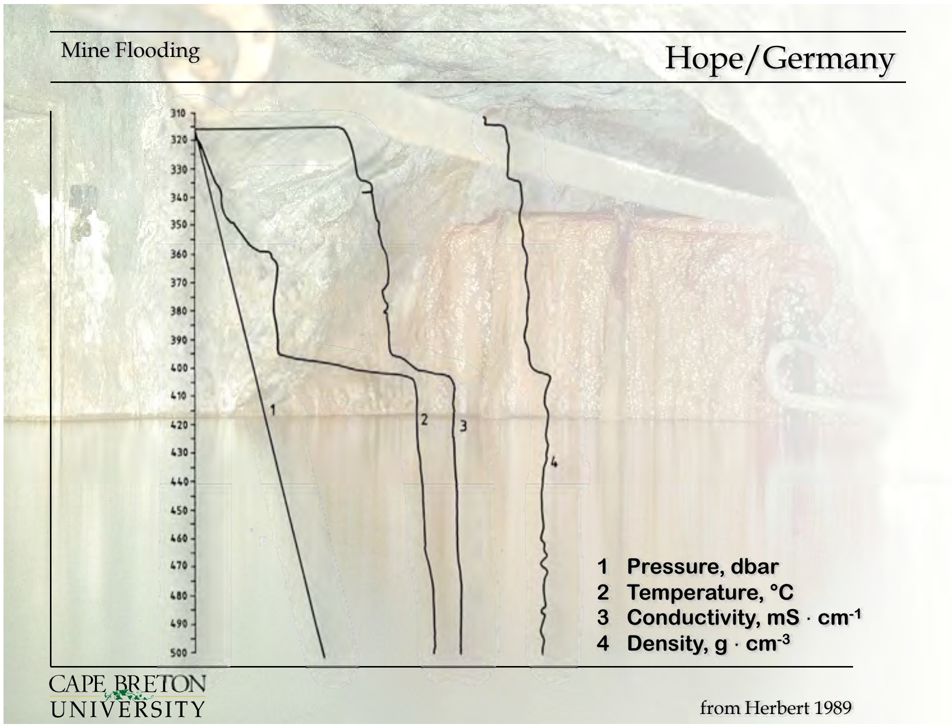
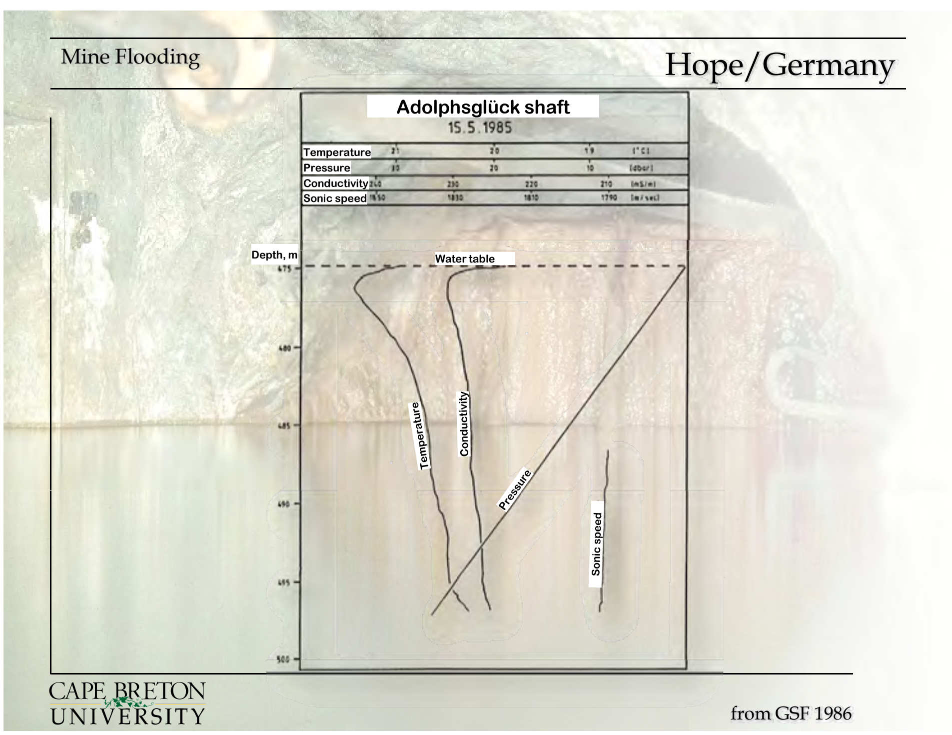
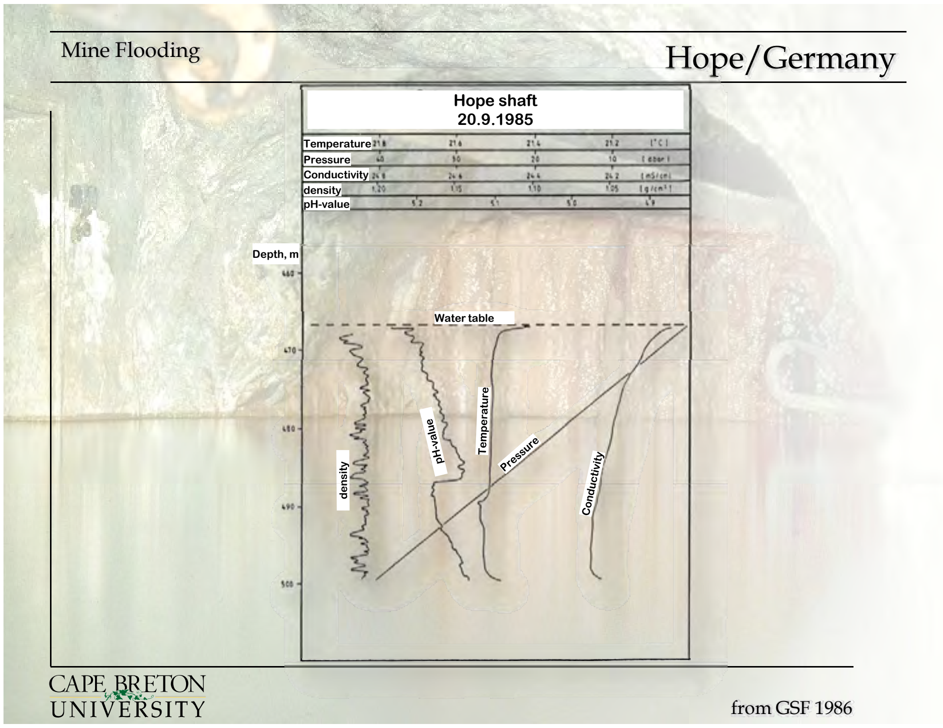
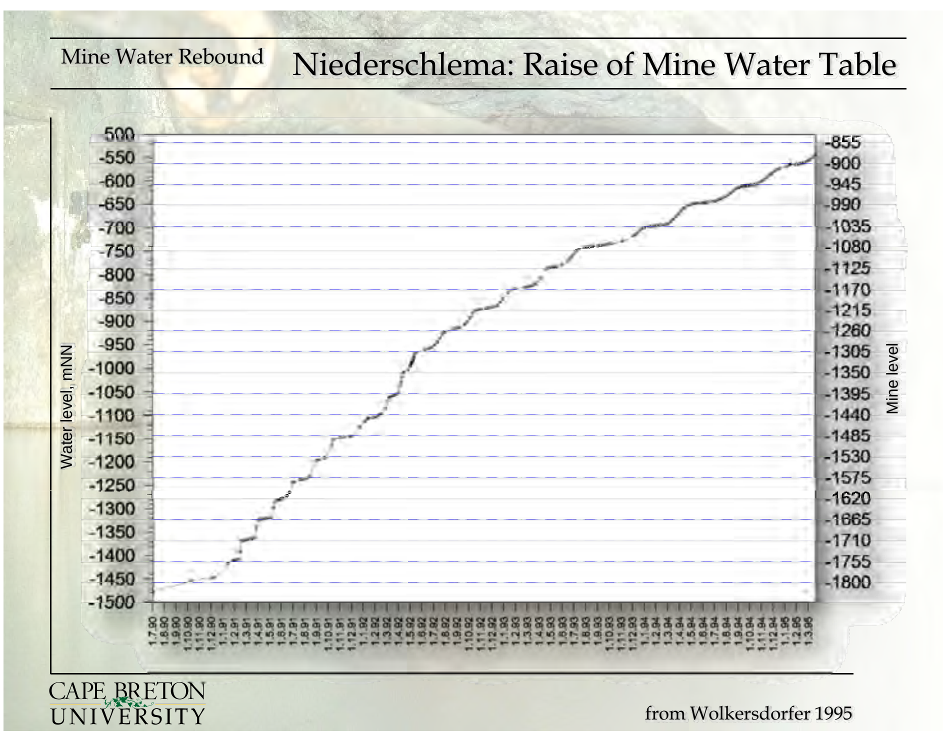
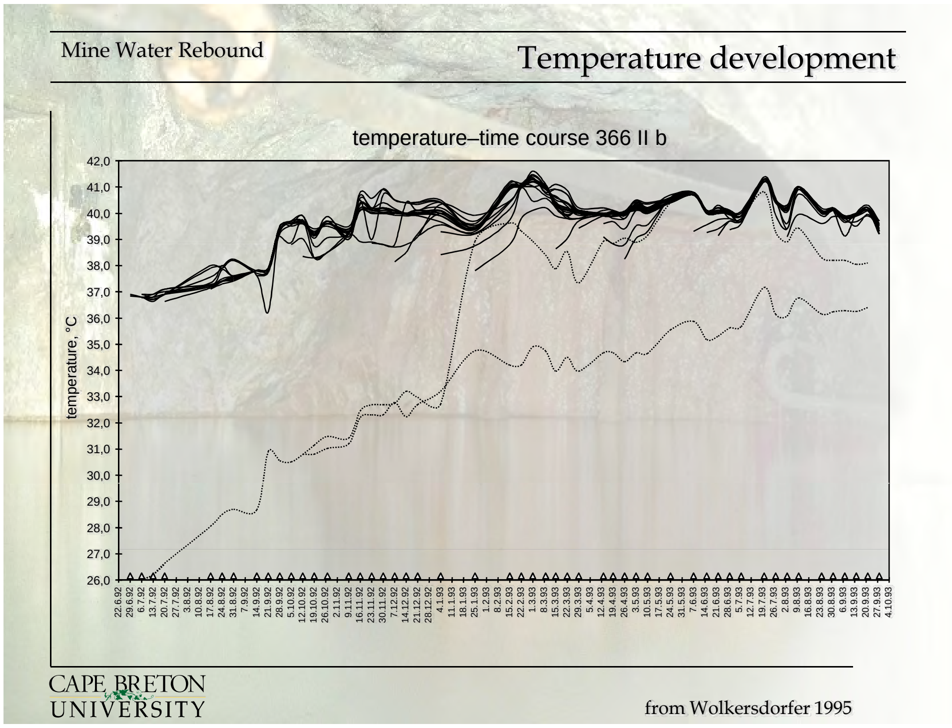
from GSF 1985

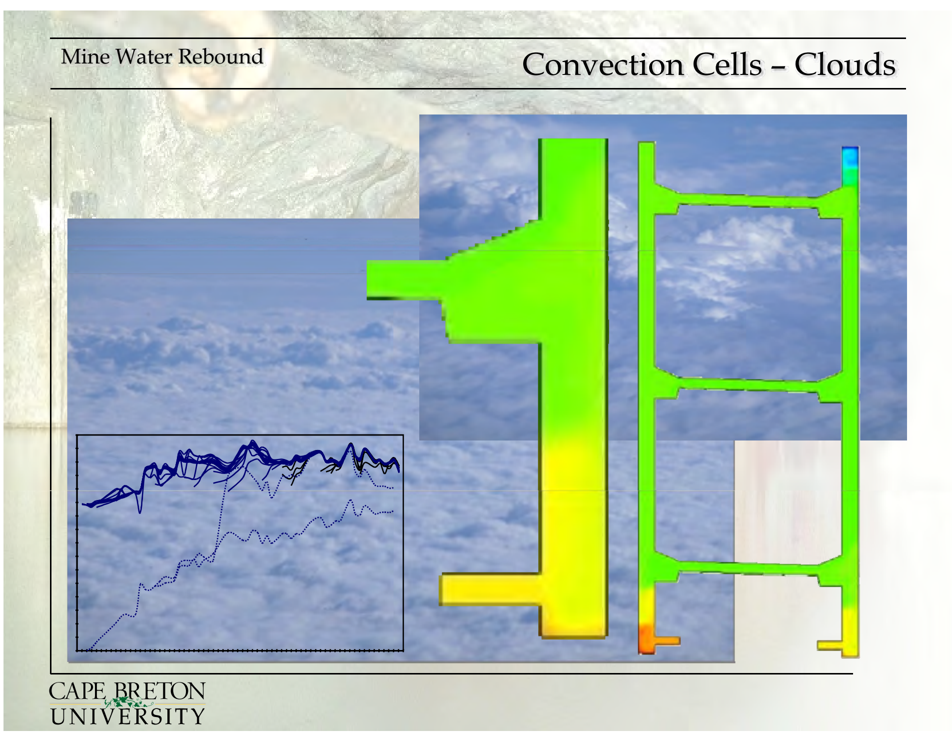

Mine Flooding
Hope/Germany
1 Pressure, dbar
2 Temperature, °C
3 Conductivity, mS · cm-1
4 Density, g · cm-3
CAPE BRETON UNIVERSITY
from Herbert 1989

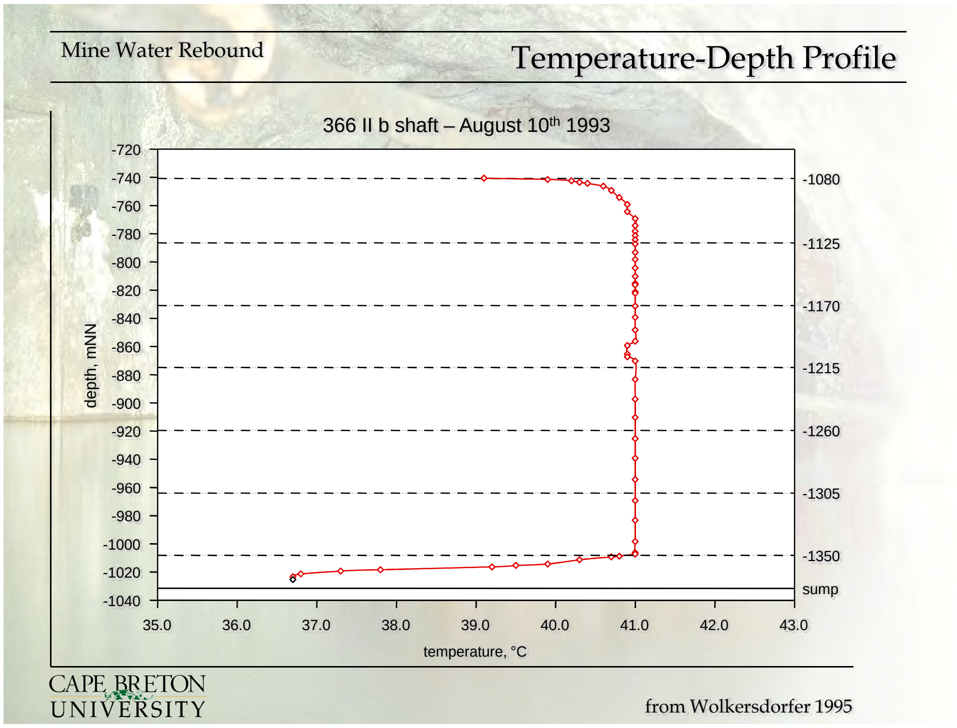

Mine Flooding
Hope/Germany
Adolphsglück shaft
15.5.1985
Temperature
Pressure
Conductivity
Sonic speed
Depth, m
Water table
Temperature
Conductivity
Pressure
Sonic speed
CAPE BRETON UNIVERSITY
from GSF 1986

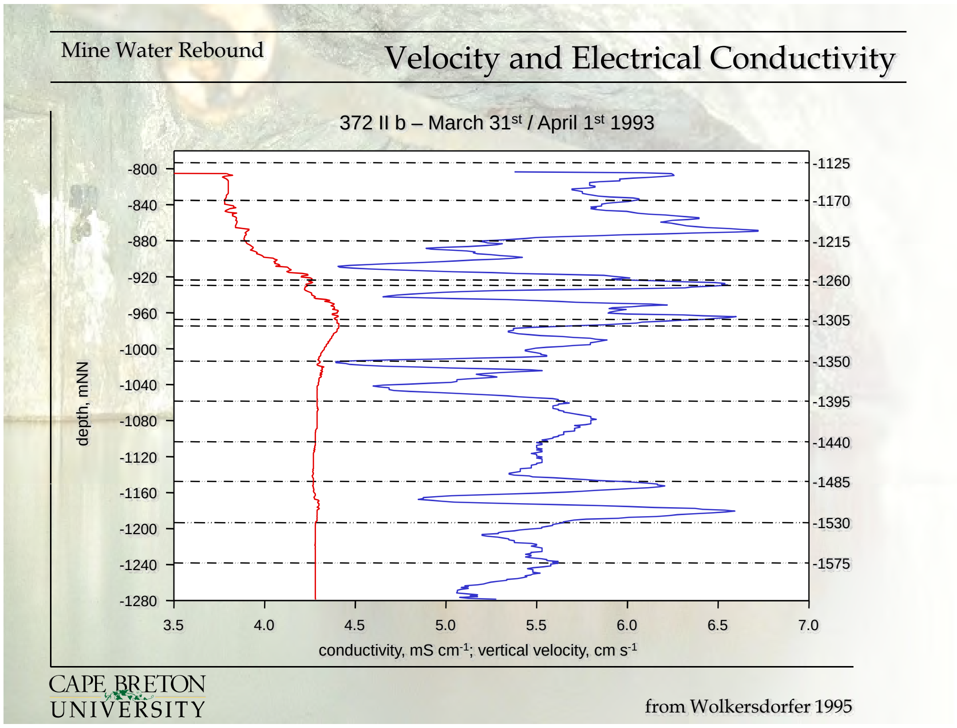

Mine Flooding
Hope/Germany
Hope shaft
20.9.1985
Temperature
Pressure
Conductivity
density
pH-value
Depth, m
Water table
density
pH-value
Temperature
Pressure
Conductivity
CAPE BRETON UNIVERSITY
from GSF 1986

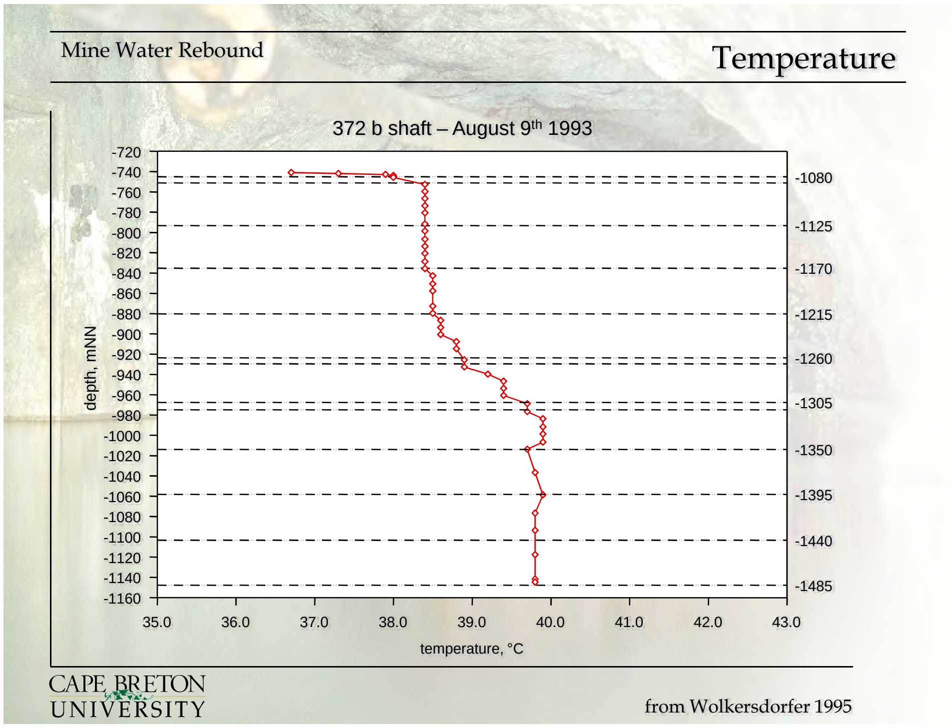

Mine Water Rebound
Niederschlema: Raise of Mine Water Table
Water level, mNN
-500
-550
-600
-650
-700
-750
-800
-850
-900
-950
-1000
-1050
-1100
-1150
-1200
-1250
-1300
-1350
-1400
-1450
-1500
Mine level
-855
-900
-945
-990
-1035
-1080
-1125
-1170
-1215
-1260
-1305
-1350
-1395
-1440
-1485
-1530
-1575
-1620
-1665
-1710
-1755
-1800
CAPE BRETON UNIVERSITY
from Wolkersdorfer 1995


Mine Water Rebound
Temperature development
temperature–time course 366 II b
temperature, °C
42,0
41,0
40,0
39,0
38,0
37,0
36,0
35,0
34,0
33,0
32,0
31,0
30,0
29,0
28,0
27,0
26,0
CAPE BRETON UNIVERSITY
from Wolkersdorfer 1995


Mine Water Rebound
Convection Cells – Clouds
CAPE BRETON UNIVERSITY


Mine Water Rebound
Temperature-Depth Profile
366 II b shaft – August 10th 1993
depth, mNN
-720
-740
-760
-780
-800
-820
-840
-860
-880
-900
-920
-940
-960
-980
-1000
-1020
-1040
-1080
-1125
-1170
-1215
-1260
-1305
-1350
sump
35.0
36.0
37.0
38.0
39.0
40.0
41.0
42.0
43.0
temperature, °C
CAPE BRETON UNIVERSITY
from Wolkersdorfer 1995


Mine Water Rebound
Velocity and Electrical Conductivity
372 II b – March 31st / April 1st 1993
depth, mNN
-800
-840
-880
-920
-960
-1000
-1040
-1080
-1120
-1160
-1200
-1240
-1280
-1125
-1170
-1215
-1260
-1305
-1350
-1395
-1440
-1485
-1530
-1575
3.5
4.0
4.5
5.0
5.5
6.0
6.5
7.0
conductivity, mS cm-1; vertical velocity, cm s-1
CAPE BRETON UNIVERSITY
from Wolkersdorfer 1995


Mine Water Rebound
Temperature
372 b shaft – August 9th 1993
depth, mNN
temperature, °C
-720
-740
-760
-780
-800
-820
-840
-860
-880
-900
-920
-940
-960
-980
-1000
-1020
-1040
-1060
-1080
-1100
-1120
-1140
-1160
35.0
36.0
37.0
38.0
39.0
40.0
41.0
42.0
43.0
-1080
-1125
-1170
-1215
-1260
-1305
-1350
-1395
-1440
-1485
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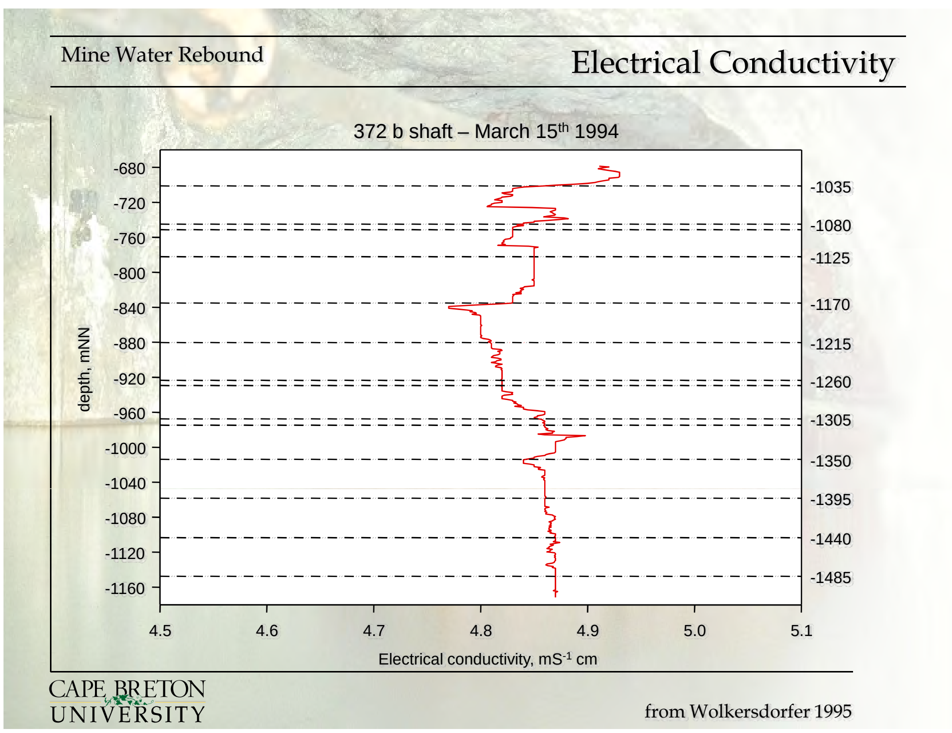
Mine Water Rebound
Electrical Conductivity
372 b shaft – March 15th 1994
depth, mNN
Electrical conductivity, mS-1 cm
-680
-720
-760
-800
-840
-880
-920
-960
-1000
-1040
-1080
-1120
-1160
4.5
4.6
4.7
4.8
4.9
5.0
5.1
-1035
-1080
-1125
-1170
-1215
-1260
-1305
-1350
-1395
-1440
-1485
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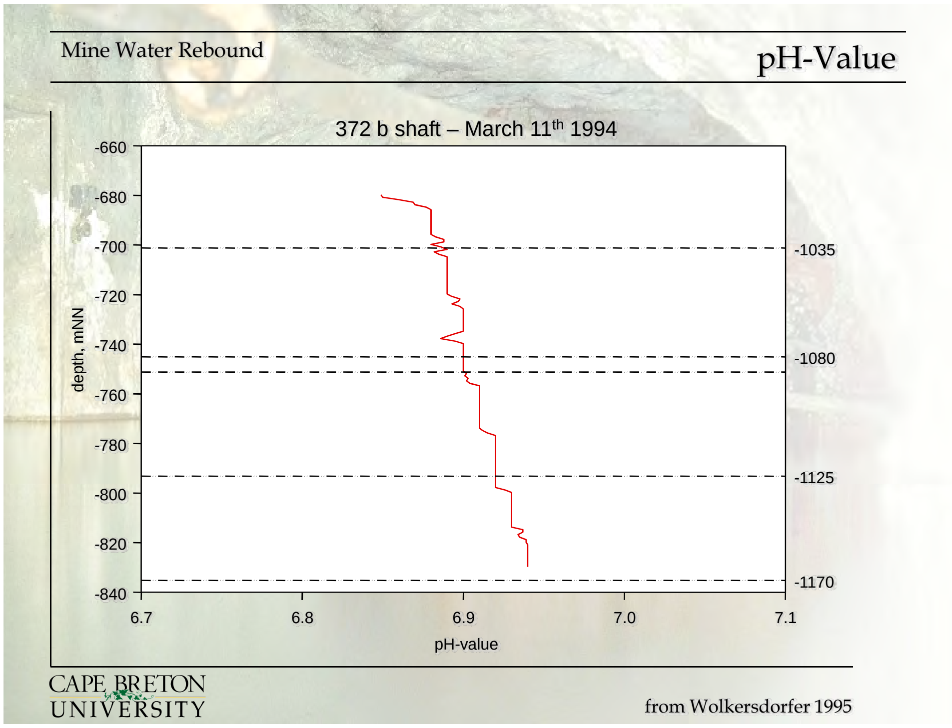
Mine Water Rebound
pH-Value
372 b shaft – March 11th 1994
-660
-680
-700
-720
-740
-760
-780
-800
-820
-840
depth, mNN
-1035
-1080
-1125
-1170
6.7
6.8
6.9
7.0
7.1
pH-value
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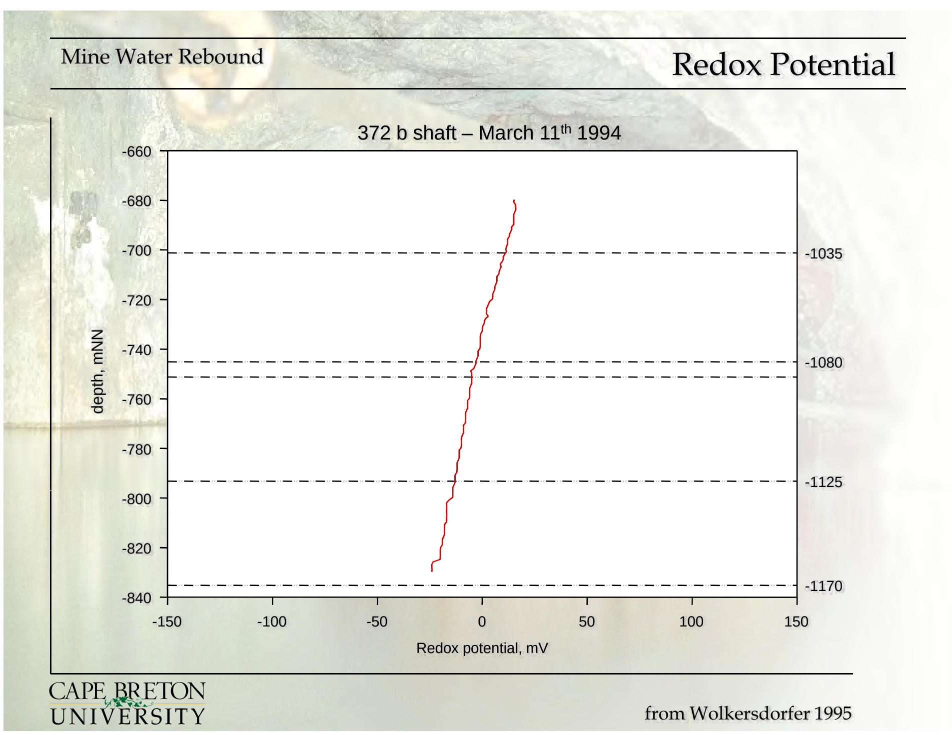
from Wolkersdorfer 1995


Mine Water Rebound
Redox Potential
372 b shaft – March 11th 1994
-660
-680
-700
-720
-740
-760
-780
-800
-820
-840
depth, mNN
-1035
-1080
-1125
-1170
-150
-100
-50
0
50
100
150
Redox potential, mV
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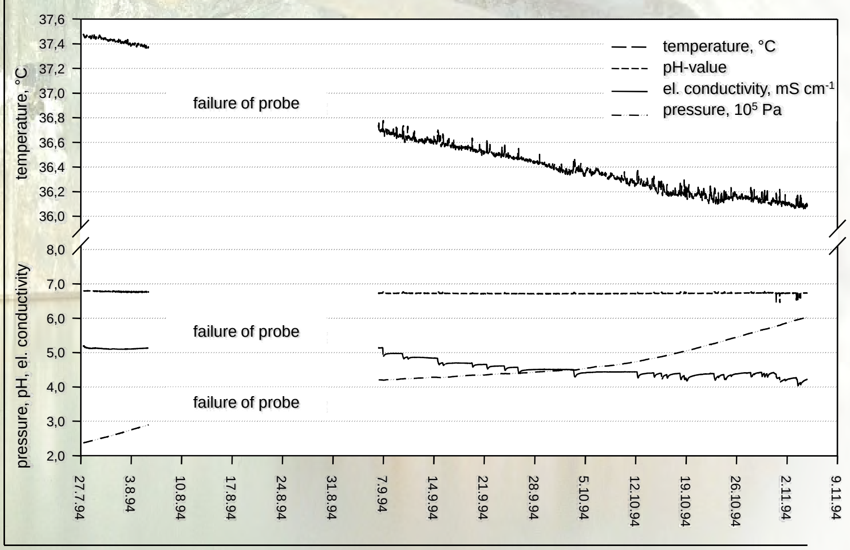
from Wolkersdorfer 1995

Mine Water Rebound

Raise of Mine Water Table



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Mine Flooding

Legislation (e.g. Germany)

- Federal Mining Law (BBergG)
  - as of February 12th 1990
- Federal (WHG) and State Water Laws
  - as of November 12th 1996
  - EU-Water Framework Directive
- Environmental Acceptability Law (UVPG)
  - 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

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Legislation

Federal Mining Law

- Types of operation companies:
  - Prospecting
  - Mining
  - Processing
- Strategic working plan
  - does not include the right to start mining
  - simple (facultative), qualifying (compulsary)
- Main working plan (2 years effective)
- Special working plan
- Common working plans
- Closure plan

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Legislation

Federal Mining Law

- *Strategic working plan*
- Water authorities
  - BBergG (facultative): hearing, participation

    Mining authorities not necessarily bound to recommondations
  - UVPG (qualified): participation

    Mining authorities are definitely bound to recommondations
- *Main working plan*
- Water authorities
  - 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 Energierecht **32**. – S. 57—81; Stuttgart u.a. (Boorberg).

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From Ground Water to Mine Water

Environmental Hydrogeology in Mining

Mine Water Geochemistry

Prof. Dr. Christian Wolkersdorfer

Industrial Research Chair in Mine Water Remediation & Management

From Ground Water to Mine Water

Contents

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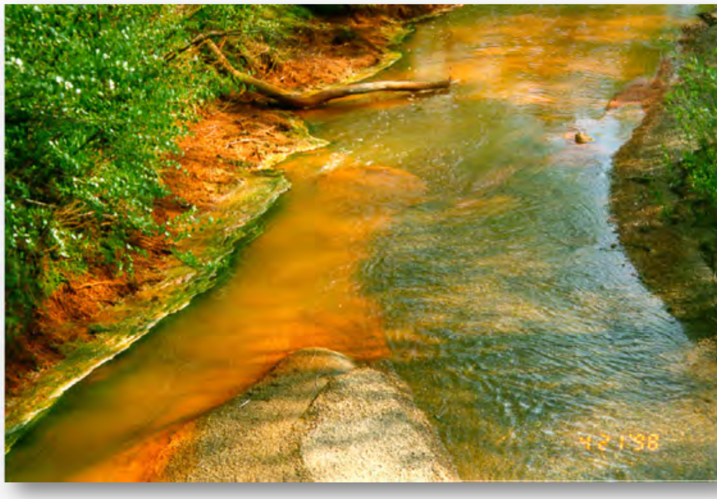
Mine Water Geochemistry

Why to deal with mine water chemistry?



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Picher Superfund Site: Tar Creek into Lytle Creek (nelphi.org)

Mine Water Geochemistry

Why to deal with mine water chemistry?

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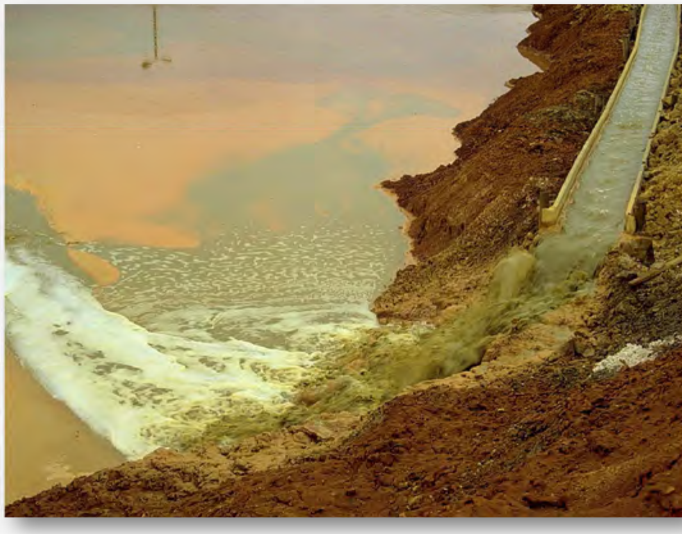
Eagle Picher Superfund Site: Mark R. Boardman

Mine Water Geochemistry

Why to deal with mine water chemistry?



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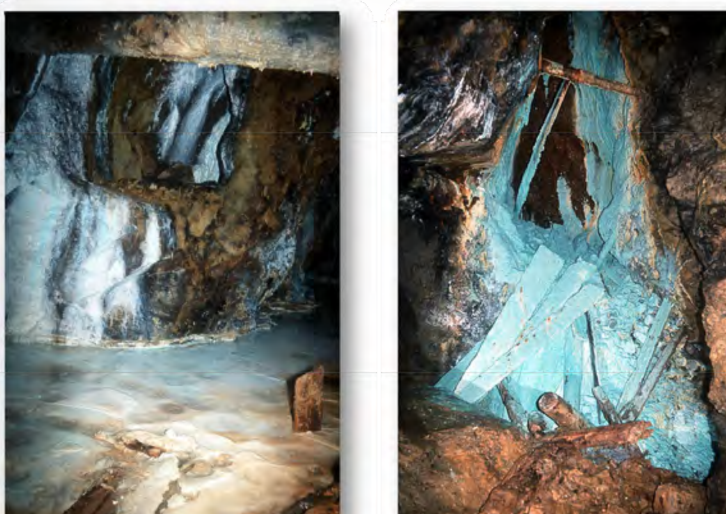
Former Königstein Uranium Mine / Saxony

Mine Water Geochemistry

Why to deal with mine water chemistry?



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Pfunderer Berg: Armin Hanneberg

Mine Water Geochemistry

Why to deal with mine water chemistry?

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Georgi Unterbau / Tirol

Mine Water Geochemistry

Factors to be taken into Account

- Source - Pathway - Target - Concept
- Pyrite weathering
- pH-dependence of metal dissolution
- Natural attenuation of contaminants
- Buffer reactions
- Microbiological processes
- Control of the source („in-situ-methods“)

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Mine Water Geochemistry

What affects Mobility and Bioavailability

- Speciation
  - Hydrolyses, complexation
  - Solubility effects
- Redox transformations
  - e.g. $U^{4+} \rightarrow U^{6+} + 2\ e^{-}$
- Sorption (Adsorption/Absorption)
  - Especially onto iron hydroxide mineral
  - Silt, clay
  - Wood
  - Pore space

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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, alumosilicate weathering)
  - Precipitation, sorption of metal ions
  - ochre precipitation
- „Targets"
  - Surface water
  - Ground water

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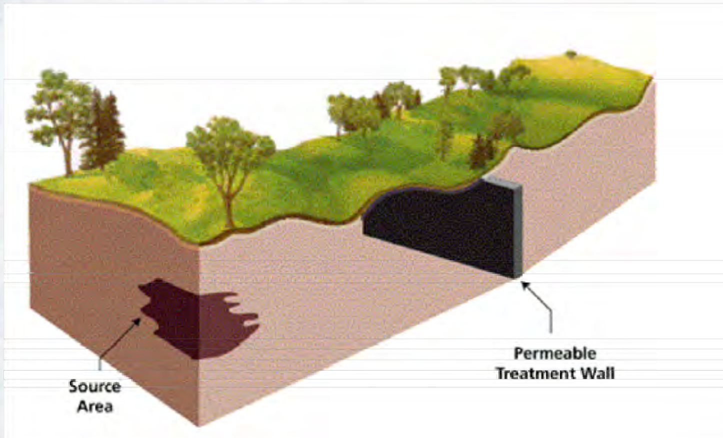
Mine Water Geochemistry

Source - Pathway - Target - Concept



Source → Pathway → Target

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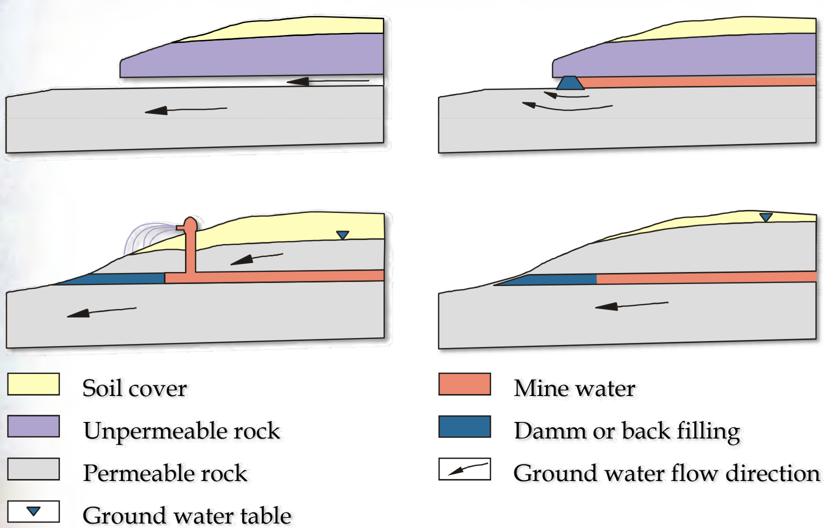
http://www.epa.gov/nrmrl/news/news092005.html

Mine Water Geochemistry

Mine Closure Systems



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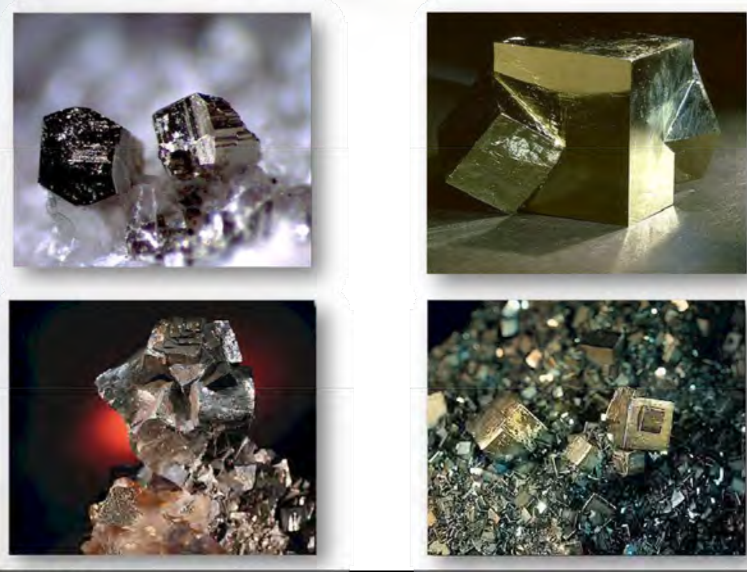
Fernandez-Rubio 1987

Mine Water Geochemistry

Pyrite Weathering Processes



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Mine Water Geochemistry

Pyrite Weathering Processes

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Mine Water Geochemistry

Pyrite Weathering Processes (1/2)

(1) $2\ FeS_{2\,(s)} + 7\ O_{2(aq)} + 2\ H_2O \rightarrow 2\ Fe^{2+} + 4\ SO_4^{2-} + 4\ H^+$

(2) $2\ Fe^{2+} + ½\ O_2 + 2\ H^+ \rightarrow 2\ Fe^{3+} + H_2O$

(3) $2\ Fe^{3+} + 6\ H_2O \leftrightarrow 2\ Fe(OH)_{3(s)} + 6\ H^+$

(4) $14\ Fe^{3+} + FeS_2 + 8\ H_2O \rightarrow 15\ Fe^{2+} + 2\ SO_4^{2-} + 16\ H^+$

(5) Fe^{2+} further reacts in reactions 2 – 4

(1) and (2) are catalysed by bacteria: e.g.

Acidithiobacillus thiooxidans, Gallionella

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Mine Water Geochemistry

Pyrite Weathering Processes (2/2)

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Weyer 2002

Mine Water Geochemistry

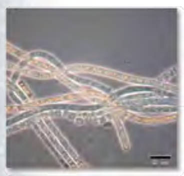
Bacterial Processes

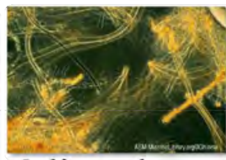
Acidithiobacillus thiooxidans, Gallionella, Beggiatoa and *Thiothrix* increase the reaction speed 10^6-fold

$$ADP + P^- \leftrightarrow ATP \quad \Delta G^{\circ\prime} = +32\ kJ$$

$$2\ S^{2-} + 4\ H_3O^+ + O_2 \leftrightarrow 2\ S + 6\ H_2O$$

$$2\ S + 6\ H_2O + 3\ O_2 \leftrightarrow 2\ SO_4^{2-} + 4\ H_3O^+ \quad \Delta G^{\circ\prime} = -498\ kJ$$





	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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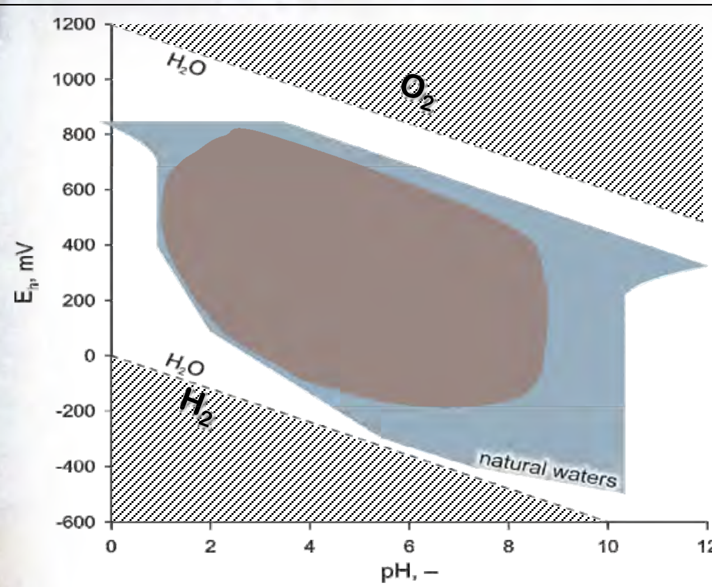
Mine Water Geochemistry

Bacterial Processes



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Baas-Becking *et al.* 1960

Mine Water Geochemistry

Sulphide Weathering

sphalerite	$ZnS_{(s)} + 2\,O_{2(aq)} \rightarrow Zn^{2+} + SO_4^{2-}$
galena	$PbS_{(s)} + 2\,O_{2(aq)} \rightarrow Pb^{2+} + SO_4^{2-}$
millerite	$NiS_{(s)} + 2\,O_{2(aq)} \rightarrow Ni^{2+} + SO_4^{2-}$
greenockite	$CdS_{(s)} + 2\,O_{2(aq)} \rightarrow Cd^{2+} + SO_4^{2-}$
covellin	$CuS_{(s)} + 2\,O_{2(aq)} \rightarrow Cu^{2+} + SO_4^{2-}$
copper pyrite	$CuFeS_{(s)} + 4\,O_{2(aq)} \rightarrow Cu^{2+} + Fe^{2+} + 2\,SO_4^{2-}$

- Release of toxic metals and sulphate, but no acidity (except copper pyrite)

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Mine Water Geochemistry

Mineral weathering

- 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

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Mine Water Geochemistry

pH-Values and Metal Concentrations

lokality	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 Harz Mountains	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 Ore Mountains	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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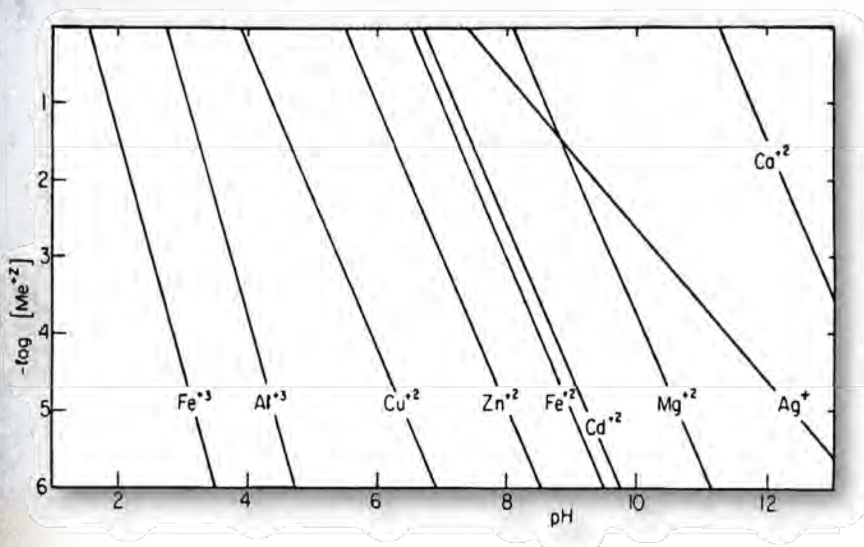
Mine Water Geochemistry

pH-Dependency of Metal Solubility



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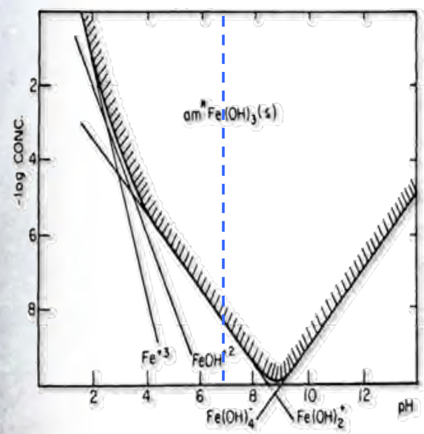
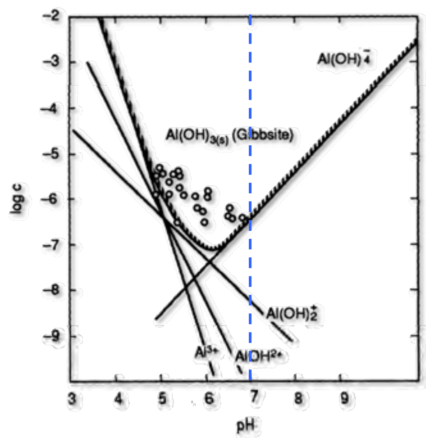
Stumm & Morgan 1981

Mine Water Geochemistry

pH-Dependency of Metal Solubility





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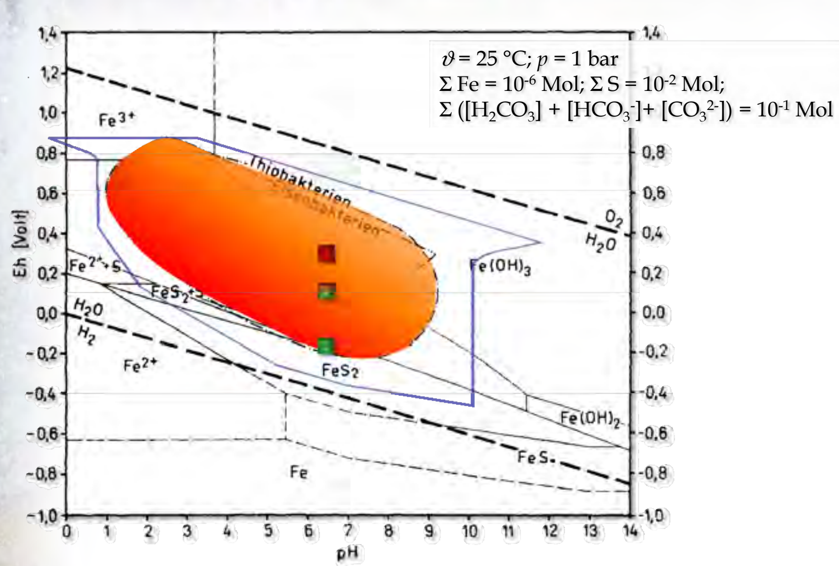
Stumm & Morgan 1981;
Sigg & Stumm1994

Mine Water Geochemistry

Pourbaix-diagram: Fe–S–CO_2–H_2O



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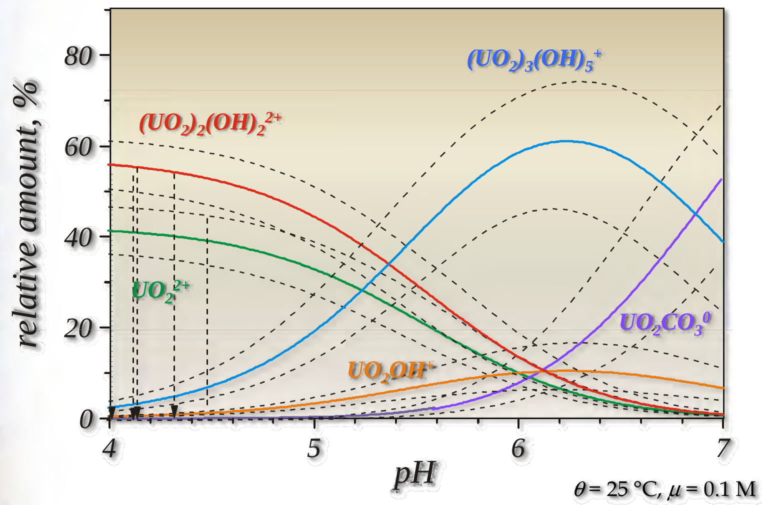
Tischendorf & Ungethüm 1965

Mine Water Geochemistry

Uranium Speciation (U^{6+})



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Meinrath 1998

Natural Attenuation

Weathering Processes

- The weathering of minerals (except di-sulphides such as pyrite) produces alkalinity and, therefore, buffers the acid

- Carbonates
- Feldspar
- Mica

mineral	formula	pH-buffer range
Calcite	$CaCO_3$	6.5 … 7.5
Dolomite	$CaMg[CO_3]_2$	6.5 … 7.5
Siderite	$FeCO_3$	4.8 … 6.3
Mix carbonates	(Ca, Mg, Fe, Mn)CO_3	4.8 … 6.3
Gibbsite	$Al(OH)_3$	4.0 … 4.3
Ferrihydrite	$Fe(OH)_3$	< 3.5
Goethite	α-FeOOH	1.3 … 1.8
K-Jarosite	$KFe_3[(OH)_6|(SO_4)_2]$	1 … 2 (laboritory experiments)
Alumino-silikates		1 … 2 (laboritory experiments)

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Natural Attenuation

Weathering Processes

- ***Carbonates***
- Calcite (buffers at pH 6.5…7.5)
  - $CaCO_3 + H^+ \leftrightarrow Ca^{2+} + HCO_3^-$
- Dolomite (buffers at pH 6.5…7.5)
  - $CaMg[CO_3]_2 + 2\,H^+ \leftrightarrow Ca^{2+} + Mg^{2+} + 2\,HCO_3^-$
- Siderite (buffers at pH 4.8 …6.3)
  - $FeCO_3 + H^+ \leftrightarrow Fe^{2+} + HCO_3^-$
  - $Fe^{2+} + \frac{1}{4}\,O_2 + \frac{5}{2}\,H_2O \rightarrow Fe(OH)_3 + 2\,H^+$

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Natural Attenuation

Weathering Processes

- ***Feldspar***
- K-Feldspar

  $KAlSi_3O_8 + H^+ + \frac{9}{2}\,H_2O \rightarrow 2\,H_4[SiO_4] + \frac{1}{2}\,Al_2Si_2O_5(OH)_4$
- Anorthite

  $CaAl_2Si_2O_8 + H^+ + H_2O \rightarrow Ca^{2+} + 2\,H_4[SiO_4] + \frac{1}{2}\,Al_2Si_2O_5(OH)_4$
- Albite

  $NaAlSi_3O_8 + H^+ + \frac{9}{2}\,H_2O \rightarrow Na^+ + 2\,H_4[SiO_4] + \frac{1}{2}\,Al_2Si_2O_5(OH)_4$

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Natural Attenuation

Weathering Processes

- ***Mica***
- Biotite

  $KMg_{3/2}Fe_{3/2}[AlSi_3O_{10}](OH)_2 + 7\,H^+ + \tfrac{1}{2}\,H_2O \rightarrow K^+ + \tfrac{3}{2}\,Mg^{2+} + \tfrac{3}{2}\,Fe^{2+} + 2\,H_4[SiO_4] + \tfrac{1}{2}\,Al_2Si_2O_5(OH)_4$
- Muscovite

  $KAl_2[AlSi_3O_{10}](OH)_2 + H^+ + \tfrac{3}{2}\,H_2O \rightarrow K^+ + \tfrac{3}{2}\,Al_2Si_2O_5(OH)_4$

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Natural Attenuation

Keep in Mind: Mineralogy and Kinetics

- Disulphides are abundant in nearly all rocks as trace minerals
- Other minerals, for example silicates, are fare 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 (1/2)

- Metal oxides and -hydroxides

Gibbsite	$Al(OH)_3$
Iron hydroxide	$Fe(OH)_3$
Zinc hydroxide	$Zn(OH)_2$

- Metal carbonates and hydroxy-carbonates

Cerrusite	$PbCO_3$
Malachite	$Cu_2(OH)_2(CO_3)$

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Immobilisation of Metals

Secondary Minerals (2/2)

- Metal sulphates and -hydroxy-sulphates

Jarosite	$KFe_3(SO_4)_2(OH)_6$
Melanterite	$FeSO_4 \cdot 7H_2O$
Szomolnokite	$FeSO_4 \cdot H_2O$
Epsomite	$MgSO_4 \cdot 7H_2O$
Alunite	$KAl_3(SO_4)_2(OH)_6$
Jurbanite	$AlSO_4(OH) \cdot 5H_2O$
Basaluminite	$Al_4SO_4(OH)_{10} \cdot 5H_2O$
Anglesite	$PbSO_4$

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Alpers; Graeme

Mine Water Geochemistry

Control of Contamination Source

- Contaminant load (e.g. metals, acidity, sulphate) depends on:
  - Red-Ox conditions (does O_2 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

Metal loads released from a mine (or dump) reflect the weathering reactions involved

Q_{in} (Infiltration):

$$FeS_2 + 7/2\, O_2 + H_2O \rightarrow Fe^{2+} + 2\, SO_4^{2-} + 2\, H^+$$
$$ZnS + 2\, O_2 \rightarrow Zn^{2+} + SO_4^{2-}$$
$$PbS + 2\, O_2 \rightarrow Pb^{2+} + SO_4^{2-}$$
$$NiS + 2\, O_2 \rightarrow Ni^{2+} + SO_4^{2-}$$
$$CuS + 2\, O_2 \rightarrow Cu^{2+} + SO_4^{2-}$$
$$CuFeS_2 + 2\, O_2 \rightarrow Cu^{2+} + Fe^{2+} + 2\, SO_4^{2-}$$

Q_{out} (mine water):

H^+, SO_4^{2-}, Fe^{2+}, Zn^{2+}, Pb^{2+}, Ni^{2+}, Cu^{2+}

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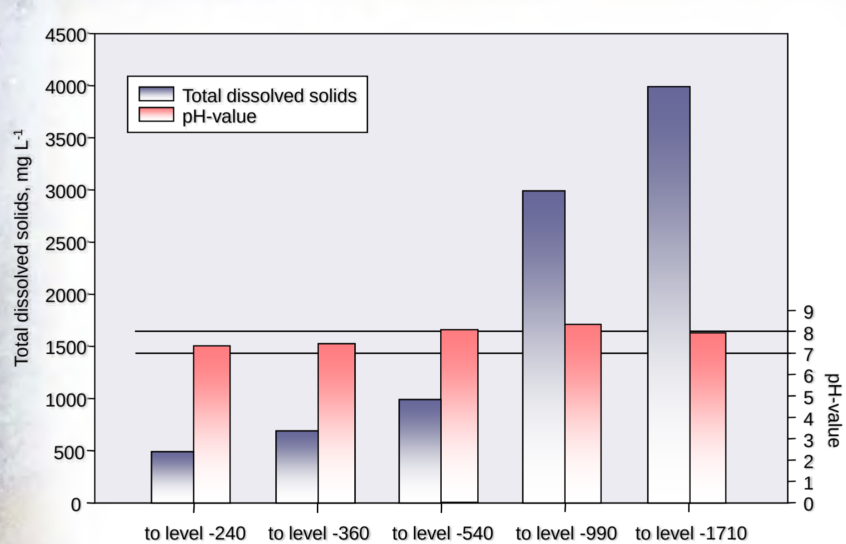
Mine Water Geochemistry

Niederschlema Uranium Mine



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Mine Water Geochemistry

Acidity – Alkalinity

- Acidity of mine water is due to the mixing of infiltration waters that are
  - in contact with pyrite and produce acidity
  - in contact with carbonates or silicates and produce alkalinity
- Weathering rate acidity > alkalinity ⇒ mine water is acidic
- Weathering rate alkalinity > acidity ⇒ mine water is alkaline
- Acidity: „base capacity“; alkalinity: „acid capacity“

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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 the 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

- Complete dissociation
- Strong bases (base cation + OH^-)
  - $NaOH \leftrightarrow Na^+ + OH^-$
  - $Mg(OH)_2 \leftrightarrow Mg^{2+} + 2\ OH^-$
- Strong acids (acid anion + H^+)
  - $HCl \leftrightarrow Cl^- + H^+$
  - $H_2SO_4 \leftrightarrow SO_4^{2-} + 2\ H^+$
- $[Aci] = „\Sigma [H^+] - \Sigma [OH^-]“ = 2 [SO_4^{2-}] + [Cl^-] - [Na^+] – 2 [Mg^{2+}]$
- $[Alk] = -[Aci] = [Na^+] + 2 [Mg^{2+}] - 2 [SO_4^{2-}] - [Cl^-]$
- $[Aci]_{calculated} = 2 [Fe^{2+}]/56 + 3 [Fe^{3+}]/56 + 3 [Al]/27 + 2 [Mn]/55 + 2 [Zn]/65 + 1000 (10^{-pH})$, mol L^{-1}

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Acidity – Alkalinity

Weak Acids and Bases

- Carbon acid is a weak acid resulting from the dissolution of CO_2 in water
- Stepwise dissociation
- Partly protonated, partly deprotonated species:
  - $CO_2\ (g) + H_2O \leftrightarrow H_2CO_3$ log $K_H = -1.27$
  - $H_2CO_3 \leftrightarrow HCO_3^- + H^+$ log $K_1 = -6.35$
  - $HCO_3^- \leftrightarrow CO_3^{2-} + H^+$ log $K_2 = -10.3$
  - $H_2O \leftrightarrow H^+ + OH^-$ log $K_W = -14.0$

  for all K: $\vartheta = 25$ °C; $I = 0$ mol
- at pH 5.6 $[HCO_3^-]$ significantly increases (↗ titration curve)

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Acidity – Alkalinity

Thermodynamic Laws

- Carbon acid balance (mass action law)

$$K_H = 10^{-1.27} = \frac{[H_2CO_3]}{[H_2O]\ pCO_2(g)} \quad (\vartheta = 25\,°C;\ I = 0\text{ mol};\ pCO_2 = 10^{-3.5}\,atm)$$

$$K_1 = 10^{-6.35} = \frac{[HCO_3^-][H^+]}{[H_2CO_3]} \quad (\vartheta = 25\,°C;\ I = 0\ \text{ mol})$$

$$K_2 = 10^{-10.3} = \frac{[CO_3^{2-}][H^+]}{[HCO^{3-}]} \quad (\vartheta = 25\,°C;\ I = 0\ \text{ mol})$$

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

CO_2
(gaseos)
↑↓
$CO_2 + H_2O \leftrightarrow H_2CO_3 \leftrightarrow H^+ + HCO_3^-$
(aqueous)

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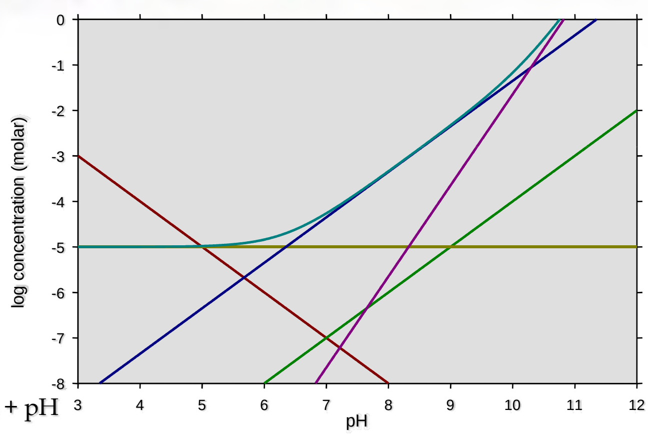
Acidity – Alkalinity

Distribution of Carbon Species



- log[H+] = -pH
- log[OH-] = -14 + pH
- $\log[H_2CO_3] = -1.27 + \log pCO_2$
- $\log[HCO_3^-] = -6.35 + \log[H_2CO_3] + pH$
- $\log[CO_3^{2-}] = -10.3 + \log[HCO_3^-] + pH$

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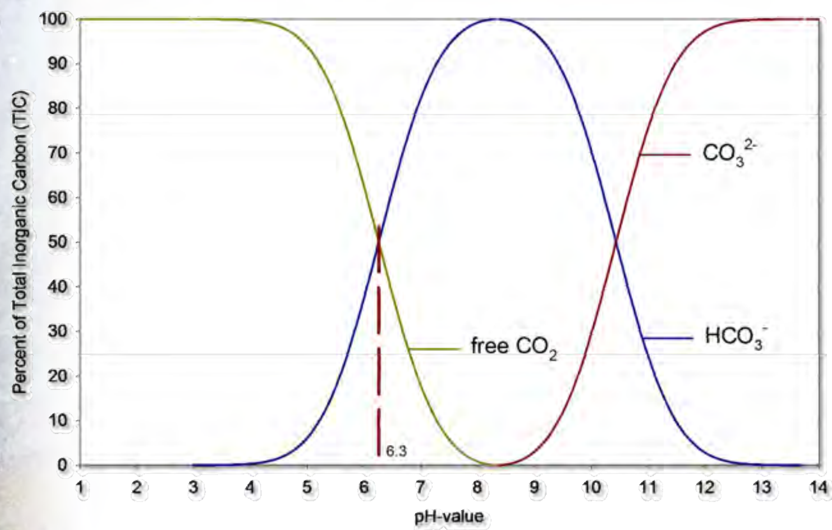
Acidity – Alkalinity

Distribution of Carbon Species



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Aqueous Solutions

Mass and charge balance

- Ground water is always electro-neutral:
  Σ [positive charged ions] = Σ [negative charged ions]
- Charge balance results of the summation of all cations and anions of all strong and weak acids and bases:
  $[H^+] + [Na^+] + [K^+] + 2\,[Ca^{2+}] + 2\,[Mg^{2+}] =$
  $= [OH^-] + [HCO_3^-] + 2\,[CO_3^{2-}] + [Cl^-] + [NO_3^-] + 2\,[SO_4^{2-}]$
- Rearranging results in (strong acids and bases to the left side):
  $[Na^+] + [K^+] + 2\,[Ca^{2+}] + 2\,[Mg^{2+}] - [Cl^-] - [NO_3^-] - 2\,[SO_4^{2-}] =$
  $= [HCO_3^-] + 2\,[CO_3^{2-}] + [OH^-] - [H^+]$
- And, finally, expressed as a term of the bicarbonate buffer system:
  $[Alk] = [HCO_3^-] + 2\,[CO_3^{2-}] + [OH^-] - [H^+]$

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Acidity – Alkalinity

Bicarbonate Buffer System

- Alkalinity in relation to the bicarbonate buffer system:

  $[Alk] = [HCO_3^-] + 2\,[CO_3^{2-}] + [OH^-] - [H^+]$
- Conservation of matter for HCO_3^-, CO_3^{2-}, OH^- results in a relation between alkalinity and pH-value:

$$[\mathrm{Alk}] = \frac{\mathrm{pCO2\,(g)}\,K_1}{[\mathrm{H}^+]} + \frac{[\mathrm{HCO_3^-}]K_2}{[\mathrm{H}^+]} + \frac{K_\mathrm{W}}{[\mathrm{H}^+]} - [\mathrm{H}^+]$$

- for 6 < pH < 9 the following simplification applies

  $[CO_3^{2-}], [OH^-], [H^+] << [HCO_3^-]$
- consequently:

  $[Alk] = [HCO_3^-]$ for most *natural waters*

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Acidity – Alkalinity

Relation to the pH-value

- 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:

$$[\mathrm{Alk}] \cong \frac{[\mathrm{H_2CO_3}]K_1}{[\mathrm{H}^+]} - [\mathrm{H}^+] \quad \mathrm{mol\,L^{-1}} \quad (\mathrm{pH} < 8{,}3)$$

- solving the equation for $[H^+]$:

$$[\mathrm{H}^+] = \frac{-[\mathrm{Alk}] + \sqrt{[\mathrm{Alk}]^2 + 4\,[\mathrm{H_2CO_3}]K_1}}{2}$$

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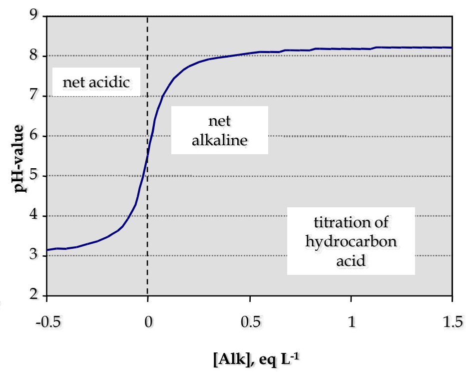
Acidity – Alkalinity

pH-Value and 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 be dissolved
- High mobility and bioavailability



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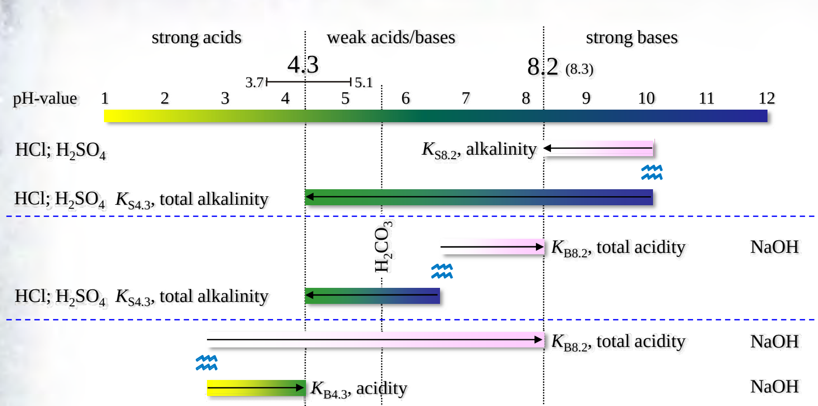
Acidity – Alkalinity

Acidity – Alkalinity



K_S acid capacity 8.2 (phenolphtalein): alkalinity (strong bases); old: p-value
K_S acid capacity 4.3 (methylred-bromcresolgreen): total alkalinity (weak/strong bases); old: m-value
K_B base capacity 8.2 (phenolphtalein): total acidity (weak/strong acids); old: -p-value
K_B base capacity 4.3 (bromphenolblue): acidity (strong acids) ; old: -m-value

1 [mmol L^{-1}] = 1 [meq L^{-1}] = ~~50.04 [mg L^{-1} $CaCO_3$]~~

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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):

$$[\mathrm{Alk}]_\mathrm{M} = \frac{V_\mathrm{M}(-[\mathrm{Aci}]_\mathrm{M}) + V_\mathrm{R}[\mathrm{Alk}]_\mathrm{R}}{V_\mathrm{M} + V_\mathrm{R}}$$

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

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

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

$[Alk]_M$= alkalinity downstream of mine water discharge

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

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Mine Water Geochemistry

Example (1/4)

Working example

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.

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

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Mine Water Geochemistry

Example (2/4)

1. Calculation of sulphate and copper molecular weight

element	S	O	Cu
atomical mass	32.066	15.9994	63.546, g mol-1

$M_{SO_4^{2-}} = 32.066 + 4 \cdot 15.9994 = 96.064$ g mol^{-1}

2. Molar concentration of sulphate and copper in the mine water

$[SO_4^{2-}]$ = 1350 / 96.064 = 14.05 mmol L^{-1}

[Cu] = 0.02 / 63.546 = 0.003 mmol L^{-1}

3. Release of sulphate from pyrite

$[SO_4^{2-}]_{Py} = [SO_4^{2-}]_T - 2\,[Cu^{2+}]$

$[SO_4^{2-}]_{Py} = 14.05 - 2 \cdot 0.003 = 14.04$ mmol L^{-1}

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Mine Water Geochemistry

Example (3/4)

4. Protons from pyrite weathering: 2 protons, assumed that pyrite weathers to sulphate and ochre

$[H^+] = 2\,[SO_4^{2-}]_{Py} = 2 \cdot 14.04$ mmol L^{-1} = 28.08 mmol L^{-1}

Annotation: the 7 mg L^{-1} of iron (0.13 mmol L^{-1}) prove, that nearly all Fe^{2+} (14.04 mmol L^{-1} = 784 mg L^{-1}) precipitates as ochre

5. pH-value from proton activity

$pH = -\log[H^+] = -\log[2.808 \cdot 10^{-2}] = 1.6$

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^+, Ca^{2+}, K^+, Mg^{2+}).
$[Aci]_{calculated}$ = 23 mg $CaCO_3$; $[Alk]_{calculated}$ = 308 mg $CaCO_3$

$[Aci]_{calculated} = 50\,\{2\,[Fe^{2+}]/56 + 3\,[Fe^{3+}]/56 + 3\,[Al]/27 + 2\,[Mn]/55 + 2\,[Zn]/65 + 1000\,(10^{-pH})\}$

$$[Alk] \cong \frac{[H_2CO_3^-]K_1}{[H^+]} - [H^+] \quad \text{mol L}^{-1} \quad (pH < 8{,}3)$$

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Mine Water Geochemistry

Example (4/4)

6. Calculate the annual sulphate and calcite flux from the mine discharge with a quantity $Q = 220\ L\ s^{-1}$
   $[SO_4^{2-}]_{Py} = 0.014\ mol\ L^{-1}$
   $[Ca^{2+}] = 0.271\ g\ L^{-1} = (0.271/40.08)\ mol\ L^{-1} = 6.76 \cdot 10^{-3}\ mol\ L^{-1}$
7. Multiply concentration with mine water make
   $F_S = Q \cdot [SO_4^{2-}]_{Py} = 220\ L\ s^{-1} \cdot 0.014\ mol\ L^{-1} = 3.08\ mol\ s^{-1}$
   $F_{Ca} = Q \cdot [Ca^{2+}] = 220\ L\ s^{-1} \cdot 6.76 \cdot 10^{-3}\ mol\ L^{-1} = 1.49\ mol\ s^{-1}$
8. Annual weathering rate pyrite and calcite ($1\ y = 3.15 \cdot 10^7\ s$)
   $R_{Py} = ½\ F_S = 1.54\ mol\ s^{-1} = 4.85 \cdot 10^7\ mol\ y^{-1} = 5500\ t\ FeS_2$
   $R_{Calcit} = F_{Ca} = 1.49\ mol\ s^{-1} = 4.69 \cdot 10^7\ mol\ y^{-1} = 4700\ t\ CaCO_3$

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Mine Water Geochemistry

Literature

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- Stumm, W. & Morgan, J. I. (1981): Aquatic chemistry – An introduction emphasizing chemical equilibria in natural waters. – 2nd edn., 780 p.; New York (Wiley & Sons).
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From Ground Water to Mine Water

Environmental Hydrogeology in Mining

Prediction of Mine Flooding

Prof. Dr. Christian Wolkersdorfer

Industrial Research Chair in Mine Water Remediation & Management

From Ground Water to Mine Water

Contents

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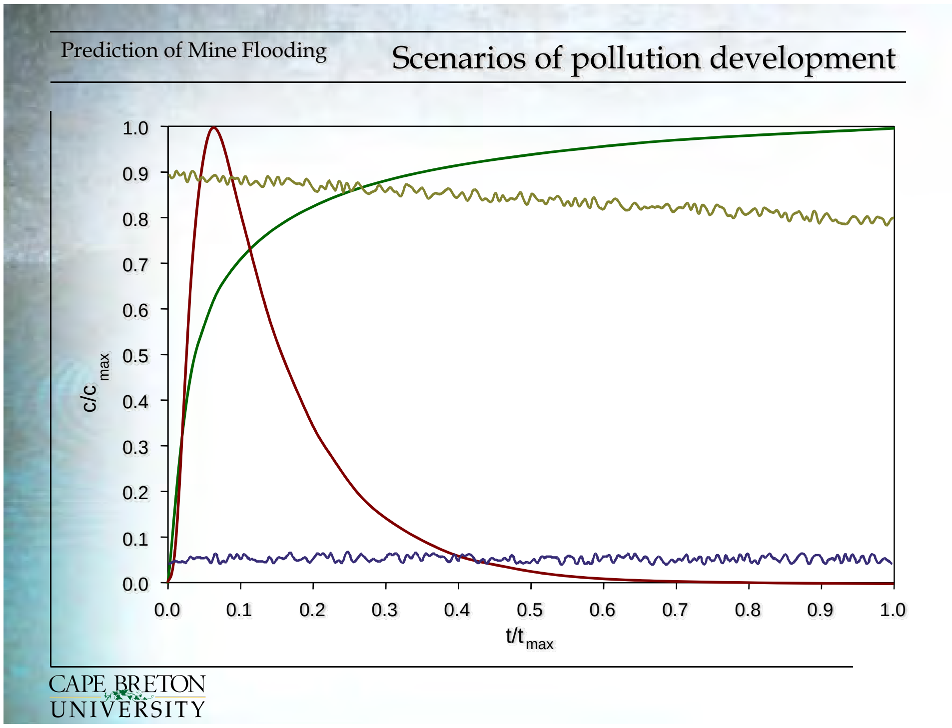
Prediction of Mine Flooding
Scenarios of pollution development
1.0
0.9
0.8
0.7
0.6
0.5
0.4
0.3
0.2
0.1
0.0
c/c max
0.0 0.1 0.2 0.3 0.4 0.5 0.6 0.7 0.8 0.9 1.0
t/t max
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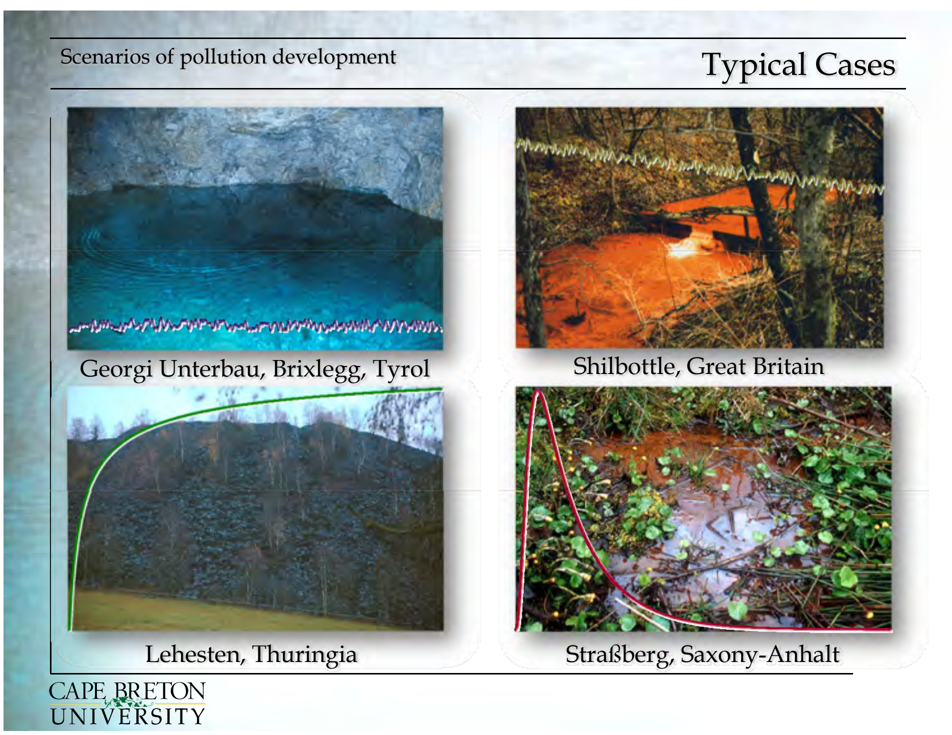
Scenarios of pollution development
Typical Cases
Georgi Unterbau, Brixlegg, Tyrol
Shilbottle, Great Britain
Lehesten, Thuringia
Straßberg, Saxony-Anhalt
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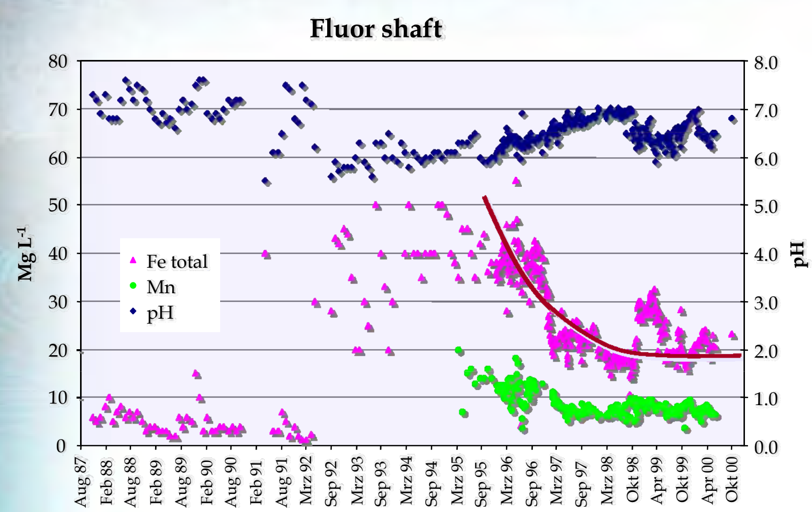
Scenarios of pollution development

Straßberg/Harz Fluorspar Mine



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after Kindermann 1998

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

$APP = 31.25 \cdot [S^{2-}]$, g kg^{-1} $CaCO_3$

$NP = 10 \cdot [CaCO_3] + 11.9 \cdot [MgCO_3]$, g kg^{-1} $CaCO_3$

Net NP = NP – APP, g kg^{-1} $CaCO_3$

	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

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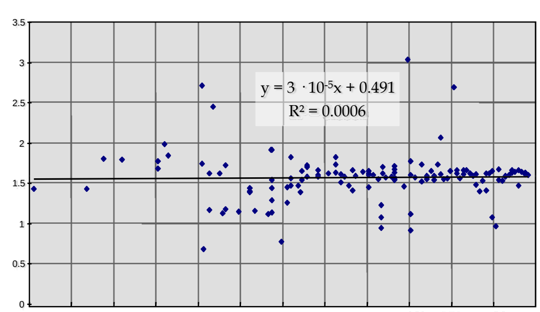
Lapakko 1990, Lapakko *et al.* 1995, Wolkersdorfer 1995

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

$$R = \frac{2([Ca^{2+}]+[Mg^{2+}])}{([HCO_3^{2-}]+2[CO_3^{2-}])}$$



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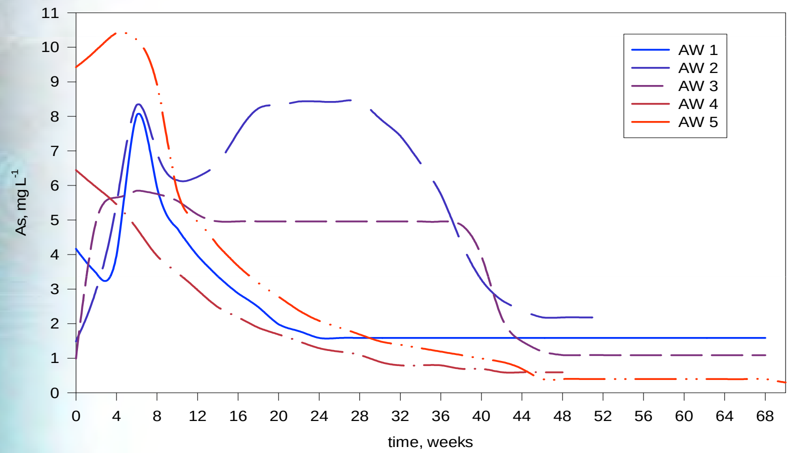
Voigt 1990, Jacks *et al.* 1984, Norberg 1985

Prediction of Mine Flooding

Batch- and Column-Tests

- different test conditions for batch- and column tests possible



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Wolkersdorfer 1996

Prediction of Mine Flooding

Statistics

- Ratio of water contents (Zn/Cu; As/U/Ca)
- Time courses (input – output: inflow – discharge)
- Geostatistics
- Multivariate statistics
- PIPER-diagram
- SCHOELLER-diagram

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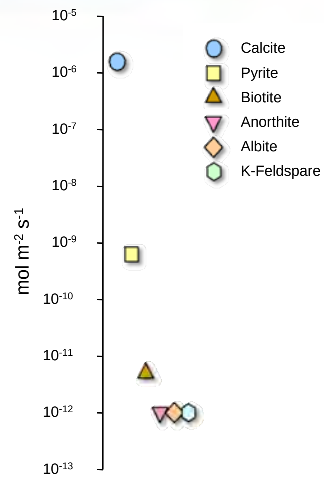
Prediction of Mine Flooding

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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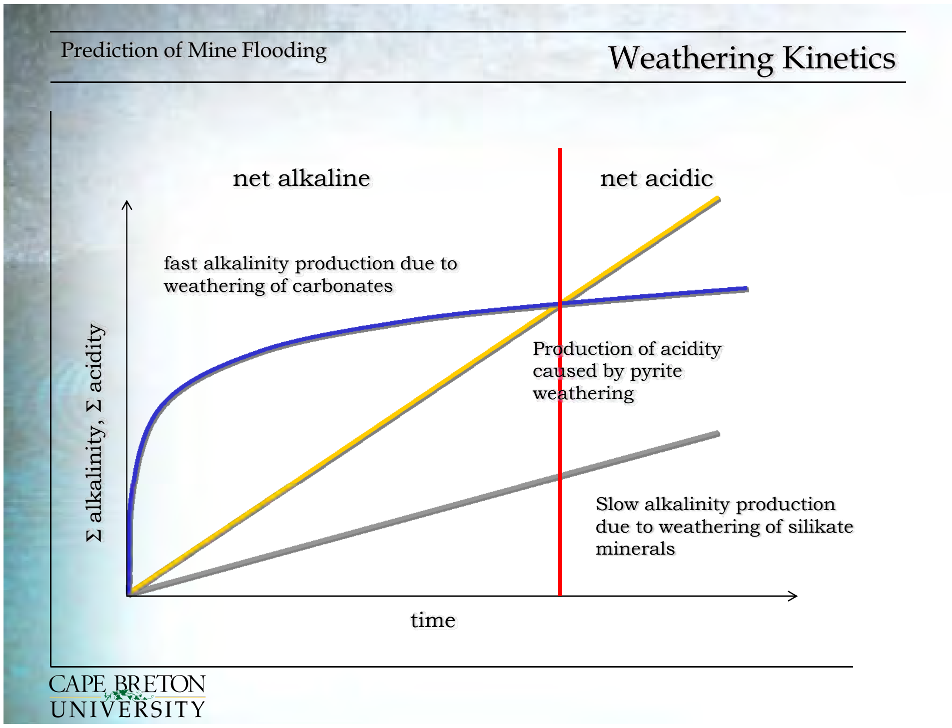
Prediction of Mine Flooding
Weathering Kinetics
net alkaline
net acidic
fast alkalinity production due to weathering of carbonates
Production of acidity caused by pyrite weathering
Slow alkalinity production due to weathering of silikate minerals
Σ alkalinity, Σ acidity
time
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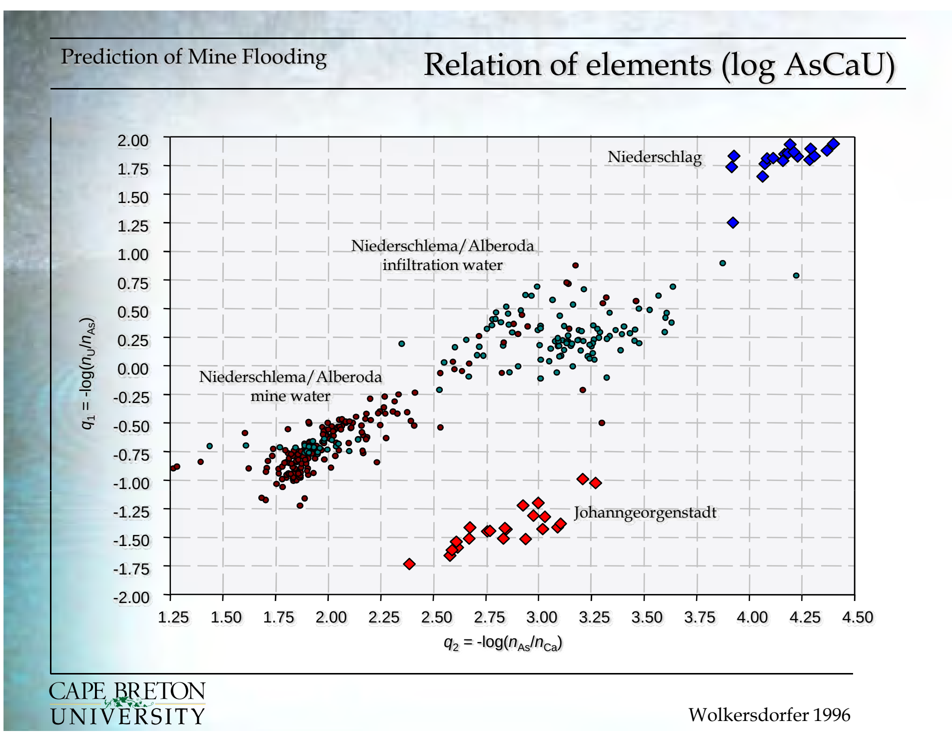
Prediction of Mine Flooding
Relation of elements (log AsCaU)
Niederschlag
Niederschlema/Alberoda infiltration water
Niederschlema/Alberoda mine water
Johanngeorgenstadt
q1 = -log(nU/nAs)
q2 = -log(nAs/nCa)
2.00 1.75 1.50 1.25 1.00 0.75 0.50 0.25 0.00 -0.25 -0.50 -0.75 -1.00 -1.25 -1.50 -1.75 -2.00
1.25 1.50 1.75 2.00 2.25 2.50 2.75 3.00 3.25 3.50 3.75 4.00 4.25 4.50
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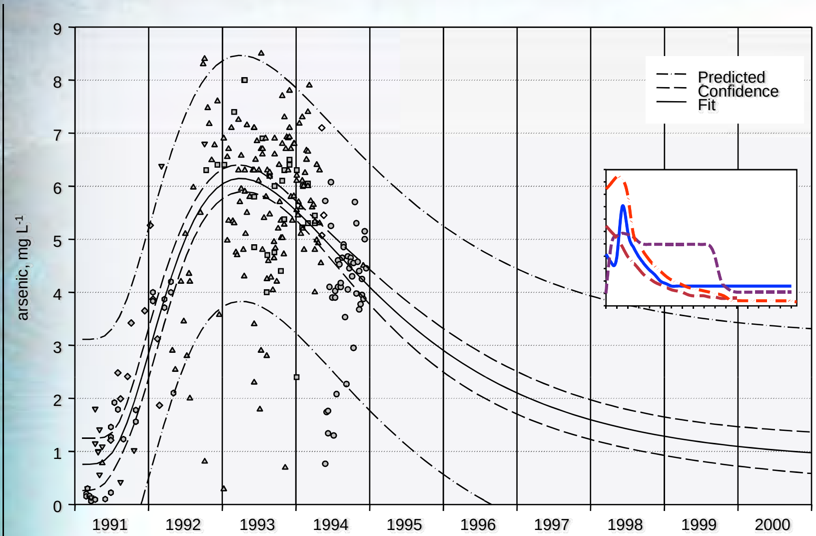
Prediction of Mine Flooding

Black Box Modelling: Regression



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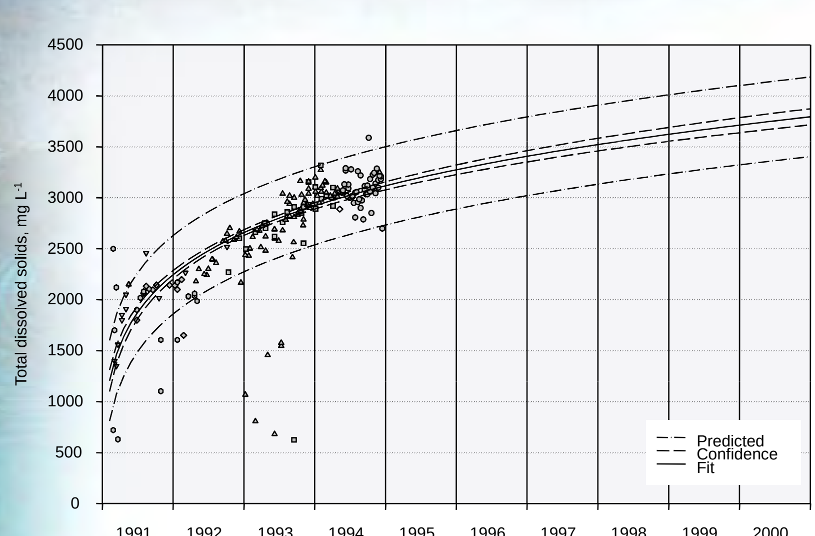
Prediction of Mine Flooding

Black Box Modelling: Regression



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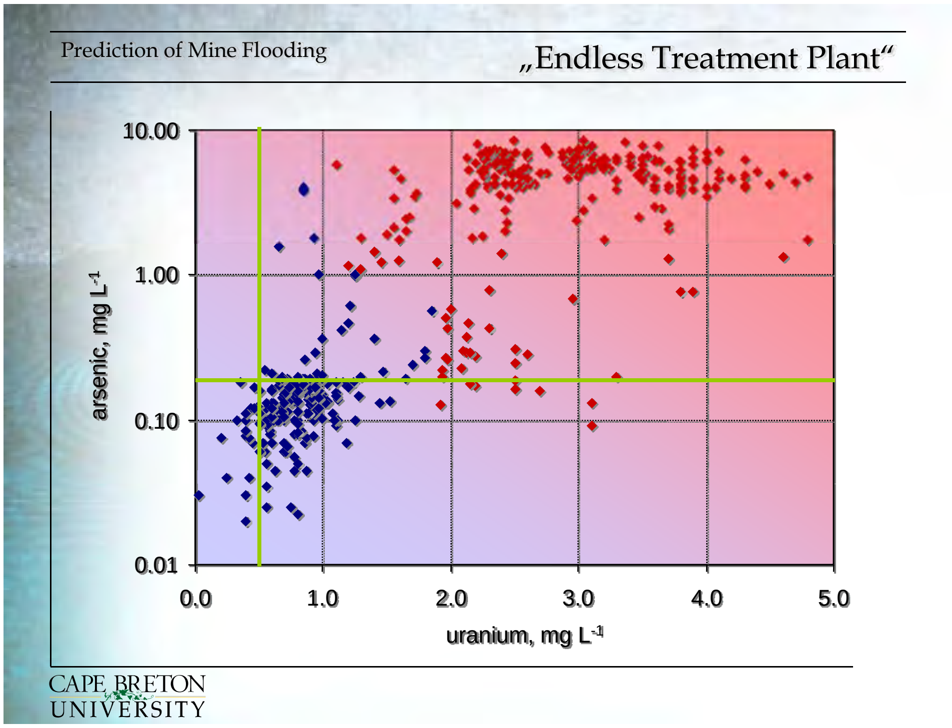
Prediction of Mine Flooding
„Endless Treatment Plant“
10.00
1.00
0.10
0.01
arsenic, mg L-1
0.0
1.0
2.0
3.0
4.0
5.0
uranium, mg L-1
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Prediction of Mine Flooding

Calculation Example (1/8)

- Lifetime for Generation and Attenuation of contamination loads from an underground coal mine
- Discharge
  $2.6 \cdot 10^6$ L day^{-1}
- Mine water constituents, mg L^{-1}

pH	6.5	SO_4^{2-}	460	Ca	127
Mg	23	Cu	0.002	Fe	62
Na	130	K	7.4	Zn	0.005
As	0.001	Cr	0.001	Ni	0.007

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Prediction of Mine Flooding

Calculation Example (2/8)

- Coal seam with 1.22 m thickness and an area covered of $3 \cdot 10^6$ m^2
- Pillar and stall: 60% of total coal were excavated
- Bed rock: mudstone with 2.5% pyrite content, 3% Calcite content, density $\rho_m = 2500$ kg m^3
- Density of coal $\rho_c = 1260$ kg m^3, 3% porosity, 0.3% S content (mainly pyrite)
- porosity after collapse of hanging wall: $n = 0.40$
- $M_{SO4} = 96.06$ g mol^{-1}; $M_{CaCO3} = 100.09$ g mol^{-1}; $M_{Ca} = 40.08$ g mol^{-1}; $M_S = 32.07$ g mol^{-1}; $M_{FeS2} = 119.97$ g mol^{-1}

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Prediction of Mine Flooding

Calculation Example (3/8)

1. Calculate total volume and mass of remaining coal
2. Calculate volume and mass of collapsed mudstone within the workings
3. Calculate amount of pyrite in coal and mudstone within workings
4. Calculate sulphate flux in discharge and pyrite lifetime
5. Calculate lifetime of calcite in the mudstone

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Prediction of Mine Flooding

Calculation Example (4/8)

1. Calculate total volume and mass of remaining coal

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Prediction of Mine Flooding

Calculation Example (5/8)

2. Calculate volume and mass of collapsed mudstone within the workings

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Prediction of Mine Flooding

Calculation Example (6/8)

3. Calculate amount of pyrite in coal and mudstone within workings

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Prediction of Mine Flooding

Calculation Example (7/8)

4. Calculate sulphate flux in discharge and pyrite lifetime

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Prediction of Mine Flooding

Calculation Example (8/8)

5. Calculate lifetime of calcite in the mudstone

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From Ground Water to Mine Water

Environmental Hydrogeology in Mining

Mine Water Treatment

Prof. Dr. Christian Wolkersdorfer

Industrial Research Chair in Mine Water Remediation & Management

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From Ground Water to Mine Water

Contents

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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
  - Limestone Drains
  - Reactive Walls
  - Wetlands

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Mine Water Treatment

General issues

- Two main requirements
  - The demands on the water quality must be achieved by all time
  - 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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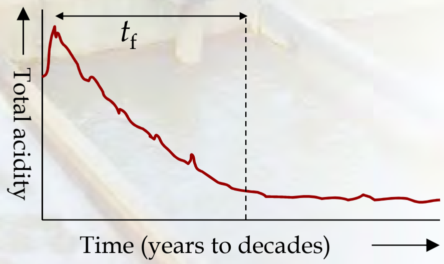
Mine Water Treatment

First Flush

- The time of mine water pollution depends on
  - Acidity removal or reduction rate („first flush“): buffering
  - Rate of which acid containing minerals weather (pyrite, siderite, secondary minerals)



$$t_f = (3.95 \pm 1.2)\ t_r$$

t_f = duration of first flush
t_r = duration of mine water rebound

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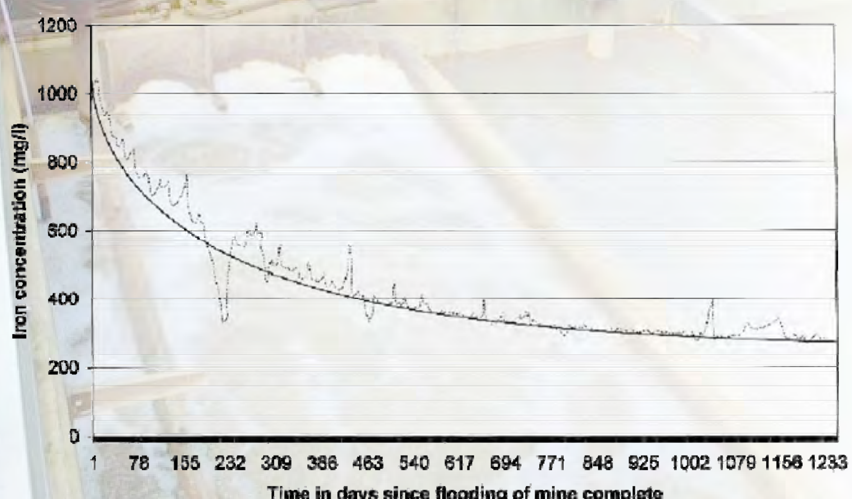
Mine Water Treatment

First Flush



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Wheal Jane (Cornwall): Paul Younger (2000)

Mine Water Treatment

First Flush

- The rate of acidity reduction is related to the drop of the „first flush“ and is mainly controlled by hydraulic factors:
  - Volume of the inter-connected workings
  - Hydraulic connections and conductivities of the mine workings
  - Ground water recharge
  - The total depletion of the „first flush“ can take up to 40 years

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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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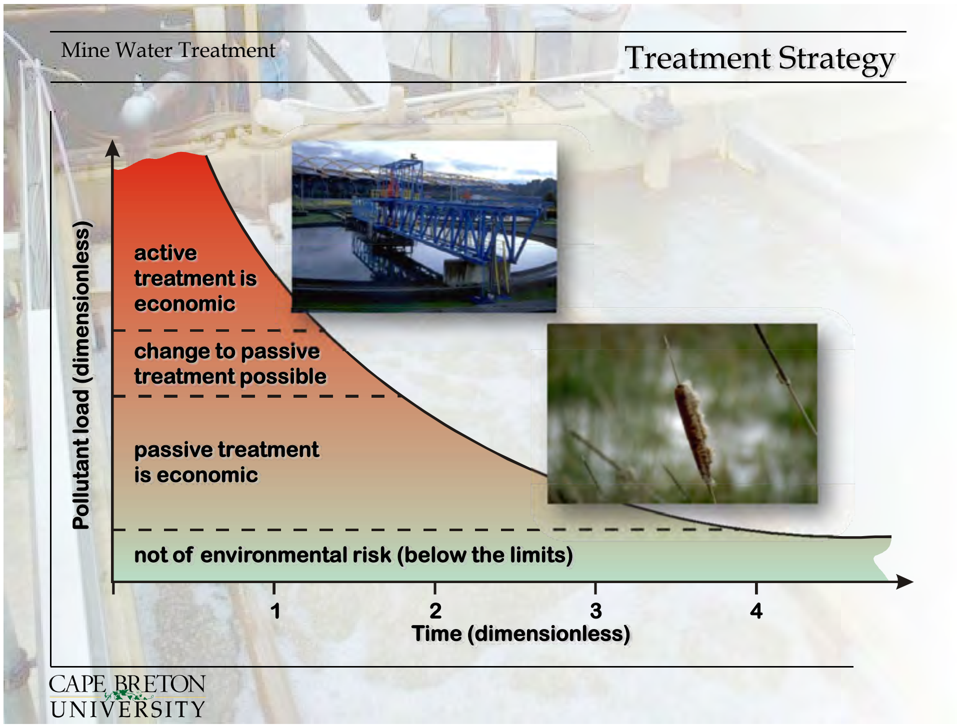
Mine Water Treatment
Treatment Strategy
Pollutant load (dimensionless)
active treatment is economic
change to passive treatment possible
passive treatment is economic
not of environmental risk (below the limits)
1
2
3
4
Time (dimensionless)
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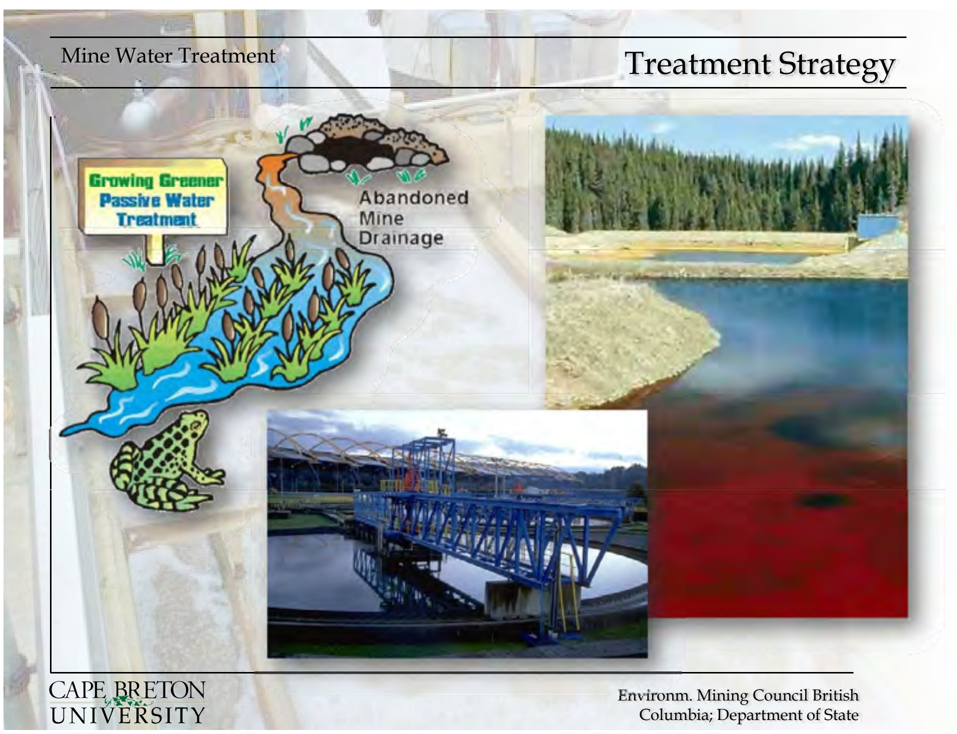
Mine Water Treatment
Treatment Strategy
Growing Greener Passive Water Treatment
Abandoned Mine Drainage
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Environm. Mining Council British Columbia; Department of State

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

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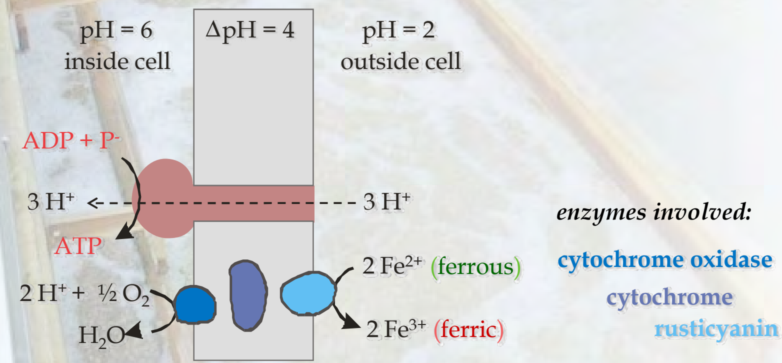
Mine Water Treatment

Neutralization

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



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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} Fe^{2+} can be oxidized, if necessary, install a second stage
- Aeration (electro energy)
- Reactions involved:

$$Fe^{2+} + \tfrac{1}{4}\,O_2 + H^+ \rightarrow Fe^{3+} + \tfrac{1}{2}\,H_2O$$
$$Fe^{3+} + 3\,H_2O \rightarrow Fe(OH)_3 + 3\,H^+$$

- Take care: two protons will be released!
- In the case, there is still too much Fe^{2+} after approximately 10 minutes: hydrogen peroxide (H_2O_2), ozone or hypochloride (OCl^-) might be necessary

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Mine Water Treatment

Liming

- Acidic mine water will be neutralized
- Metal hydroxides will co-precipitate (e.g. As)
- Fast but partly incomplete reaction
- Calcium oxide: CaO (very reactive)
- Calcium hydroxide: $Ca(OH)_2$ (extensive mixing)

$$Ca(OH)_2 + H_2SO_4 \rightarrow CaSO_4 \cdot 2H_2O$$
$$3\,Ca(OH)_2 + Fe_2(SO_4)_3 + 6\,H_2O \rightarrow 2\,Fe(OH)_3 + 3\,CaSO_4 \cdot 2H_2O$$

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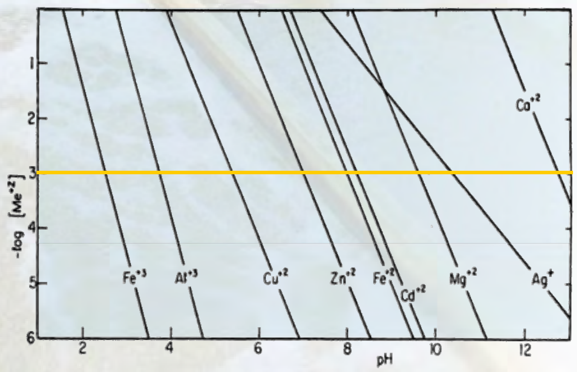
Mine Water Treatment

Liming

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

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



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Mine Water Treatment

Liming

- Necessary amount of $Ca(OH)_2$ to neutralize:
  - mg L^{-1} $Ca(OH)_2$ = total acidity (mg L^{-1} $CaCO_3$) × 0.74
  - mg L^{-1} $Ca(OH)_2$ = total acidity (meq L^{-1}) × 37
- To raise pH sufficiently high (to pH_t) for rapid precipitation:
  - For Fe, a pH of 8 — 8.5 must be achieved
  - mg L^{-1} $Ca(OH)_2$ = $[(1000 \times 10^{-pH_t}) - 10^{-3}] \times 37$
- Total amount $Ca(OH)_2$ needed is sum of both:
  - mg L^{-1} $Ca(OH)_2$ = {total acidity (meq L^{-1}) + $[(1000 \times 10^{-pH_t}) - 10^{-3}]$} × 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 flocculates
  - Anionic, cationic, polyampholites

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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

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 („π · 👍²“-rule):
  - Retention time must be greater than 24 hours
- No settlement lagoons are necessary if [Fe] < 2 mg L^{-1} and sand filters are installed

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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

Brixlegg/Tyrol, Ion Exchange Reactor

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Mine Water Treatment

Burgfey/Eifel: Pilot Plant

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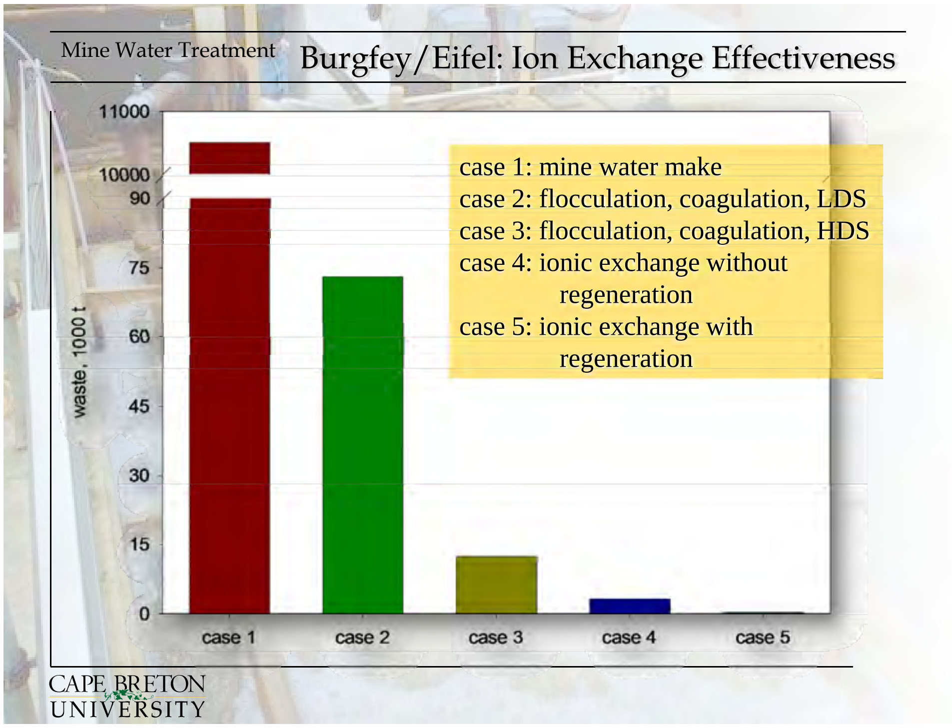
Mine Water Treatment
Burgfey/Eifel: Ion Exchange Effectiveness
11000
10000
90
75
60
45
30
15
0
waste, 1000 t
case 1
case 2
case 3
case 4
case 5
case 1: mine water make
case 2: flocculation, coagulation, LDS
case 3: flocculation, coagulation, HDS
case 4: ionic exchange without regeneration
case 5: ionic exchange with regeneration
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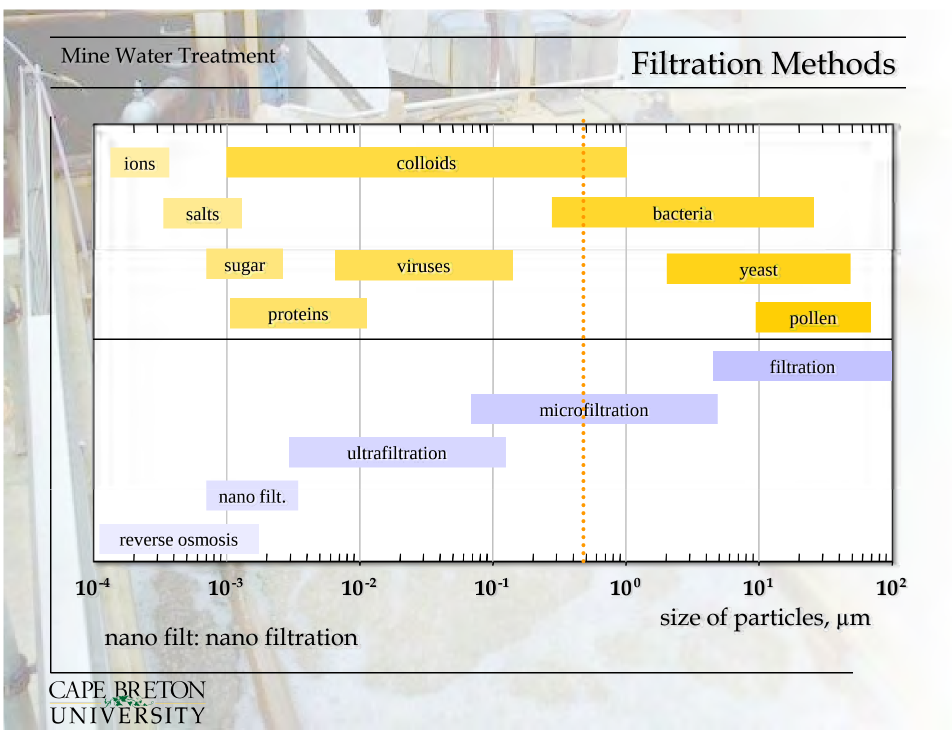
Mine Water Treatment
Filtration Methods
ions
colloids
salts
bacteria
sugar
viruses
yeast
proteins
pollen
filtration
microfiltration
ultrafiltration
nano filt.
reverse osmosis
10^{-4}
10^{-3}
10^{-2}
10^{-1}
10^{0}
10^{1}
10^{2}
size of particles, µm
nano filt: nano filtration
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Mine 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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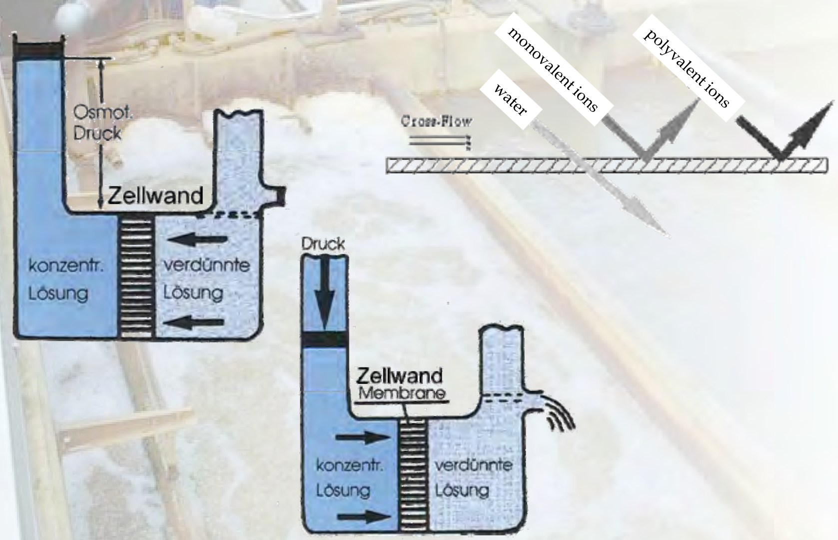
Mine Water Treatment

Osmosis/Reverse Osmosis



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Mine Water Treatment

Osmosis/Reverse Osmosis: Example

- St. Aidan 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 $m^3\ d^{-1}$ (Israel: 274,000 $m^3\ d^{-1}$)
- Water available for public water supply

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Wilson & Brown 1997

Mine Water Treatment

Žirovski vrh/Slovenia: Reverse Osmosis

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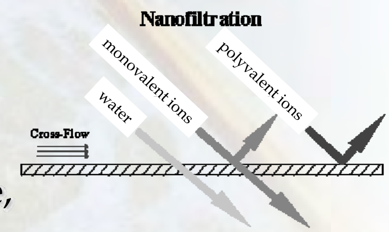
Mine Water Treatment

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, polydimethyle siloxan



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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 matter
- 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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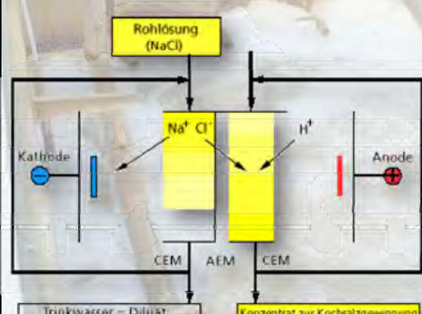
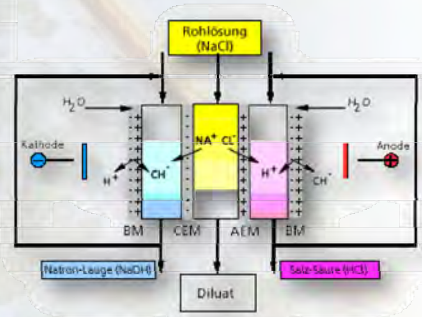
Mine Water Treatment

Electro Dialyses

- mono polar, bi-polar membranes





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Mine Water Treatment

Solvent Extraction

- Used since the 1950ies to enrich radionuklides
- Based on relative solubility of a substance in two immescible liquids (e.g. aqueous and organic)
- Extraction material: derivates and modifications of lactic acid, oxalic acid, gels and ether
- Only suitable for small amounts
- Mainly used for analytical purposes
- Up to now not used for mine water

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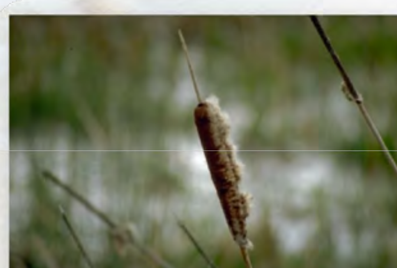
Mine Water Treatment

Passive Treatment Methods

- Reactive walls („funnel-and-gate“)
- Anoxic limestone drains
- Aerobic wetlands
- Anaerobic wetlands
- SAPS (RAPS)
  Successive Alkalinity Producing Systems
- Settlement lagoons



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Mine Water Treatment

Reactive Walls

- Ground water has to flow through a reactive barrier
- Wall 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 Walls

- Organic reactants
  - wood
  - Coal, lignite
  - peat
- Inorganic reactants
  - Iron (Fe^0)
  - phosphate
  - Amorphic iron oxides
- Micro-organisms

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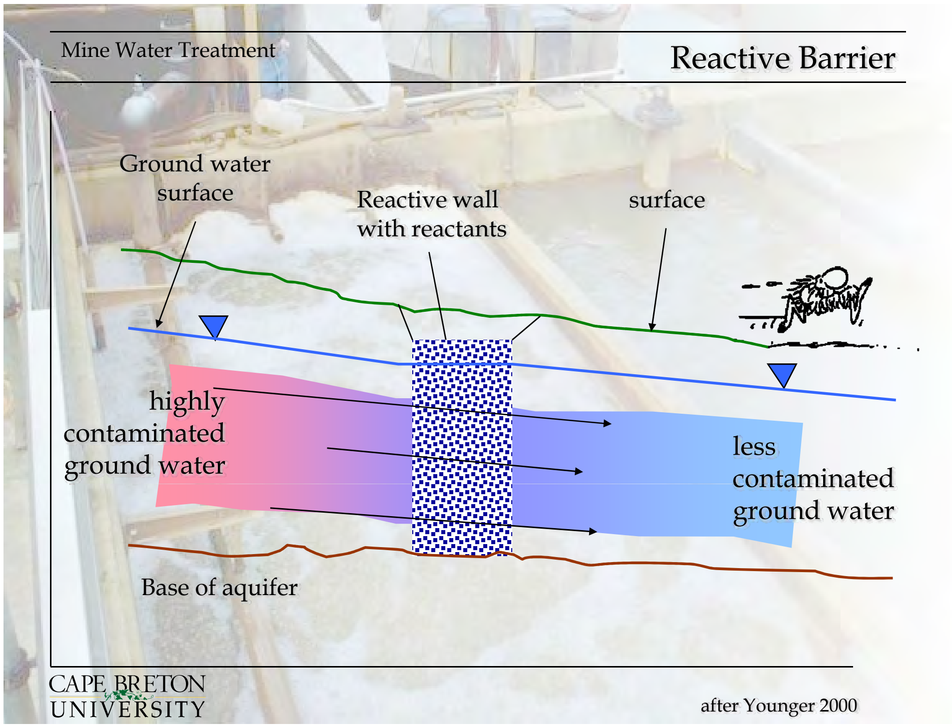
Mine Water Treatment
Reactive Barrier
Ground water surface
Reactive wall with reactants
surface
highly contaminated ground water
less contaminated ground water
Base of aquifer
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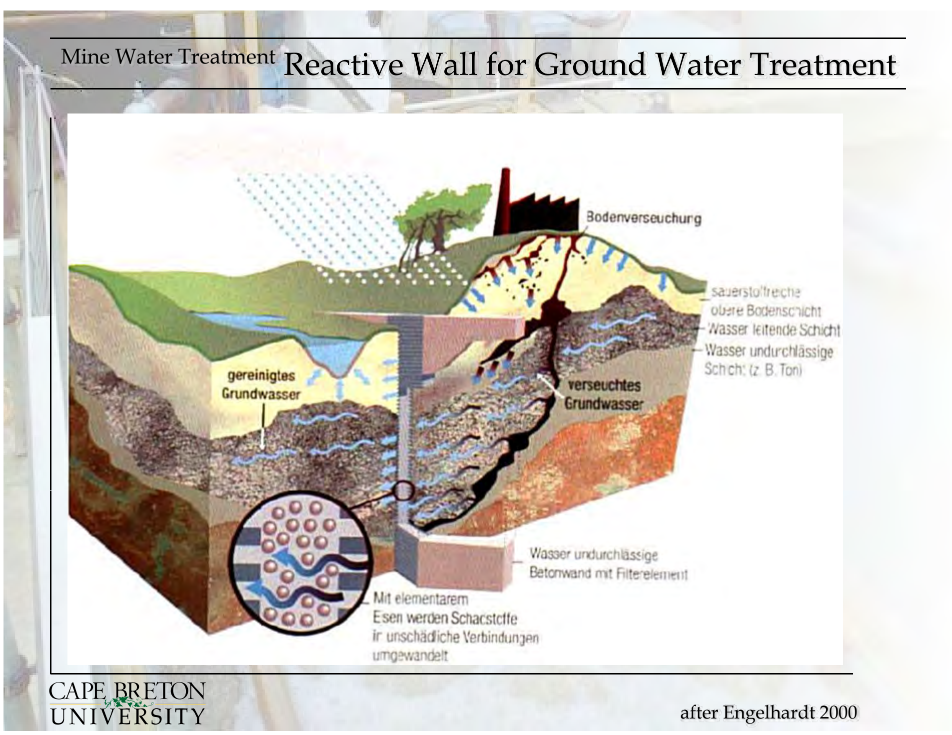
after Younger 2000


Mine Water Treatment
Reactive Wall for Ground Water Treatment
Bodenverseuchung
sauerstoffreiche obere Bodenschicht
Wasser leitende Schicht
Wasser undurchlässige Schicht (z. B. Ton)
gereinigtes Grundwasser
verseuchtes Grundwasser
Wasser undurchlässige Betonwand mit Filterelement
Mit elementarem Eisen werden Schadstoffe in unschädliche Verbindungen umgewandelt
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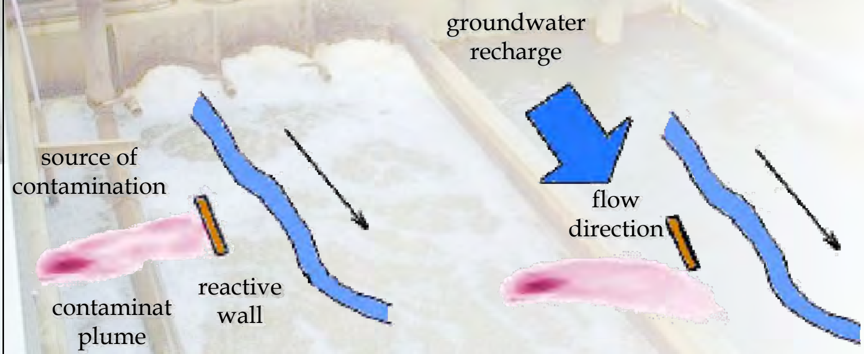
after Engelhardt 2000

Mine Water Treatment

Reactive Wall: Construction Pitfalls



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

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after Kansy 2000

Mine Water Treatment

Uranium Mine Fry Canyon, Utah

Filling of reactive barrier with reactive material

Completed reative wall before soil covering

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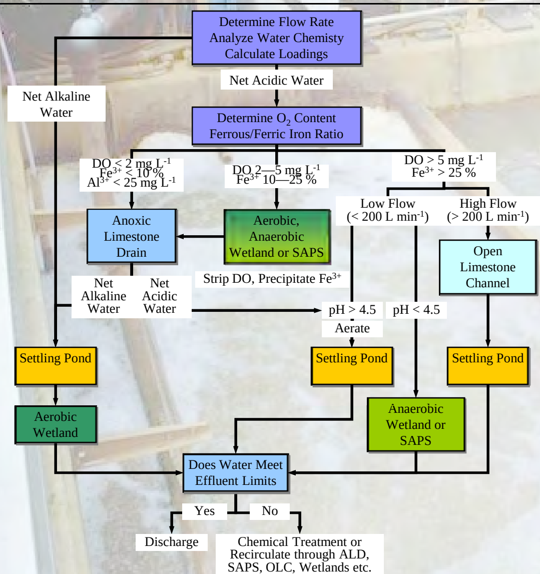
after USGS 2000

Mine Water Treatment

Passive Treatment Flow Chart



Flow chart for selecting a passive treatment system based on influent water quality. Additional treatment may be required for Mn if present at elevated concentration

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Hedin *et al.* 1994; Skousen *et al.* 1998; Skousen *et al.* 2000

Mine Water Treatment

Anoxic Limestone Drain (ALD)

- Closed channels filled with limestone
- Anoxic mine water:
  - Increase of alkalinity
  - Increase of pH-value
- Only for net acidic mine waters
- [Fe^{3+}] must not be too high: < 10 %
- [Al^{3+}] at a maximum of 25 mg L^{-1}
- Dissolved oxygen < 2 mg L^{-1}

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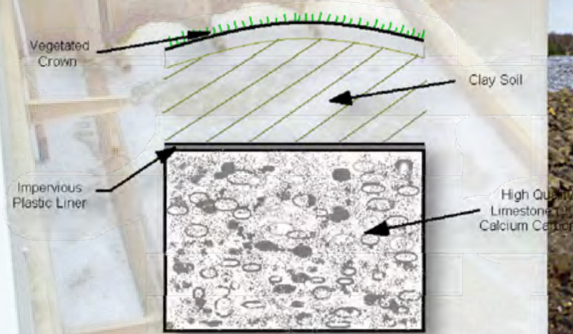
Anoxic carbonate drain

Cross Section and Construction



Cross section of anoxic carbonate drain

Tributary of Swatara Creek, PA

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Anoxic carbonate drain

Calculation of Carbonate needed (1/2)

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

$[\{t/a\} = \{L\ min^{-1}\} \cdot \{mg\ L^{-1}\ CaCO_3\} \cdot \{t \cdot min \cdot mg^{-1} \cdot a^{-1}\}]$

(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 (2/2)

„$\pi \cdot$ 👍^{2}“-rule

Residence time: 14 hours

Pore volume limestone: 50 %

lifetime: 15 years

Necessary carbonate volume:
1/0.5 · volume mine water · 14 hours

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Passive Treatment

Aerobic Wetlands

- pH of mine water *circum neutral* (> 6.5)
- Water net alkaline
- Shallow water systems (15 – 50 cm)
- Wetland plants (*Typha, Phragmites, Juncus*) to reduce water velocity
- Fe-removal rates: 10 – 20 $g \cdot m^{-2} \cdot d^{-1}$

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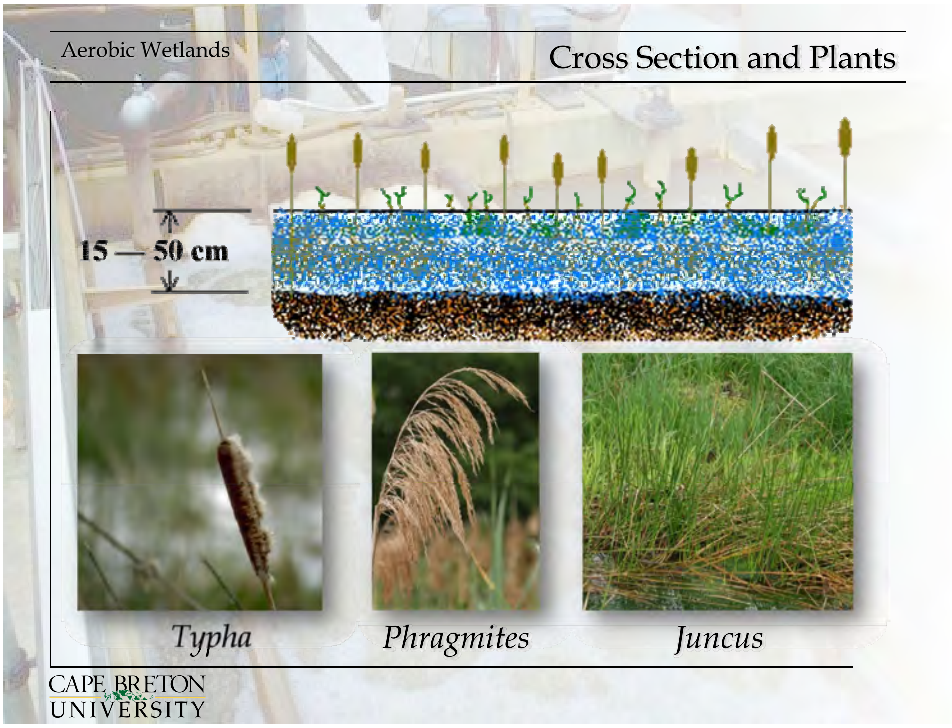
Aerobic Wetlands
Cross Section and Plants
15 — 50 cm
Typha
Phragmites
Juncus
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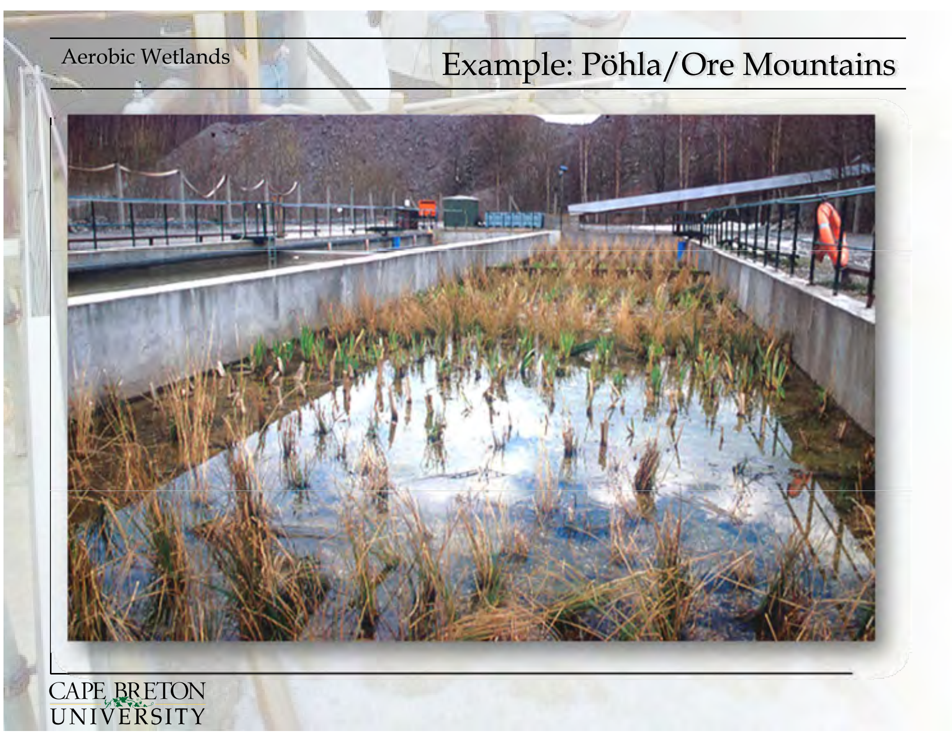
Aerobic Wetlands
Example: Pöhla/Ore Mountains
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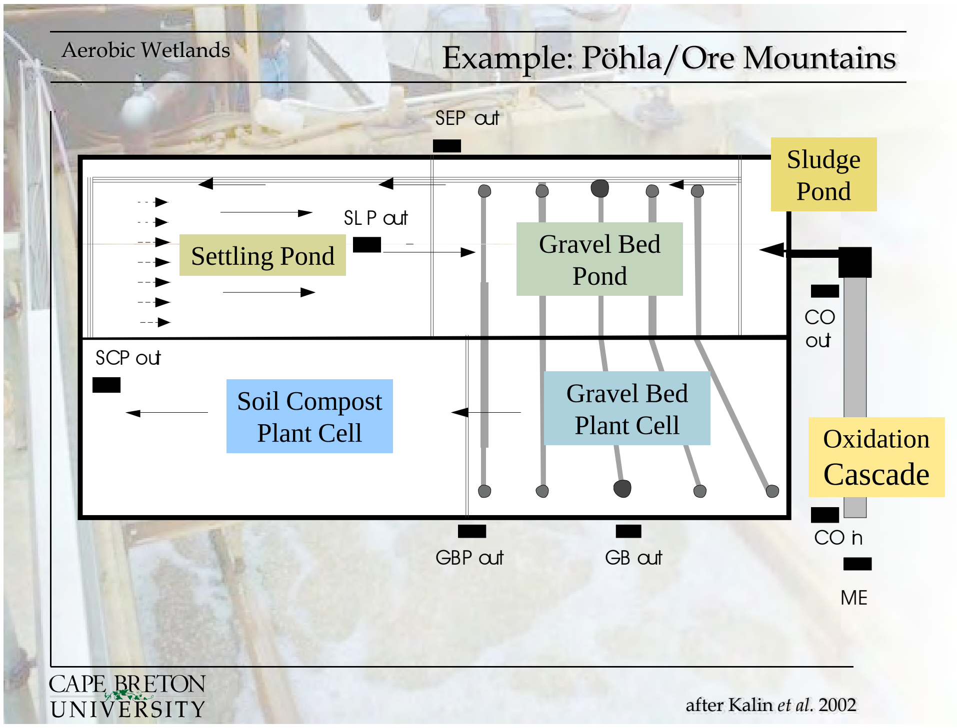
Aerobic Wetlands
Example: Pöhla/Ore Mountains
SEP out
Sludge Pond
SL P out
Settling Pond
Gravel Bed Pond
CO out
SCP out
Soil Compost Plant Cell
Gravel Bed Plant Cell
Oxidation Cascade
GBP out
GB out
CO in
ME
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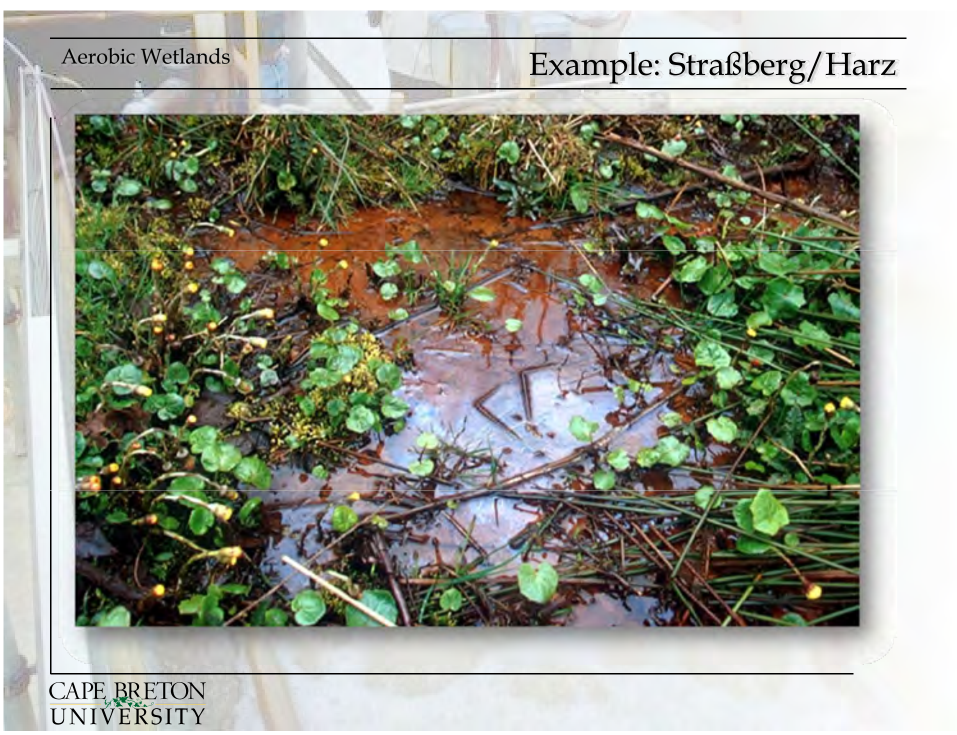
after Kalin et al. 2002


Aerobic Wetlands
Example: Straßberg/Harz
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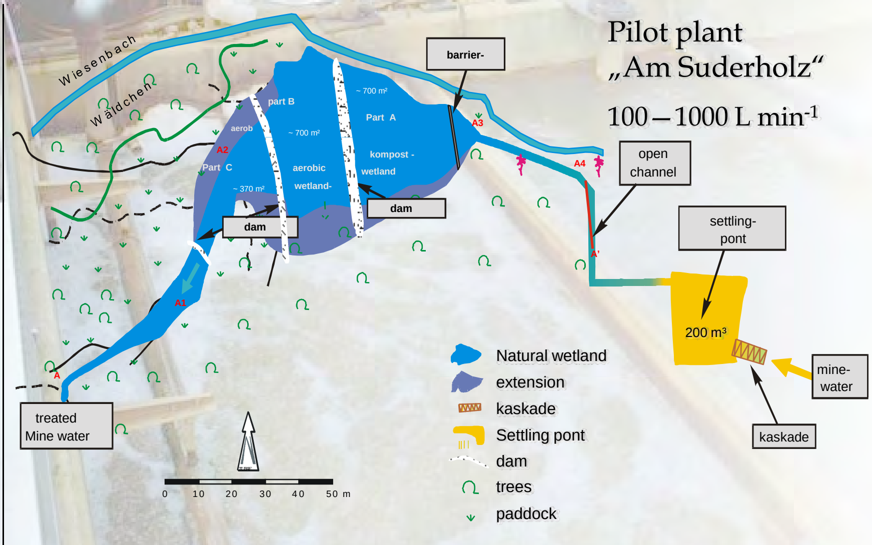
Aerobic Wetlands

Example: Straßberg/Harz



Pilot plant
„Am Suderholz“

100 – 1000 L min^{-1}

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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 $FeSO_4.7H_2O$ 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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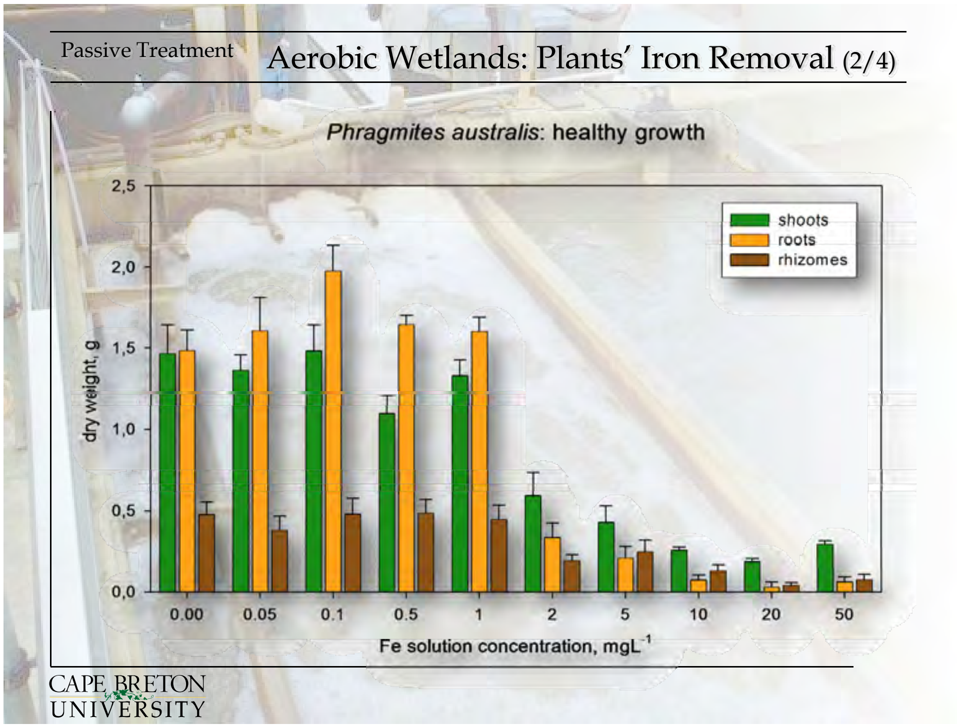
Passive Treatment
Aerobic Wetlands: Plants' Iron Removal (2/4)
Phragmites australis: healthy growth
shoots
roots
rhizomes
dry weight, g
2,5
2,0
1,5
1,0
0,5
0,0
0.00
0.05
0.1
0.5
1
2
5
10
20
50
Fe solution concentration, mgL-1
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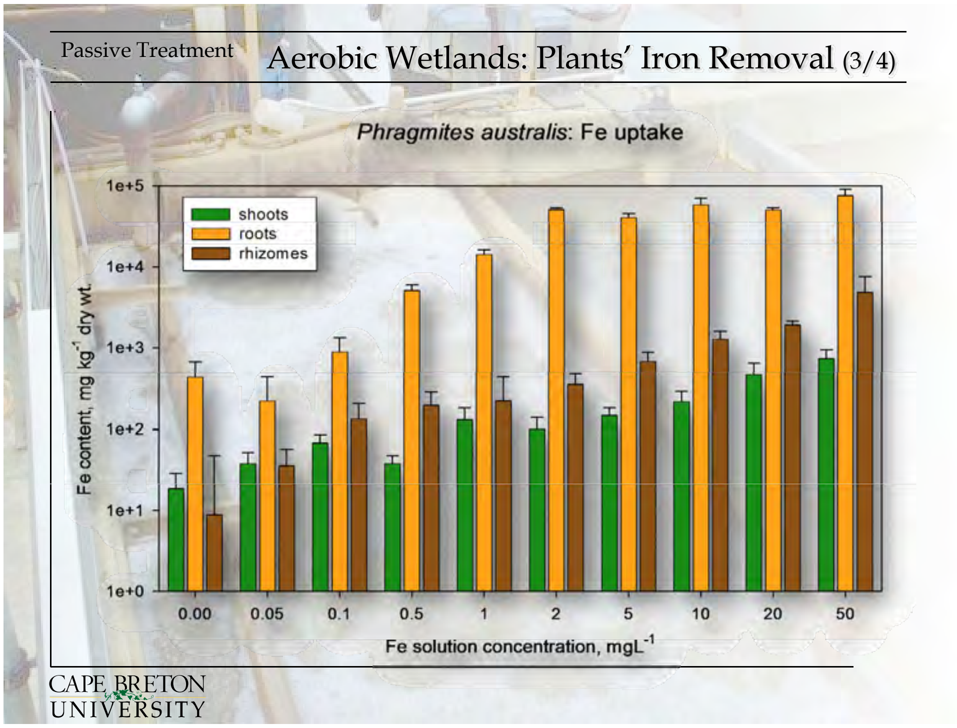
Passive Treatment
Aerobic Wetlands: Plants' Iron Removal (3/4)
Phragmites australis: Fe uptake
shoots
roots
rhizomes
Fe content, mg kg-1 dry wt.
1e+5
1e+4
1e+3
1e+2
1e+1
1e+0
0.00
0.05
0.1
0.5
1
2
5
10
20
50
Fe solution concentration, mgL-1
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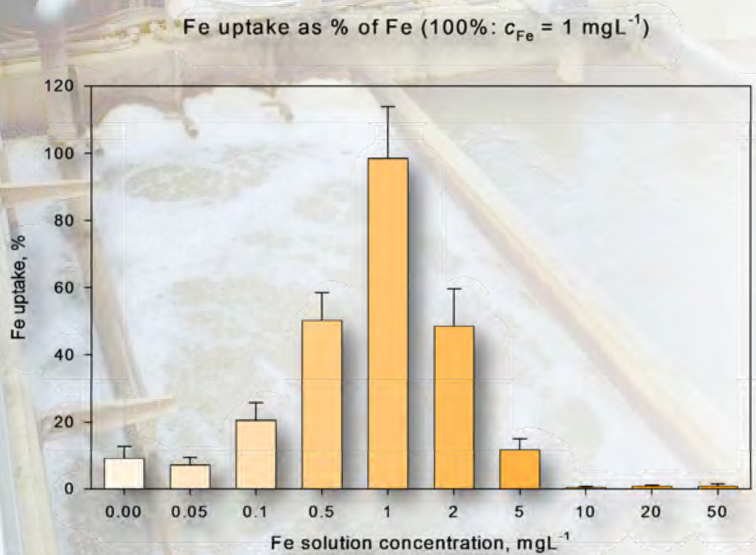
Passive Treatment

Aerobic Wetlands: Plants' Iron Removal (4/4)



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Passive Treatment

Anaerobic Wetlands: Kompost Wetland (1/2)

- 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 (2/2)

- 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: $3-7\ g \cdot m^{-2} \cdot d^{-1}$

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Passive Treatment

Anaerobic Wetlands

Typha *Phragmites* *Juncus*

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Passive Treatment

Calculation of Area Needed

- $M_f = Q \cdot c \cdot 1.44$ (load = quantity · concentration · factor)
  [{g · d^{-1}} = {L · min^{-1}} · {mg · L^{-1}} · {g · mg^{-1} · min · d^{-1}}]
  Net alkaline mine water: c = [Fe_{tot}]
  Net acidic mine water: c = [Aci]
- $A = M_f$ / RR (area = load / removal rate)
  [{m^2} = {g · d^{-1}} · {g $^{-1}$ · d · m^2}]

Determination of RR (removal rate):

standards	Net alkaline	Net acidic
CC (compliance)	10 g d^{-1} m^{-2}	3.5 g d^{-1} m^{-2}
RIC (reasonable)	20 g d^{-1} m^{-2}	7 g d^{-1} m^{-2}

RIC: reasonable improvement criterion
CC: compliance criterion

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Passive Treatment

Calculation of Area Needed: Gernrode/Harz

Flow rate	16.2	L s^{-1}
Calcium	1122	mg L^{-1}
Magnesium	100	mg L^{-1}
Sodium	333	mg L^{-1}
Potassium	16	mg L^{-1}
Iron	10.7	mg L^{-1}
Manganese	4.3	mg L^{-1}
Zinc	0.144	mg L^{-1}
Copper	0.028	mg L^{-1}
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	°C
Redox	197	mV
Conductivity	4.856	mS cm^{-1}

Q = , L min^{-1}
[Fe_{tot}] = , mg L^{-1}
[Aci] = , mg L^{-1}
$M_{f\text{-}Aci}$ = , g d^{-1}
$M_{f\text{-}Fe}$ = , g d^{-1}
$A_{RIC\text{-}Aci}$ = , m^2
$A_{CC\text{-}Aci}$ = , m^2
$A_{RIC\text{-}Fe}$ = , m^2
$A_{CC\text{-}Fe}$ = , m^2

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Passive Treatment

Calculation of Area Needed: Gernrode/Harz

Q =	972	, L min^{-1}
$[Fe_{tot}]$ =	7.7	, mg L^{-1}
[Aci] =	67.7	, mg L^{-1}
$M_{f\text{-}Aci}$ =	106236	, g d^{-1}
$M_{f\text{-}Fe}$ =	14977	, g d^{-1}
$A_{RIC\text{-}Aci}$ =	15177	, m^2
$A_{CC\text{-}Aci}$ =	30353	, m^2
$A_{RIC\text{-}Fe}$ =	749	, m^2
$A_{CC\text{-}Fe}$ =	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

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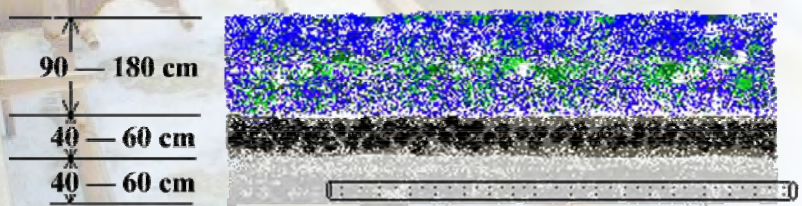
SAPS: Systems

Cross Section and Scheme



- The system ***never*** must fall dry (precipitation of Fe-oxihydrates)
- Kompost: horse manure, cow manure, mushroom compost, bark mulch
- Both, compost and limestone must be permeable
- Calculation of limestone needed equals anoxic limestone drain (ALD)

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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
  - Biolocical processes involved
- Plant uptake
  - Low in the case of uranium

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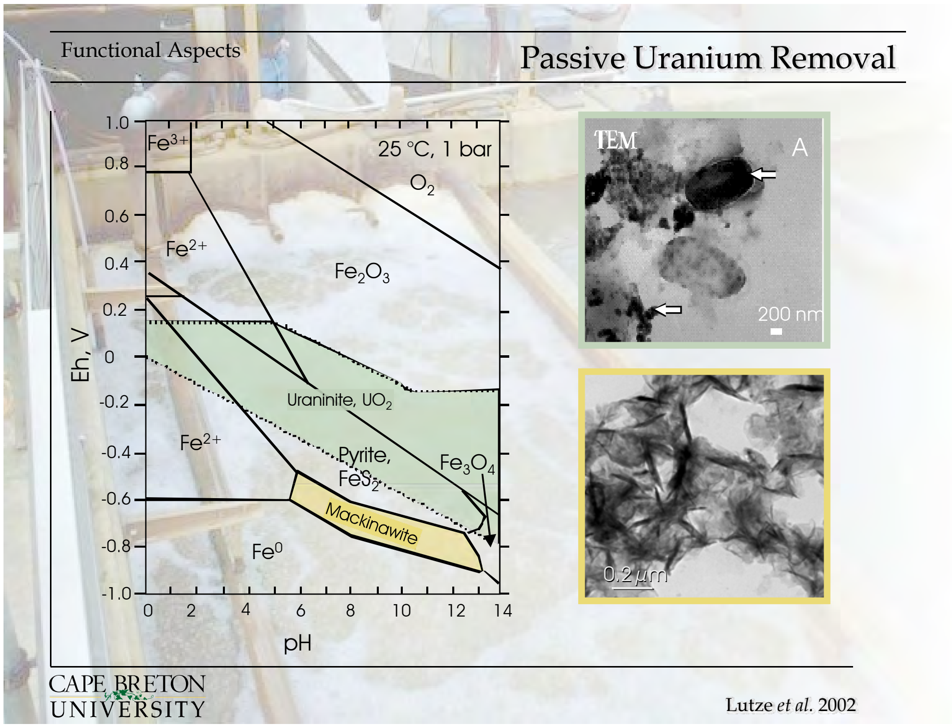
Functional Aspects
Passive Uranium Removal
25 °C, 1 bar
Fe3+
O2
Fe2+
Fe2O3
Uraninite, UO2
Fe2+
Pyrite, FeS2
Fe3O4
Mackinawite
Fe0
Eh, V
pH
TEM
A
200 nm
0.2 µm
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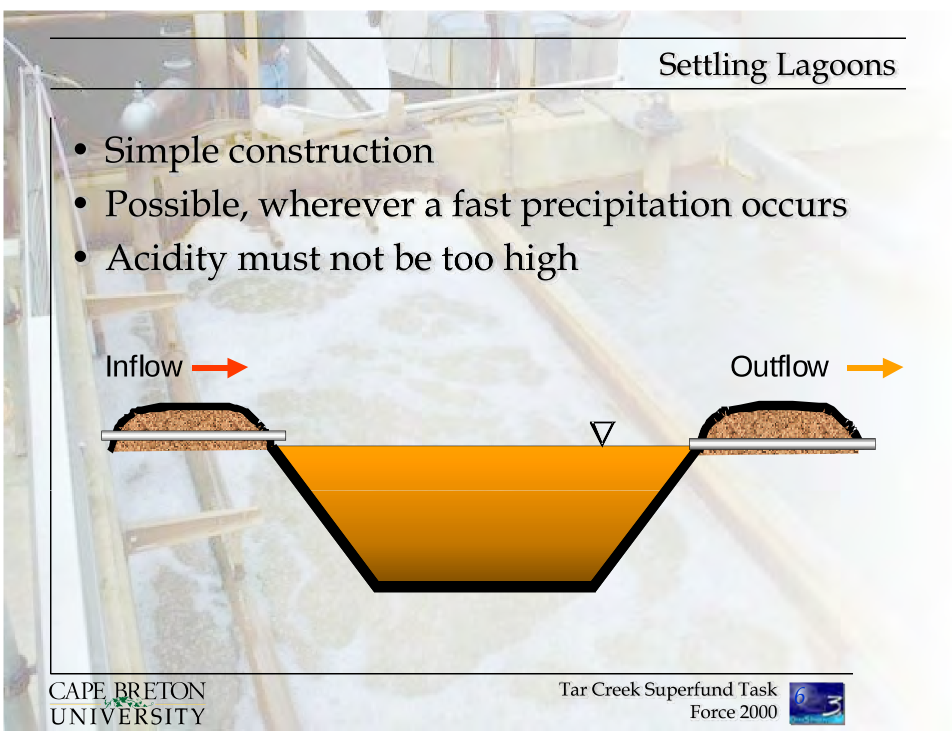
Lutze et al. 2002


Settling Lagoons
• Simple construction
• Possible, wherever a fast precipitation occurs
• Acidity must not be too high
Inflow
Outflow
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Tar Creek Superfund Task Force 2000

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