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University of Technology

From Ground Water to Mine Water

Environmental Hydrogeology in Mining

Introduction | Historical Background

Prof. Dr. Christian Wolkersdorfer (云村)

IMWA – General Secretary

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
- Mathematics: Modelling

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Introduction

Mine Water: The Good and the Ugly

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Introduction

History of Mine Water

- Water inflow ⟹ dewatering drainage, drainage
  - Manuel bucket or sack water-raising (bailing)
  - Water wheel (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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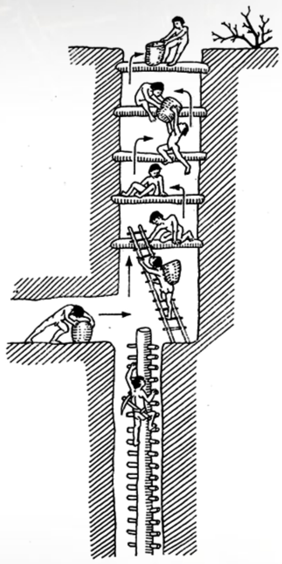
History

Dewatering Techniques

- Bailing
  - Manuel bucket or sack water-raising



from Rebrik 1987

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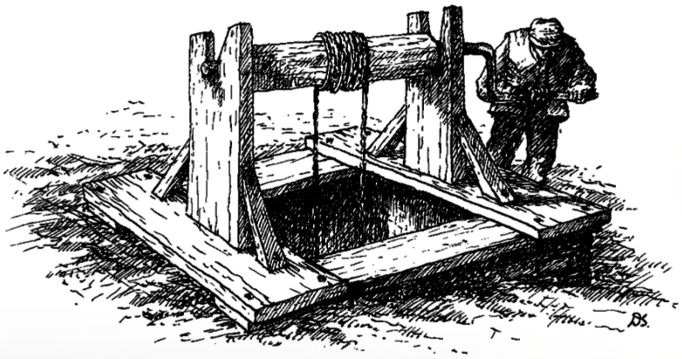
History

Dewatering Techniques

- Whinches
  - Manuel bucket or sack water-raising



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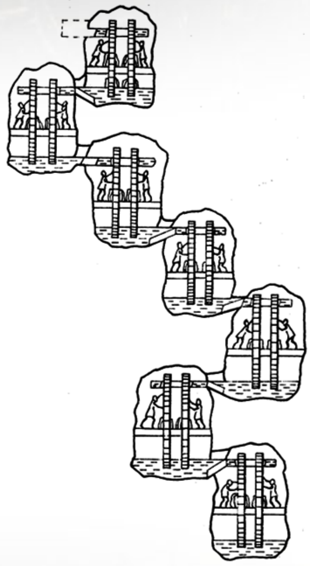
Cowman & Reilly 1988

History

Dewatering Techniques

- Man powered Water wheels
  - Egypt
  - Man power



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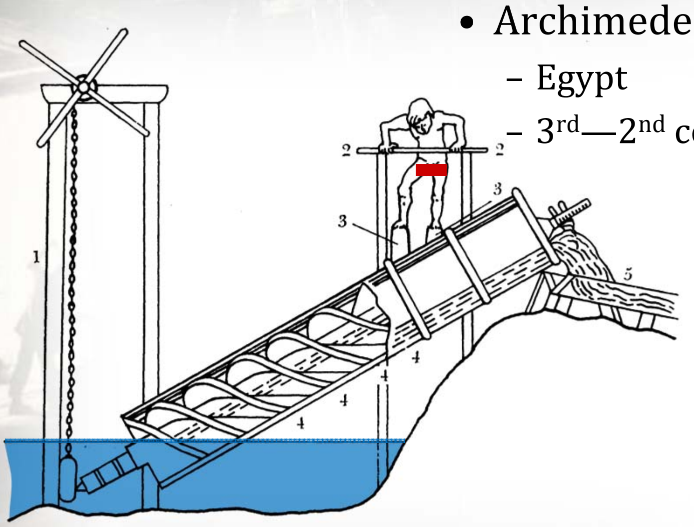
from Rebrik 1987

History

Dewatering Techniques



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

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from Rebrik 1987

History

Dewatering Techniques

- Archimedes' screw

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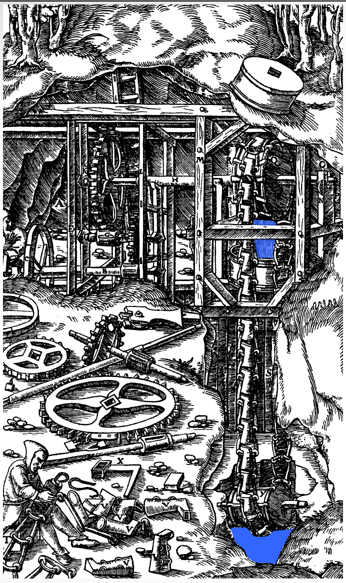
SLUB | Deutsche Fotothek | df_h_0000134

History

Dewatering Techniques

- Bulgenkunst (bucket sprocket)
  - Germany
  - 14th century



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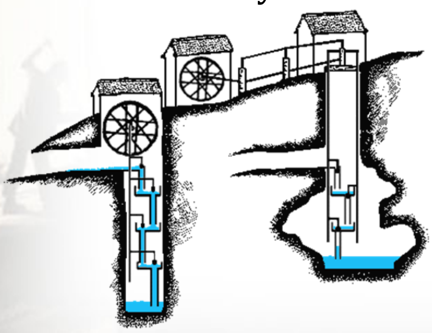
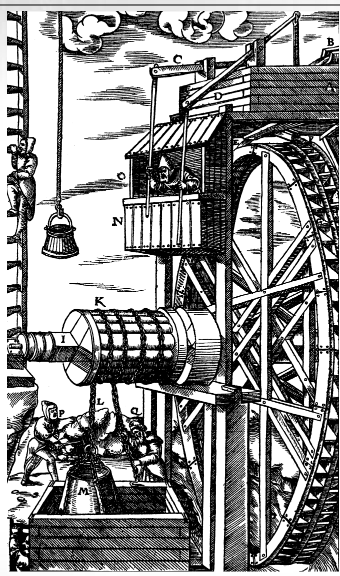
from Agricola 1556

History

Dewatering Techniques

- Water wheel
  - Germany
  - Rammelsberg
  - 15th century





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from Agricola 1556

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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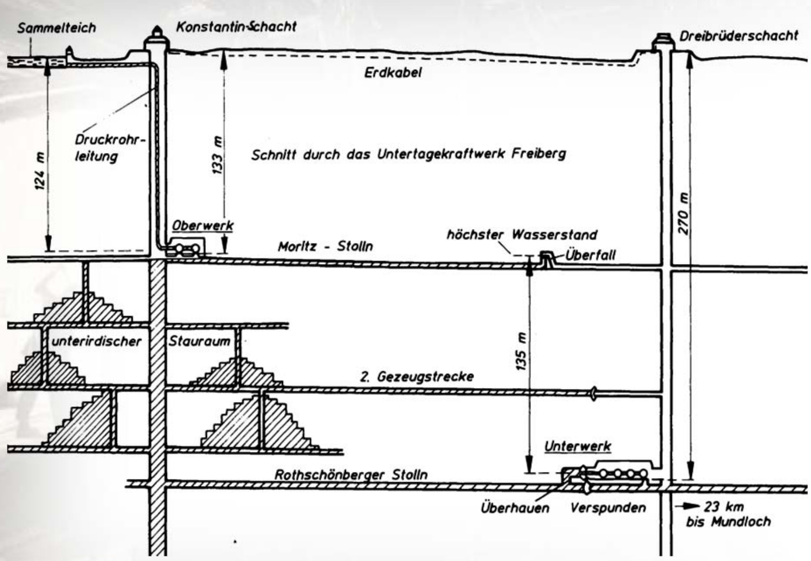
Production of Energy

Ore Mountains: Freiberg/Saxony



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from Jobst *et al.* 1994

Production of Energy

Ore Mountains: Freiberg/Saxony

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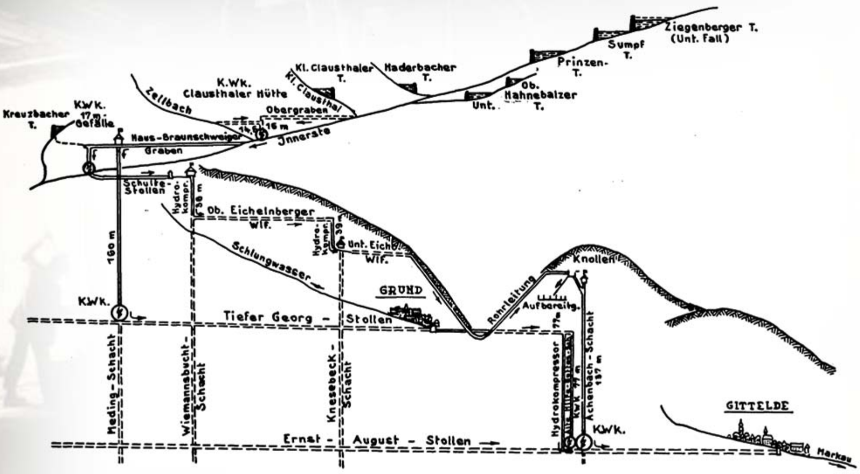
Weyer 2002

Production of Energy

Harz Mountains: Innerste Water System



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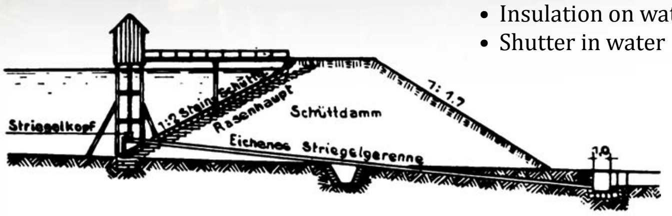
from Haase 1985

Production of Energy

Harz Mountains: Dam Constructions

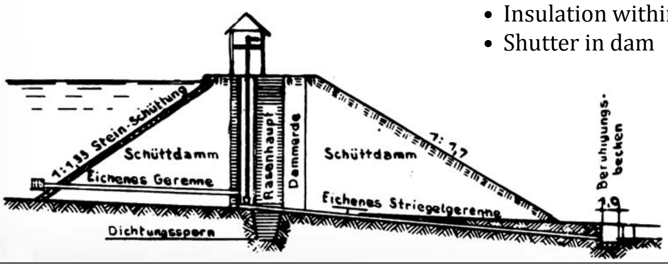
Old System

- 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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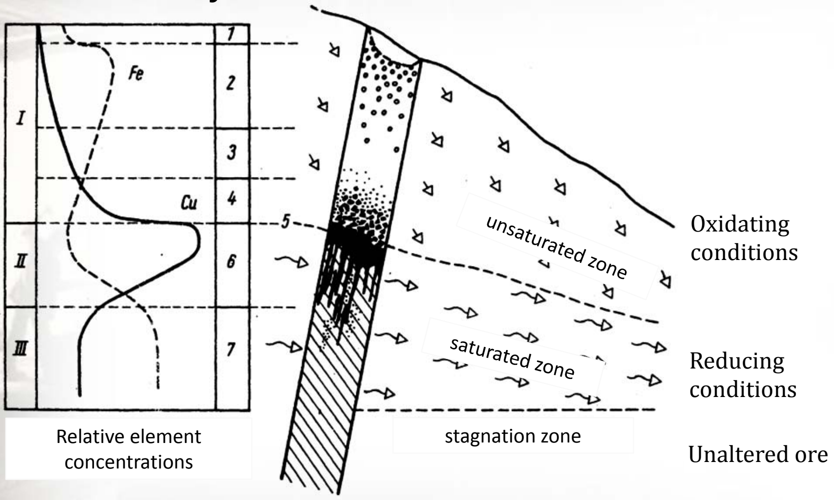
from Agricola 1556

Acidic or polluted mine water

Genesis of Ore Deposits

- Secondary zonation



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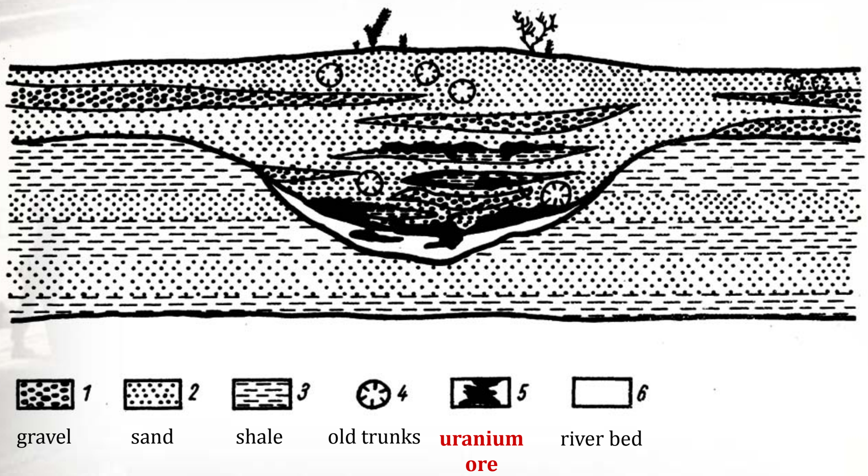
Baumann *et al.* 1979

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

Diseases

Inflation

Listlessness

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from Schönberger 1556

History

Literature

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From Ground Water to Mine Water

Environmental Hydrogeology in Mining

Mining Methods, Technical Terms

Prof. Dr. Christian Wolkersdorfer

IMWA – General Secretary

From Ground Water to Mine Water

Contents

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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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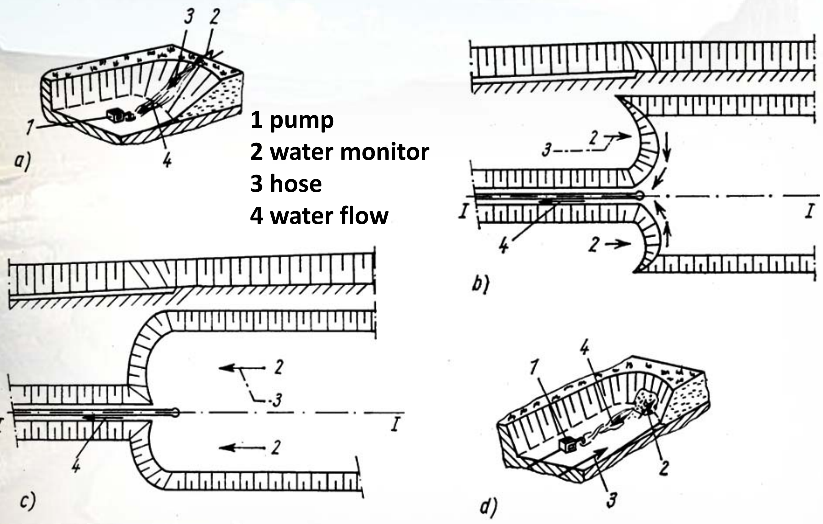
Mining Methods

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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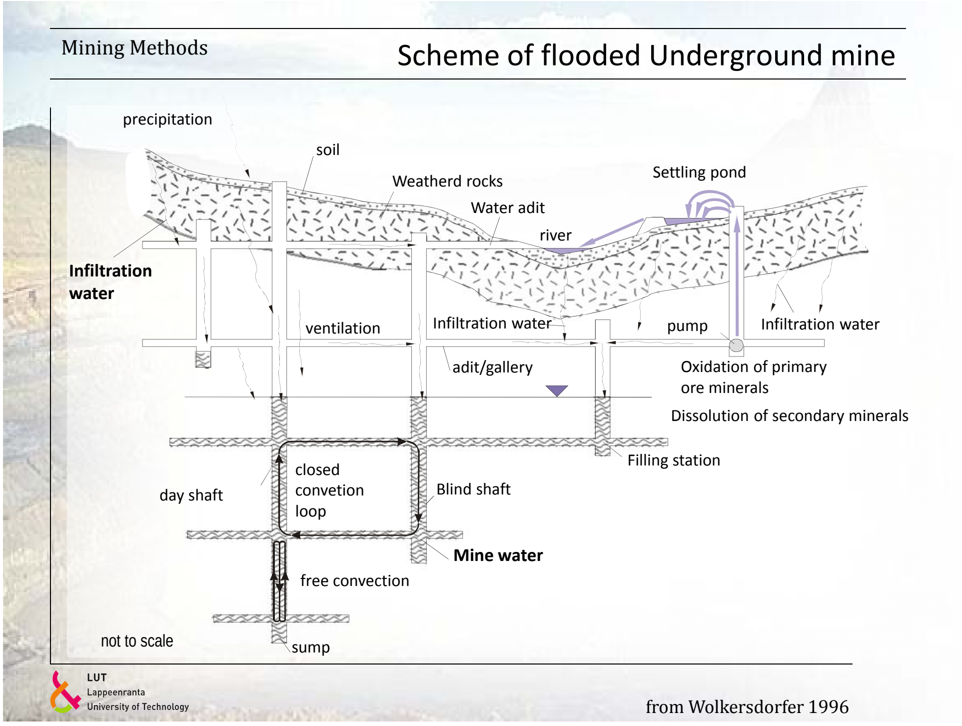
Mining Methods
Scheme of flooded Underground mine
precipitation
soil
Weatherd rocks
Settling pond
Water adit
river
Infiltration water
ventilation
Infiltration water
pump
Infiltration water
adit/gallery
Oxidation of primary ore minerals
Dissolution of secondary minerals
Filling station
closed convetion loop
day shaft
Blind shaft
Mine water
free convection
not to scale
sump
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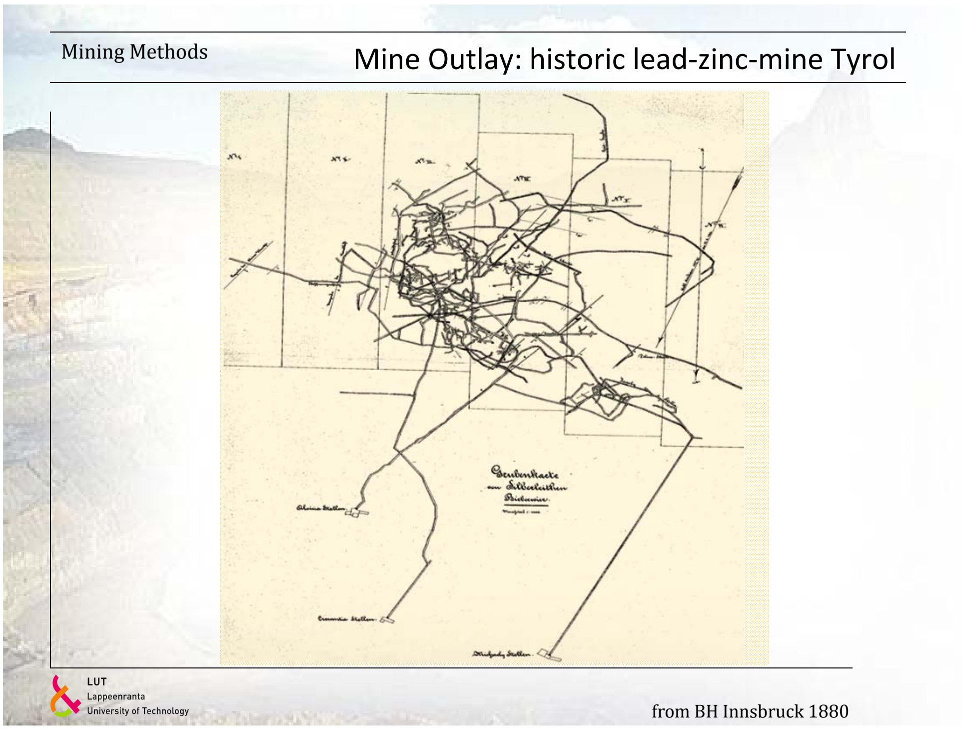
from Wolkersdorfer 1996


Mining Methods
Mine Outlay: historic lead-zinc-mine Tyrol
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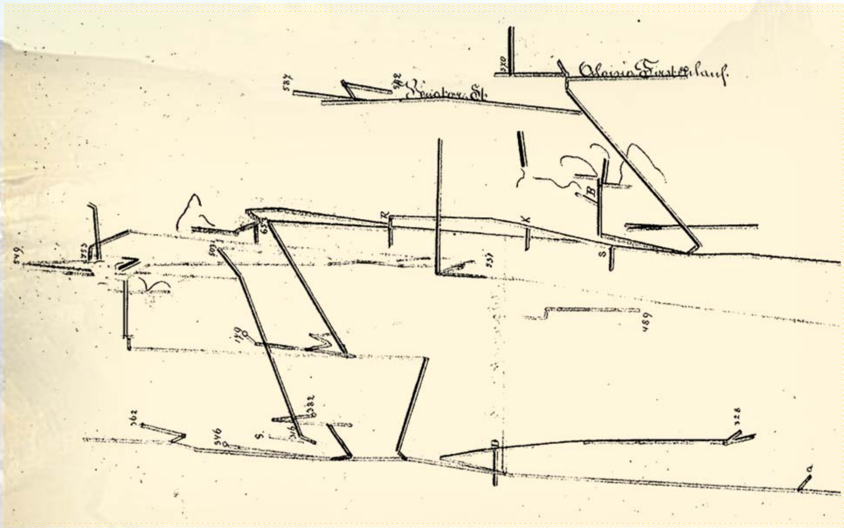
from BH Innsbruck 1880

Mining Methods

Mine Outlay: historic lead-zinc-mine Tyrol



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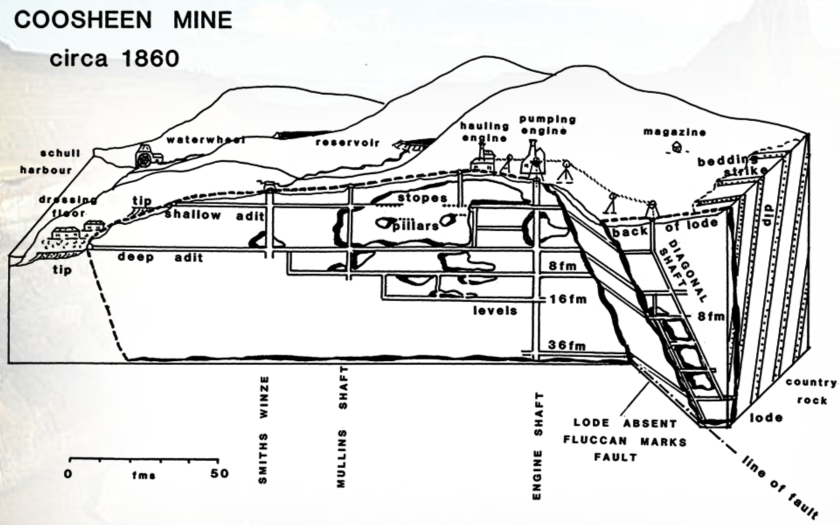
from BH Innsbruck 1880

Mining Methods

Scheme of deep underground mine



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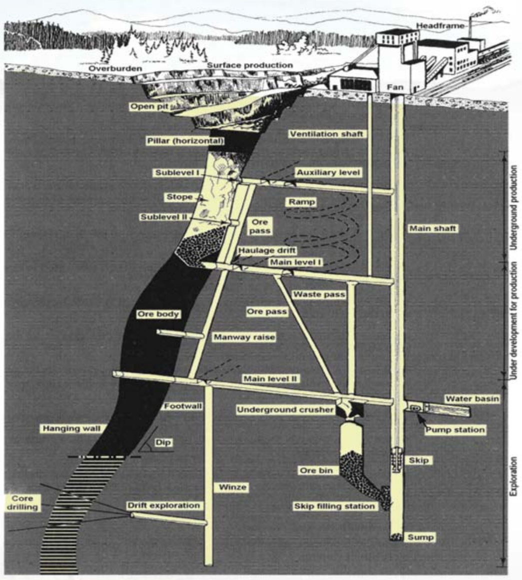
Cowman & Reilly 1988

Mining Methods

Scheme of deep underground mine



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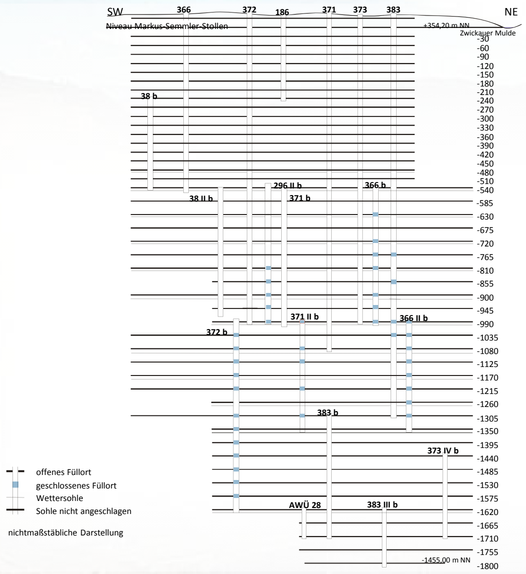
Gertsch & Bullock 1998

Mining Methods

Example: German uranium mine



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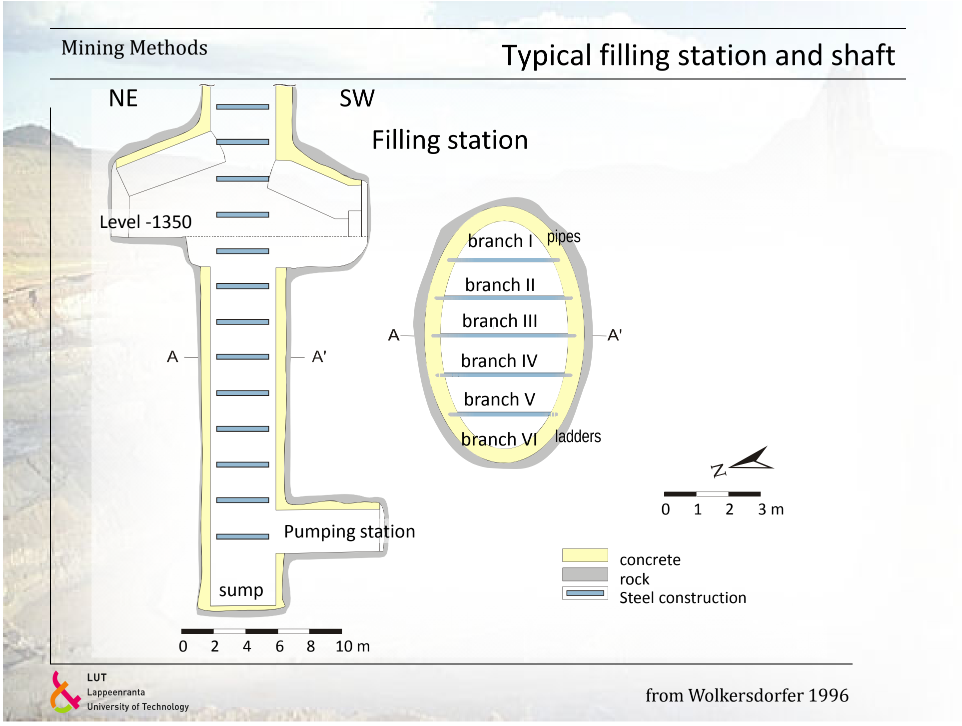
from Wolkersdorfer 1996


Mining Methods
Typical filling station and shaft
NE
SW
Filling station
Level -1350
branch I
pipes
branch II
branch III
A
A'
branch IV
branch V
branch VI
ladders
A
A'
0 1 2 3 m
Pumping station
concrete
rock
Steel construction
sump
0 2 4 6 8 10 m
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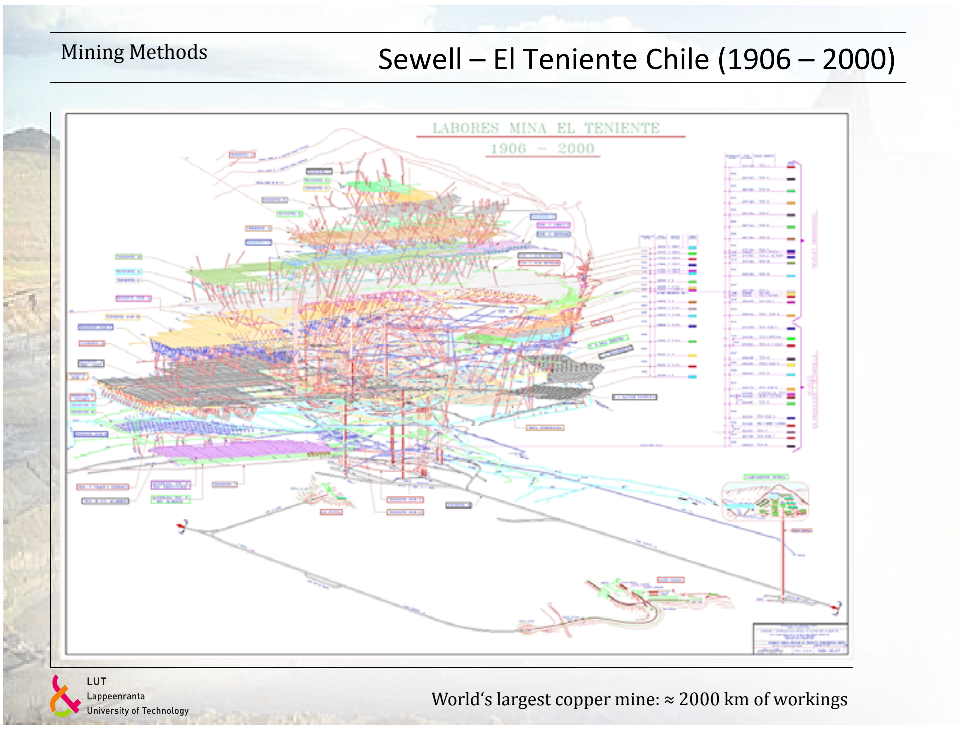
from Wolkersdorfer 1996


Mining Methods
Sewell – El Teniente Chile (1906 – 2000)
LABORES MINA EL TENIENTE
1906 – 2000
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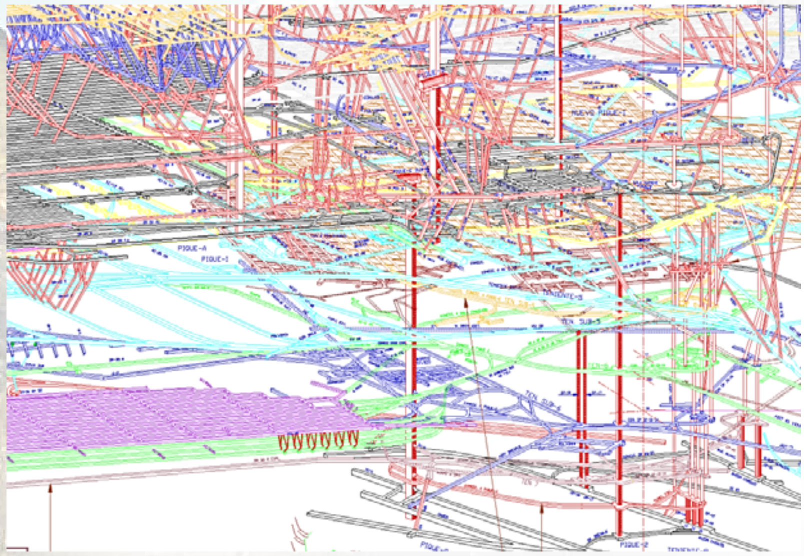
World's largest copper mine: ≈ 2000 km of workings

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
  - Raw material extraction (stopes)
  - Host rock, by-products
  - Mine ventilation (mine ventilators, ventilation shafts)
  - Mine dewatering (water drainage, mine pumps, sumps)
  - Mine power (electricity, water, pressurized air)

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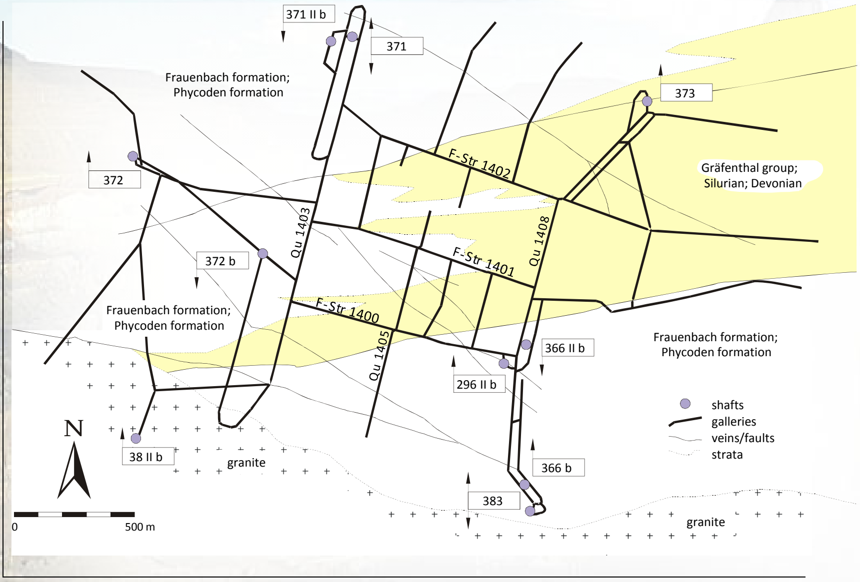
Mining Methods

Mine outlay: Uranium mine shaft 371



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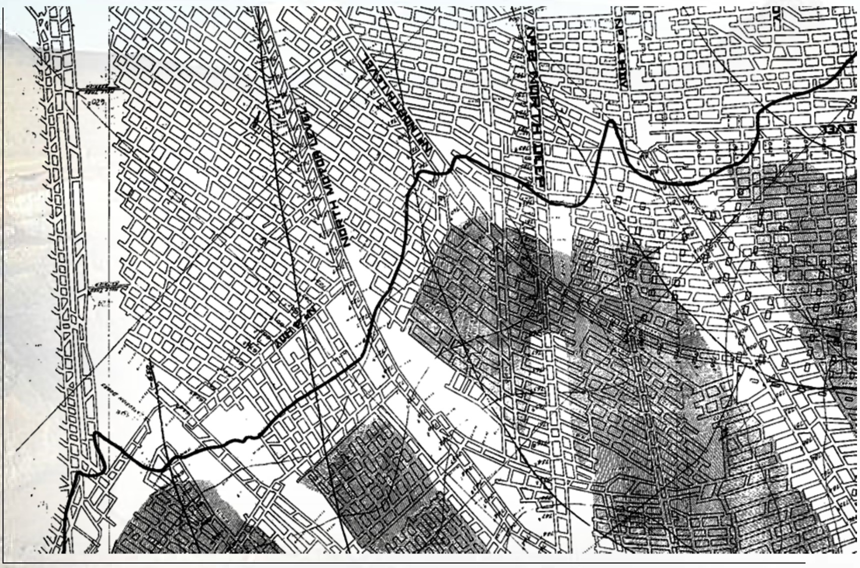
from Wolkersdorfer 1996

Mining Methods

Mine outlay: Sydney Nova Scotia



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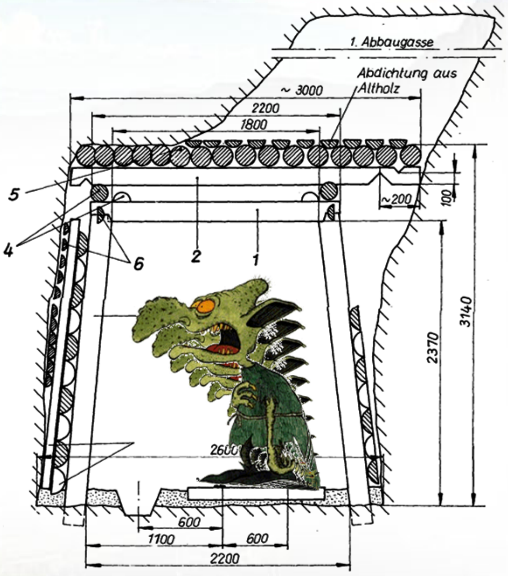
Dominion № 9 Coal Mine, Glace Bay, 1924

Mining Methods

German frame timbering

“Deutscher Türstock”



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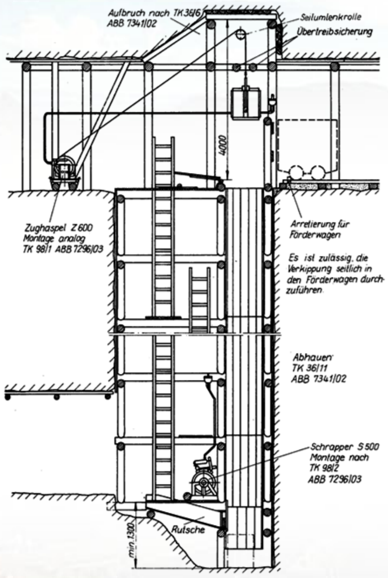
from SDAG Wismut 1987 | Walter Moers’ “Mine Troll”

Mining Methods

Downward mining



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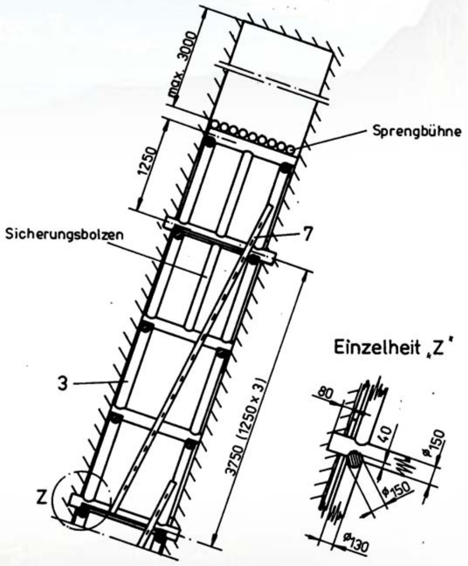
from SDAG Wismut 1987

Mining Methods

Cross/shaft timbering

"Bolzenschrot-zimmerung"

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



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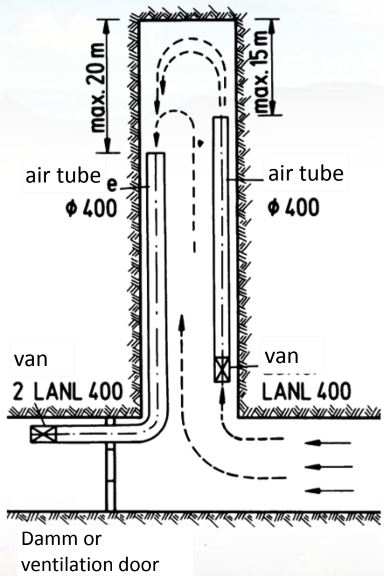
from SDAG Wismut 1987

Mining Methods

Auxillary Ventilation at Advancing Face



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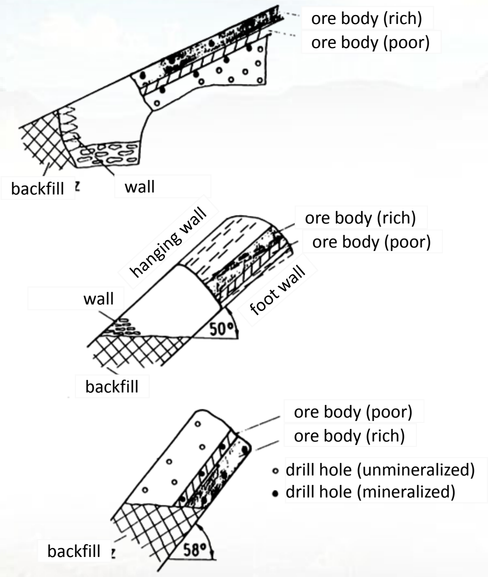
from Jobst et al. 1994

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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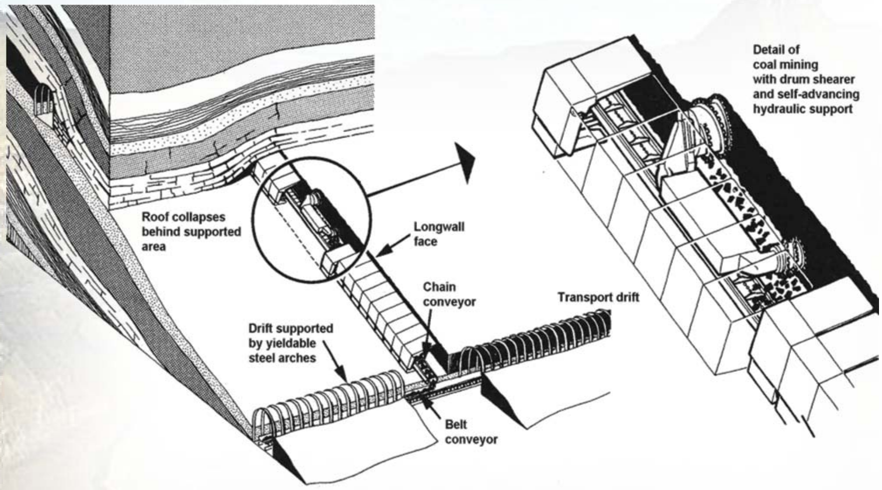
Mining Methods

Longwall mining



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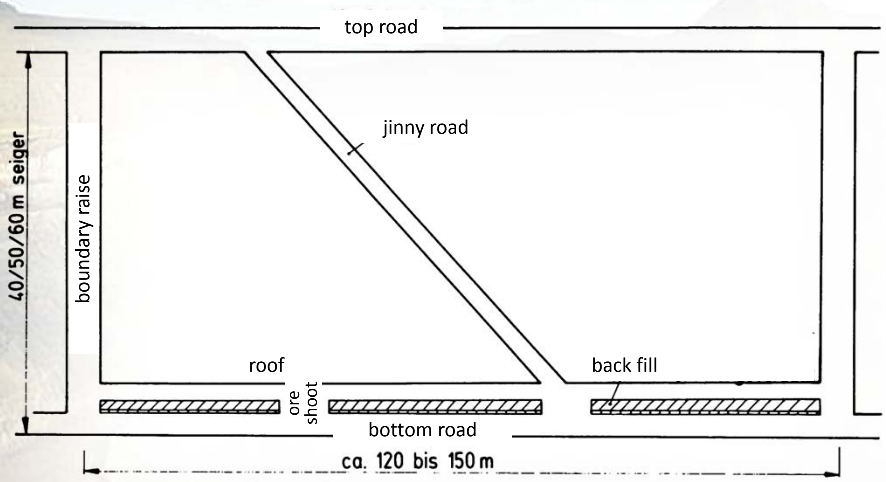
Gertsch & Bullock 1998

Mining Methods

Overhead Stoping (flat-back cut and fill)



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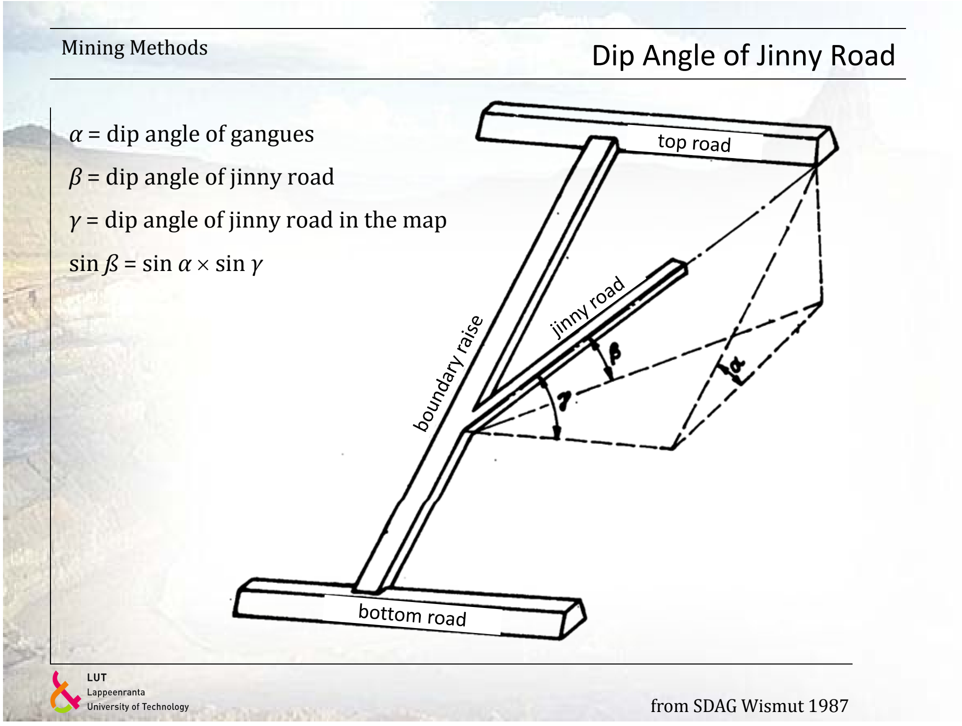
from Jobst *et al.* 1994


Mining Methods
Dip Angle of Jinny Road
α = dip angle of gangues
ß = dip angle of jinny road
γ = dip angle of jinny road in the map
sin ß = sin α × sin γ
top road
jinny road
boundary raise
bottom road
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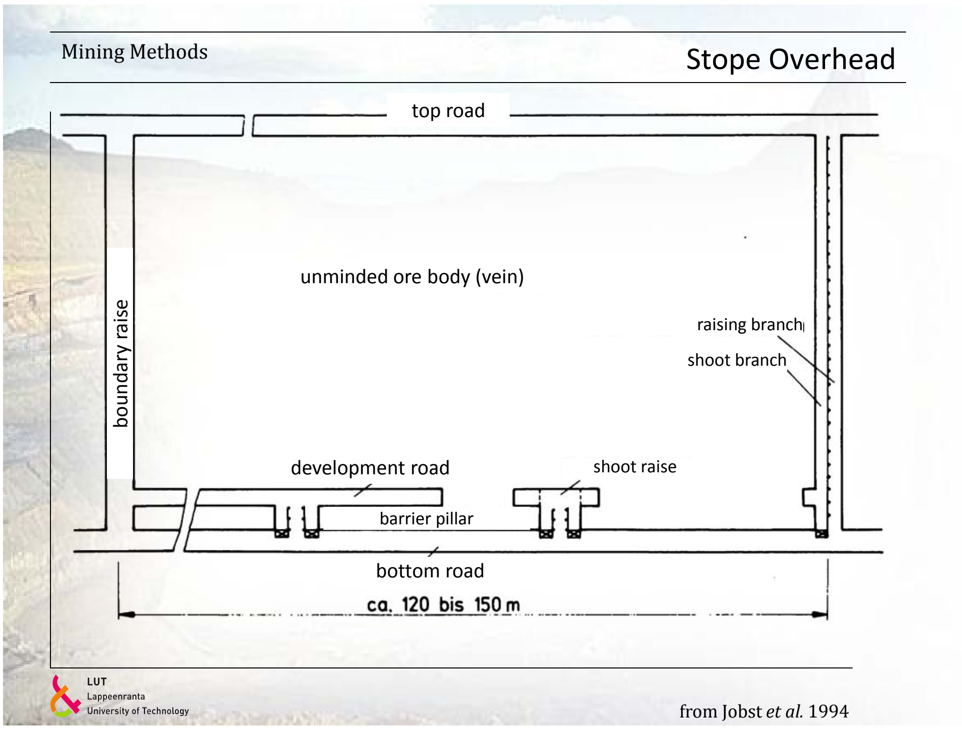
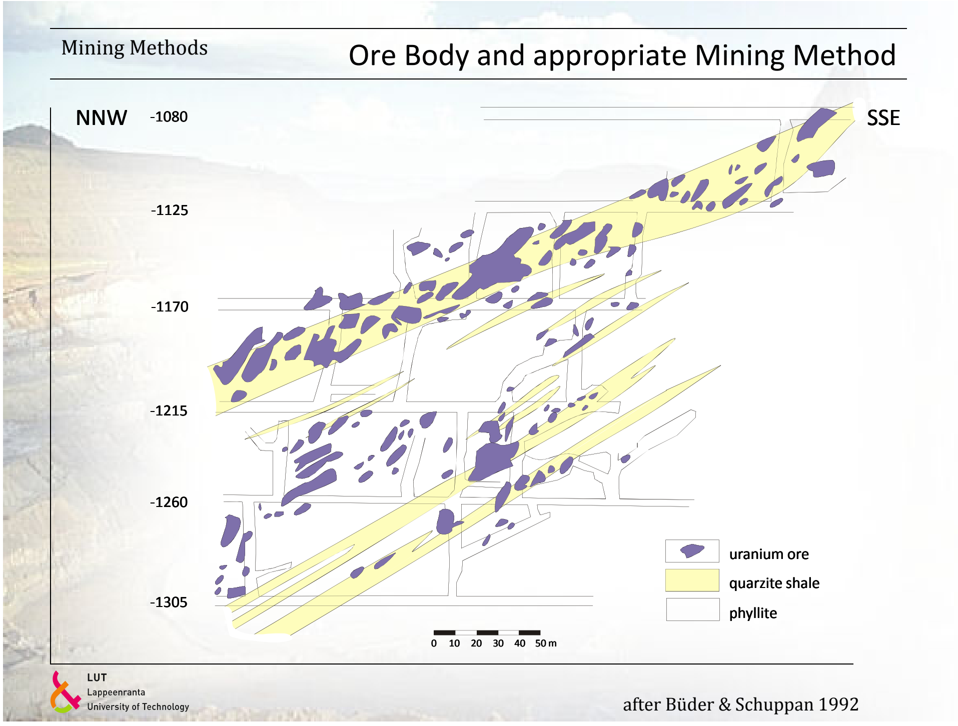
from SDAG Wismut 1987


Mining Methods
Stope Overhead
top road
unminded ore body (vein)
boundary raise
raising branch
shoot branch
development road
shoot raise
barrier pillar
bottom road
ca. 120 bis 150 m
LUT Lappeenranta University of Technology
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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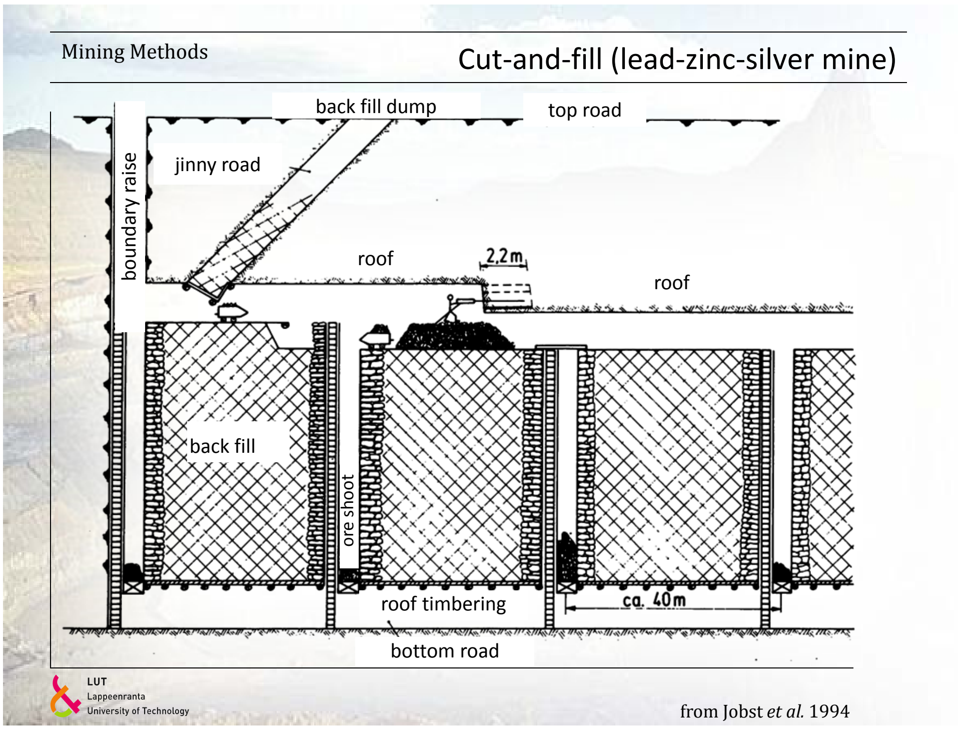
after Büder & Schuppan 1992


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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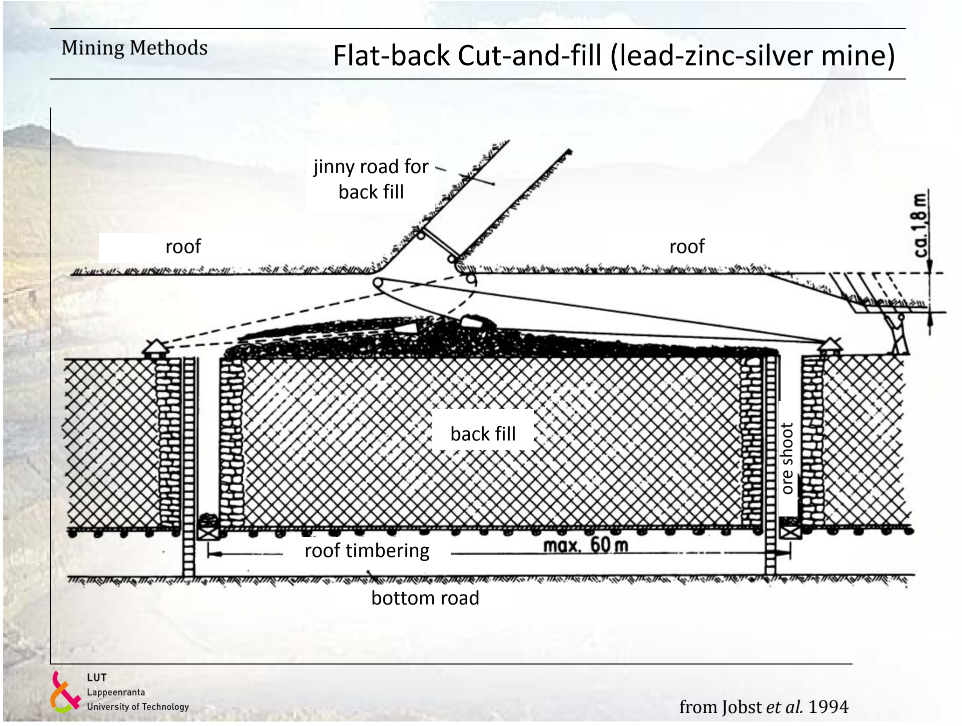
from Jobst et al. 1994


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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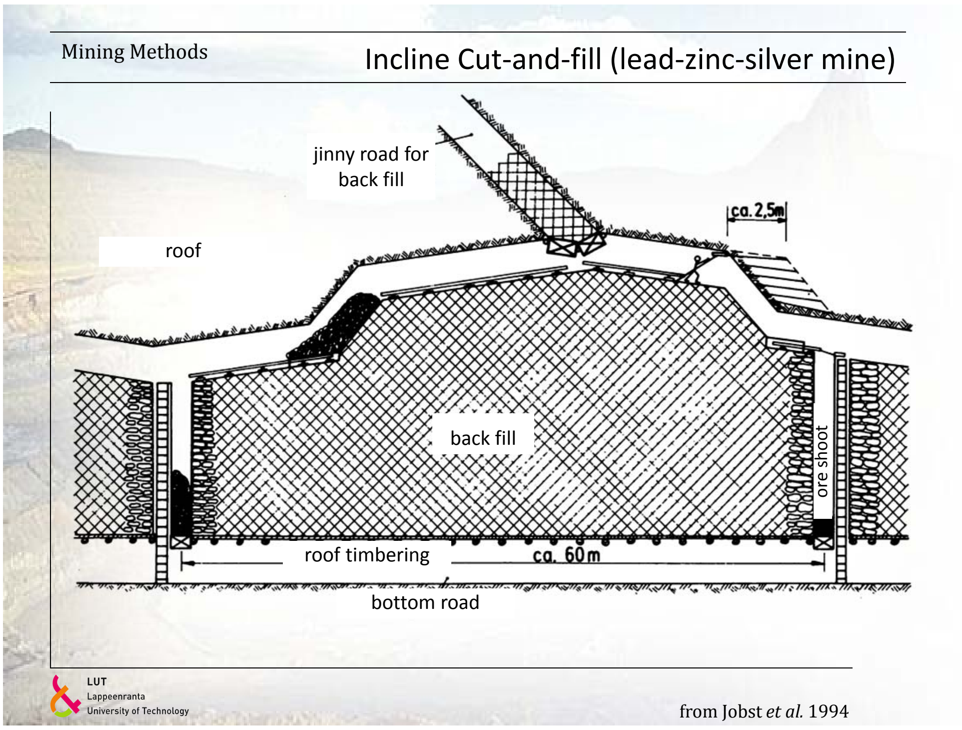
from Jobst *et al.* 1994


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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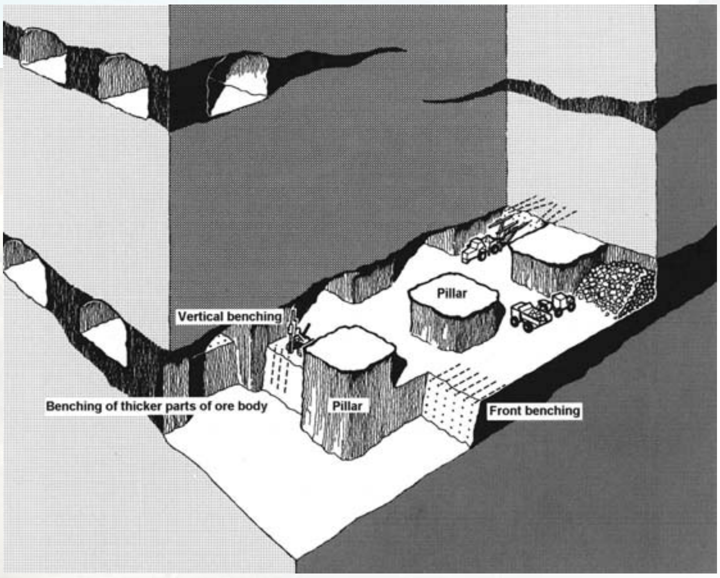
from Jobst *et al.* 1994

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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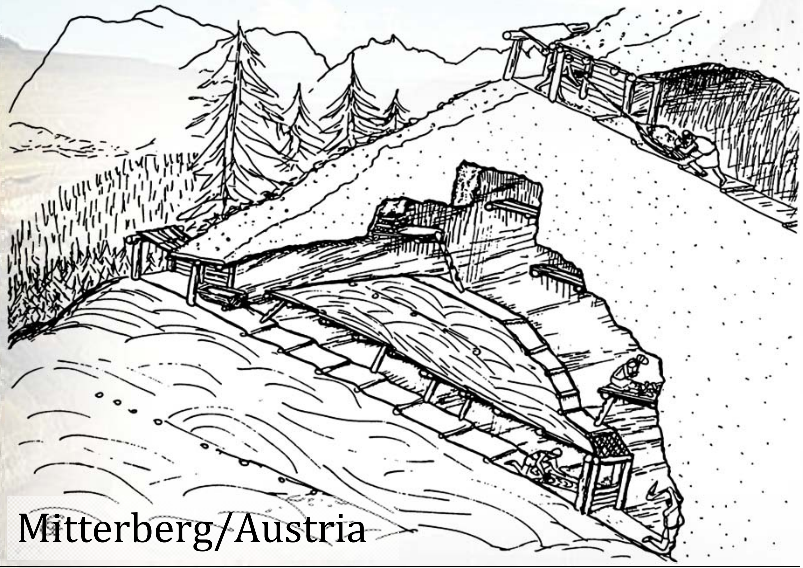
Mining Methods

Copper Mining in the Bronce Age



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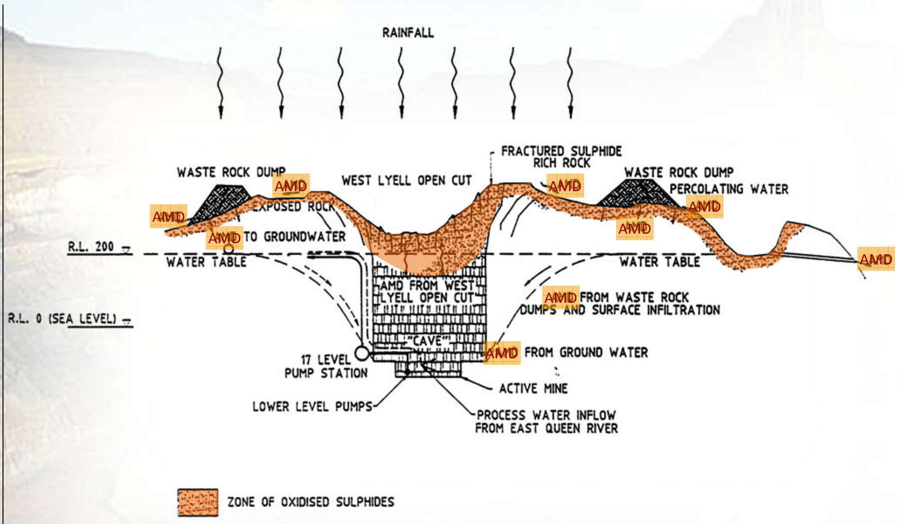
Steuer & Zimmermann 1993

Mining Methods

Sublevel Caving and Acid Mine Drainage



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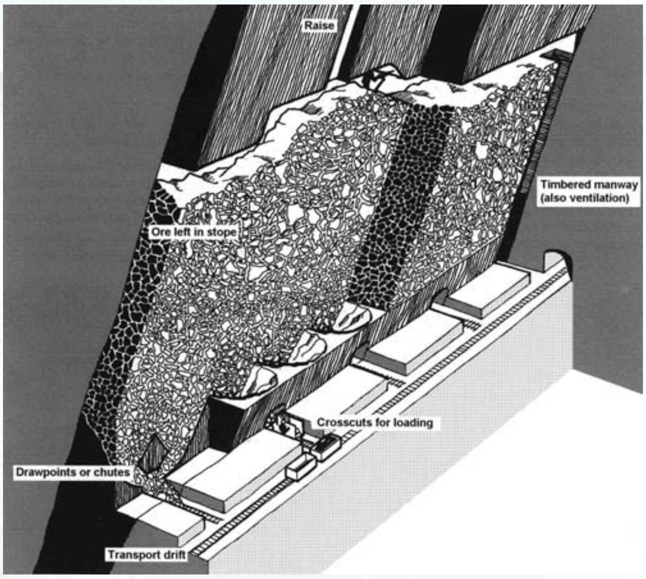
from Thompson & Brett Pty. Ltd. 1995

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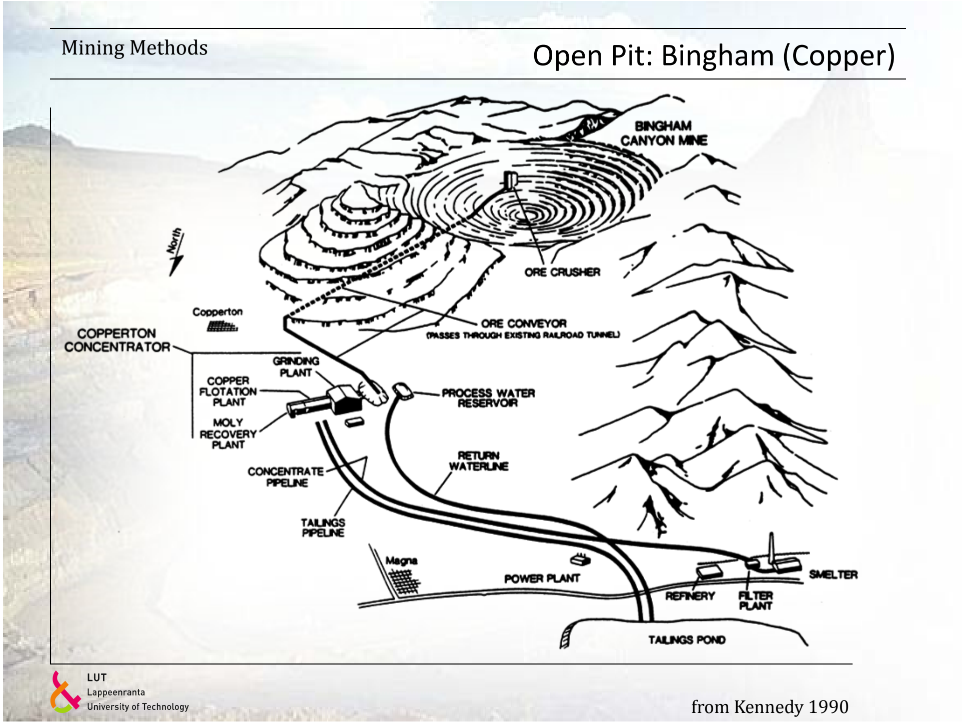
Mining Methods
Open Pit: Bingham (Copper)
BINGHAM CANYON MINE
North
ORE CRUSHER
Copperton
COPPERTON CONCENTRATOR
ORE CONVEYOR
(PASSES THROUGH EXISTING RAILROAD TUNNEL)
GRINDING PLANT
COPPER FLOTATION PLANT
MOLY RECOVERY PLANT
PROCESS WATER RESERVOIR
RETURN WATERLINE
CONCENTRATE PIPELINE
TAILINGS PIPELINE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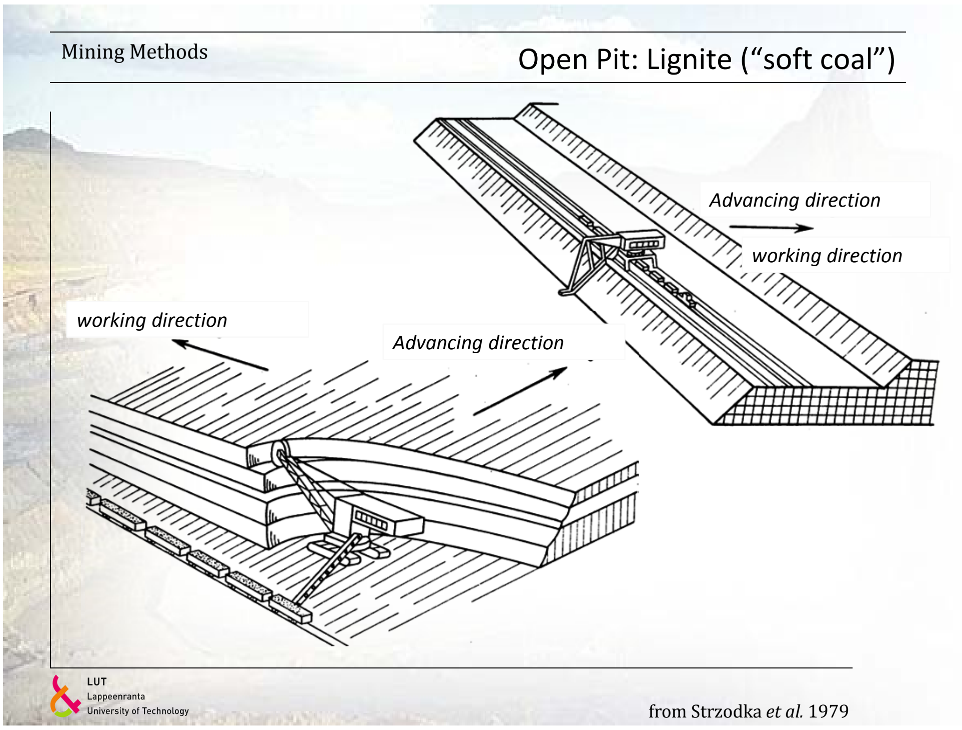
from Kennedy 1990


Mining Methods
Open Pit: Lignite (“soft coal”)
Advancing direction
working direction
working direction
Advancing direction
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University of Technology
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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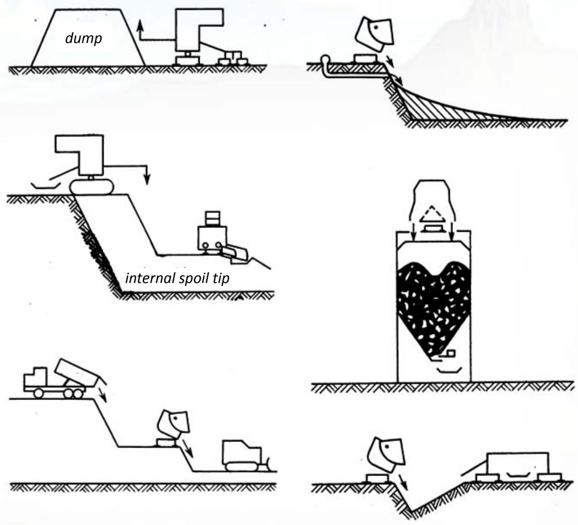
Mining Methods

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

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- Fritzsche, C. F. (1982 [1962]): Lehrbuch der Bergbaukunde mit besonderer Berücksichtigung des Steinkohlenbergbaus **II.** – 759 S.
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From Ground Water to Mine Water

Environmental Hydrogeology in Mining

Water and Water Inrushes

Prof. Dr. Christian Wolkersdorfer

IMWA – General Secretary

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/service water
  - *e.g.* Dust suppression, cooling water
  - Mean: 110 L/d/t of ore; max: 380 L/d/t of ore

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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

relative permeability

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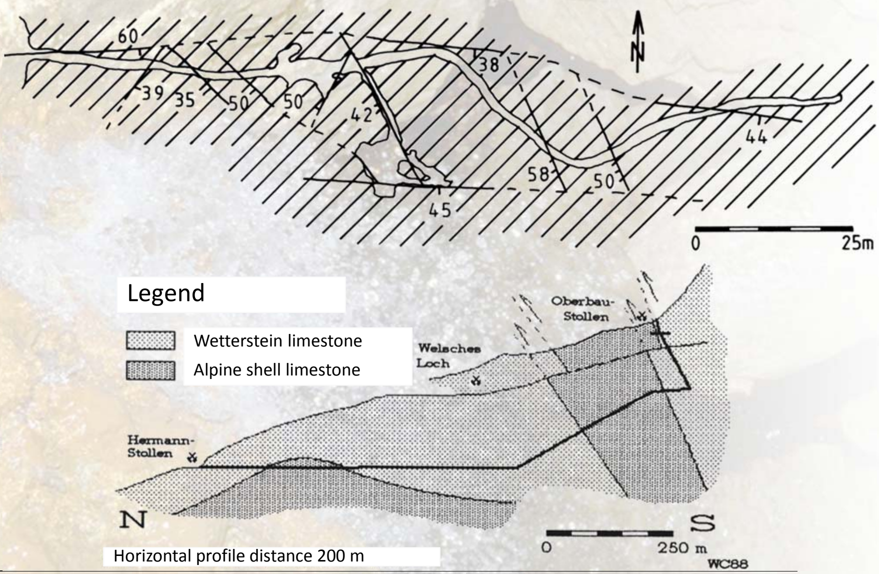
Infiltration water

Lithology, Faults Dependence



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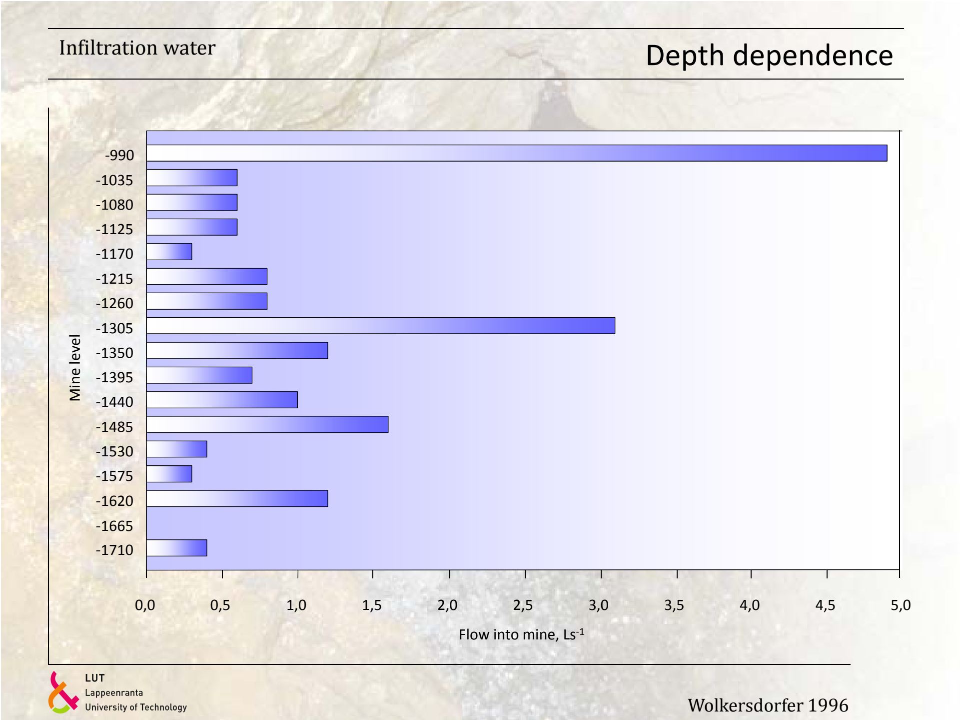
Wolkersdorfer 1989


Infiltration water
Depth dependence
Mine level
-990
-1035
-1080
-1125
-1170
-1215
-1260
-1305
-1350
-1395
-1440
-1485
-1530
-1575
-1620
-1665
-1710
0,0
0,5
1,0
1,5
2,0
2,5
3,0
3,5
4,0
4,5
5,0
Flow into mine, Ls-1
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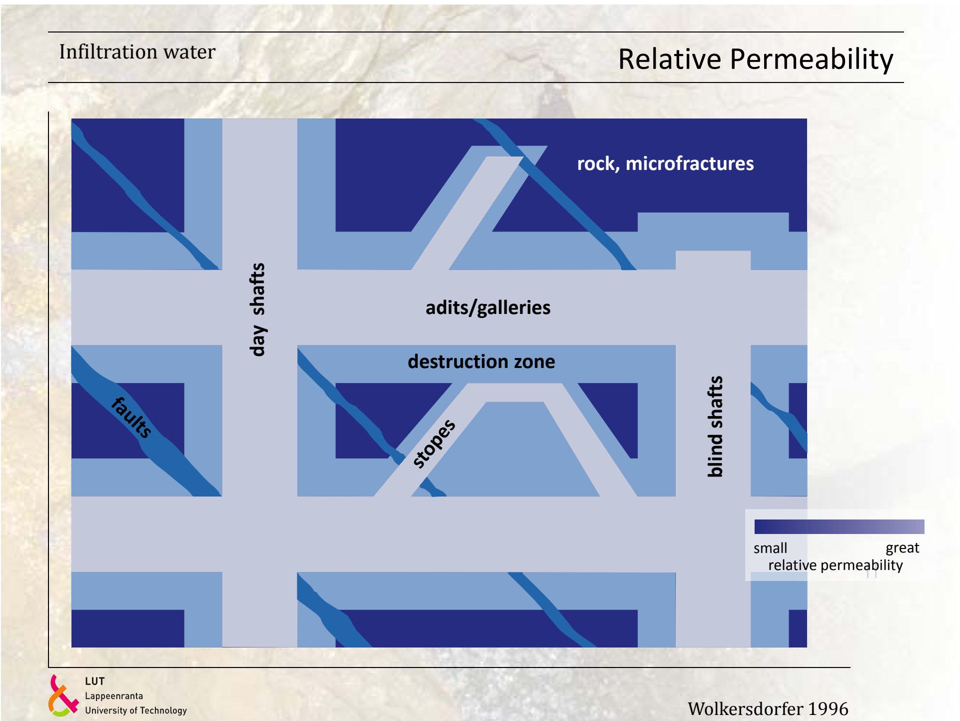
Wolkersdorfer 1996


Infiltration water
Relative Permeability
rock, microfractures
day shafts
adits/galleries
destruction zone
faults
stopes
blind shafts
small
great
relative permeability
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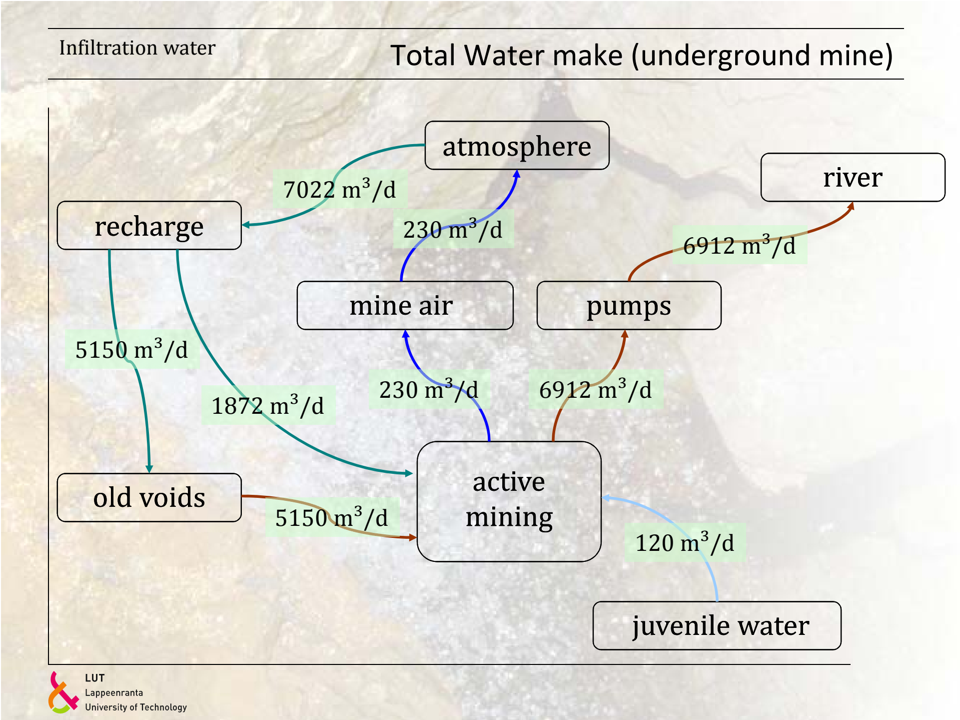
Wolkersdorfer 1996


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
1872 m³/d
230 m³/d
6912 m³/d
active mining
old voids
5150 m³/d
120 m³/d
juvenile water
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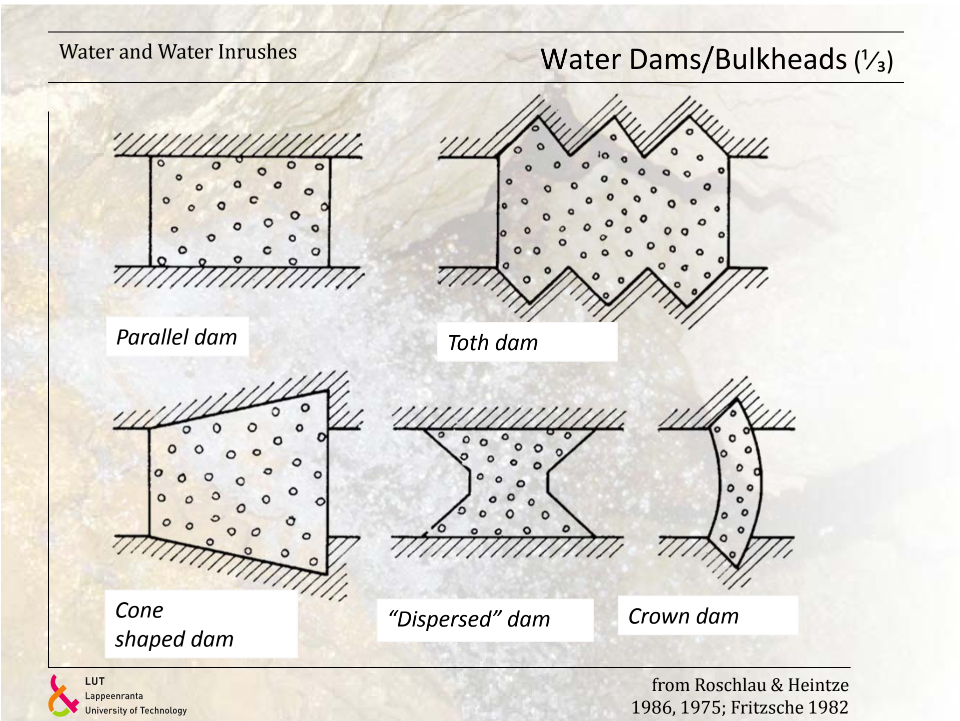
Water and Water Inrushes
Water Dams/Bulkheads (1/3)
Parallel dam
Toth dam
Cone shaped dam
"Dispersed" dam
Crown dam
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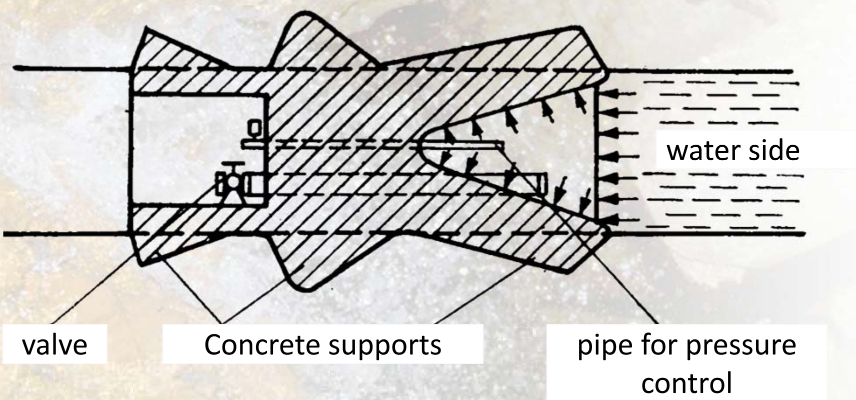
University of Technology
from Roschlau & Heintze 1986, 1975; Fritzsche 1982

Water and Water Inrushes

Water Dams/Bulkheads (2/3)



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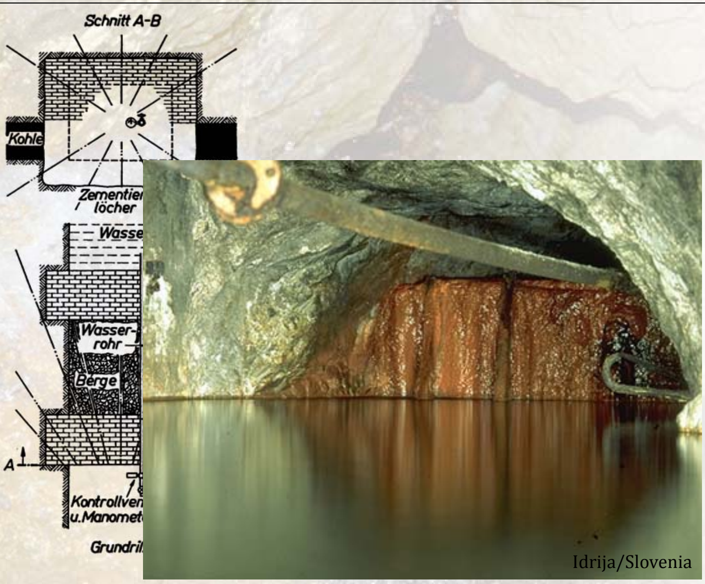
from Roschlau & Heintze 1986, 1975; Fritzsche 1982

Water and Water Inrushes

Water Dams/Bulkheads (3/3)



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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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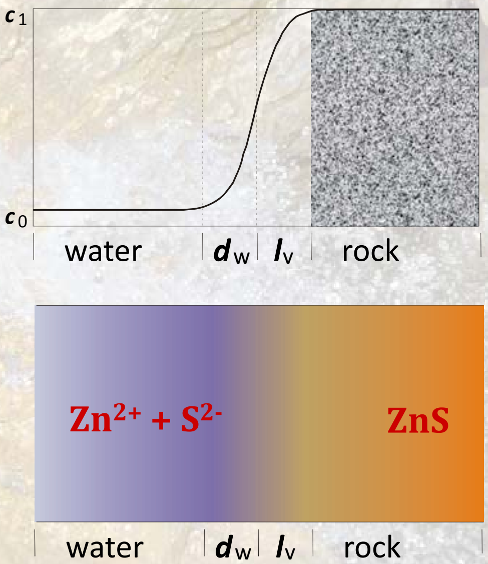
Infiltration water

Concentration gradient



d_w: diffusion zone

l_v: weathering zone

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

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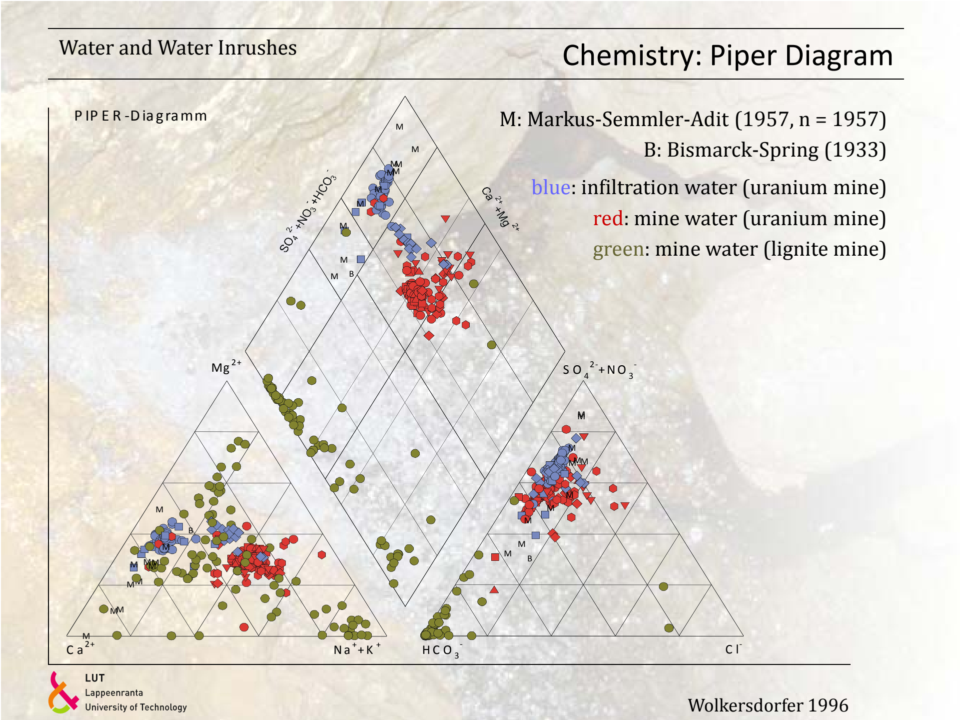
Wolkersdorfer 1996


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)
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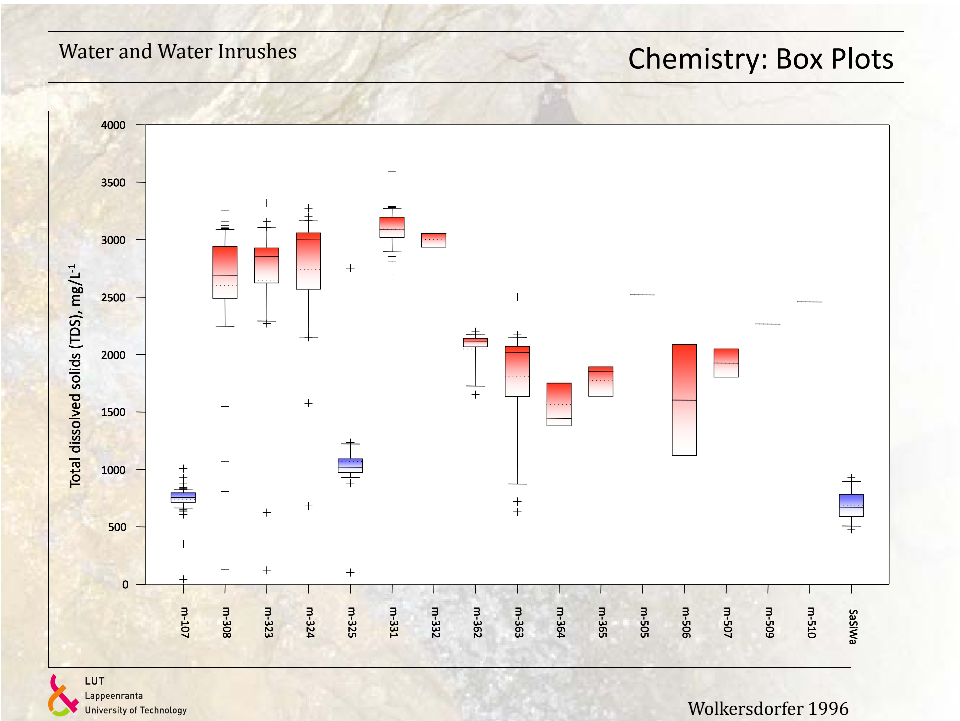
Wolkersdorfer 1996


Water and Water Inrushes
Chemistry: Box Plots
Total dissolved solids (TDS), mg/L-1
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 SaSiWa
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Wolkersdorfer 1996

Multivariate Statistics

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Humidity in the mine air: an estimation

- Air flux (min/max: 10…1,300 m³/s; mean: 120…700 m³/s)
  - $Q = 133\ m^3/s$
- Temperature
  - $\theta = 26.7\ °C$
- Relative humidity
  - $\eta = 80\%$
- Volume of Water in Steam (100%, 26.7 °C, 1000 hPa)
  - $V = 25\ mL/m^3$
- Daily water make in the mine air
  - $V_w = Q \cdot \eta \cdot V \cdot 0.0864 = 229.8\ m^3/d$

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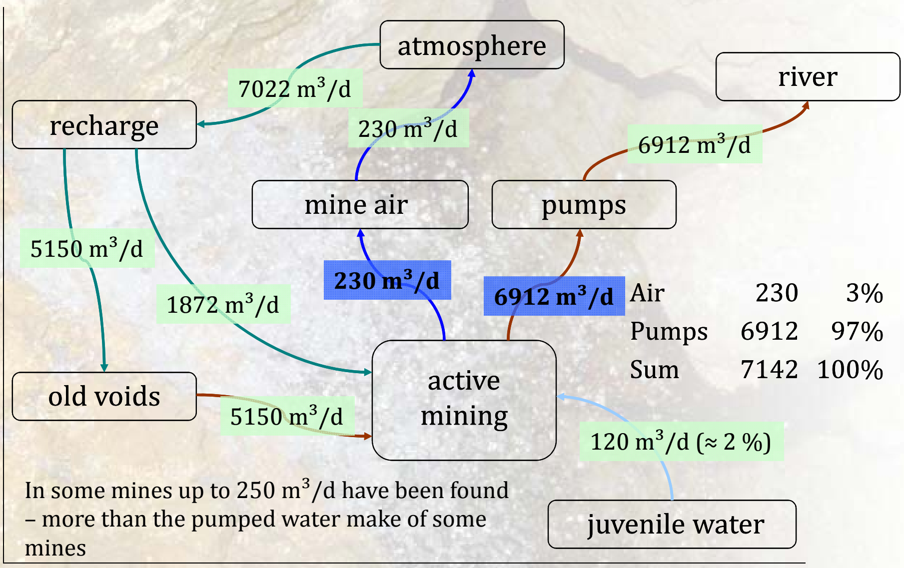
Water and Water Inrushes

Total Water make (underground mine)



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adopted after Younger

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

Weir Equations

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

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

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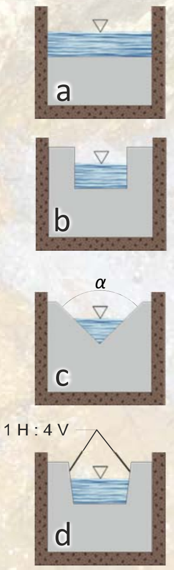
Kindsvater & Carter 1959

Water and Water Inrushes

Weir Types



a) Rectangular or PONCELET weir without end contractions

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

b) Rectangular or PONCELET weir with end contractions

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

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

d) Trapezoidal or CIPOLLETTI weir

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

Equations for metric units only; errors: –10…4%

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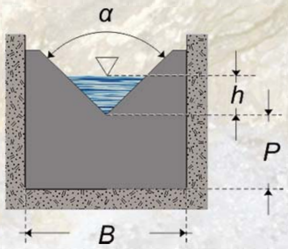
Wolkersdorfer 2008

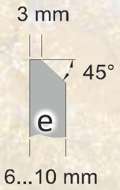
Water and Water Inrushes

Weir Types



- h gauged head related to weir crest, m
- B crest breath, m
- P crest height of weir above mean bed level, m
- Q flow over weir, $m^3\ s^{-1}$
- α angle of V-notch, °

$$Q_{90°} = 1.369 \times h^{2.5}; \alpha = 90°$$
$$Q_{½90°} = 0.684 \times h^{2.5}; \alpha = 53°8'$$
$$Q_{¼90°} = 0.348 \times h^{2.5}; \alpha = 28°4'$$



e) Detail: typical weir plate edge treatment

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Water and Water Inrushes

Weir Types: Prerequisites (½)

1. The upstream face of the weir plates and bulkhead must be plumb, smooth, and perpendicular to channel flow.
2. The weir crest needs to be level for rectangular and trapezoidal shapes. The bisector of V-notch angles must be plumb.
3. The edges of the weir opening must be located in one plane. The corners of the weir opening must have proper specified angles.
4. The top thickness of the crest and side plates should measure between 1 and 2 mm.
5. All weir plates need to have the same thickness over the entire overflow crest boundary. Plates thicker than 2 mm should be bevelled to an angle of at least 45° on the downstream edge of the crest and sides. The downstream edge of V-notches should have a 60° angle to prevent water from clinging to the downstream face of the weir.
6. Upstream edges must be straight and sharp. Burrs and scratches should be removed by machining or perpendicular filing; abrasive cloth or paper should not be used.

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

Weir Types: Prerequisites (2/2)

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

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

Weir Types: Errors

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

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

Most common errors:

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

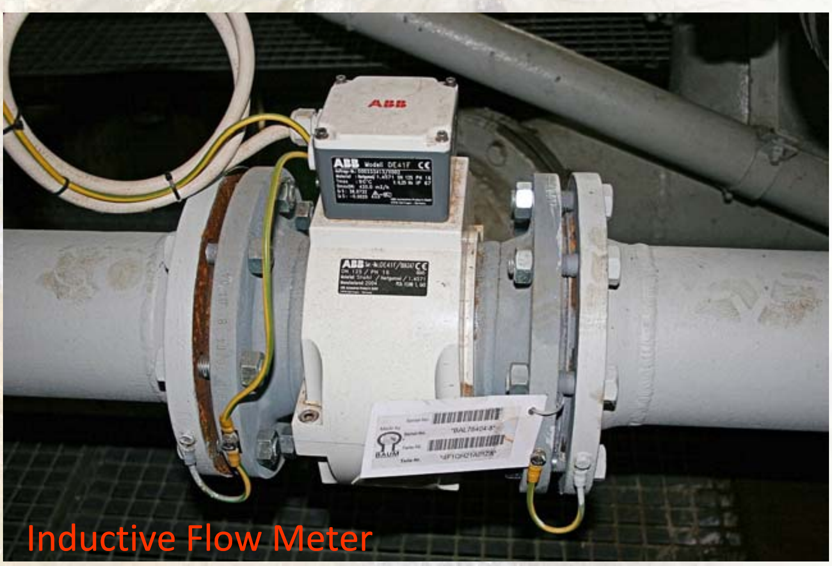
Potential Solution:

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

Thomas 1959 and personal experience

Water and Water Inrushes

Measuring of water flows



Inductive Flow Meter

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Water and Water Inrushes

Measuring of water flows

Water Meter

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Water and Water Inrushes

Measuring of water flows

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Water and Water Inrushes

Calculation of water inflows (⅓)

- Mining area: $A = 30\ \text{km}^2$
- Precipitation 1950—1990: $N = 825$ mm/a
- Mean surface flow: $a_o = 38.7\%$
- Mean evaporation: $V_E = 630$ mm/a
- Mean temperature: $\theta = 8.5$ °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).
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From Ground Water to Mine Water

Environmental Hydrogeology in Mining

Dewatering methods; Recharge

Prof. Dr. Christian Wolkersdorfer

IMWA – General Secretary

From Ground Water to Mine Water

Contents

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

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Dewatering methods

Underground Mining

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

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Dewatering methods

Underground Mining

- Water table differences in different shafts
- Density of water

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

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

$h_1 = 100$ m

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

$\rho_2 = 1.223$ g 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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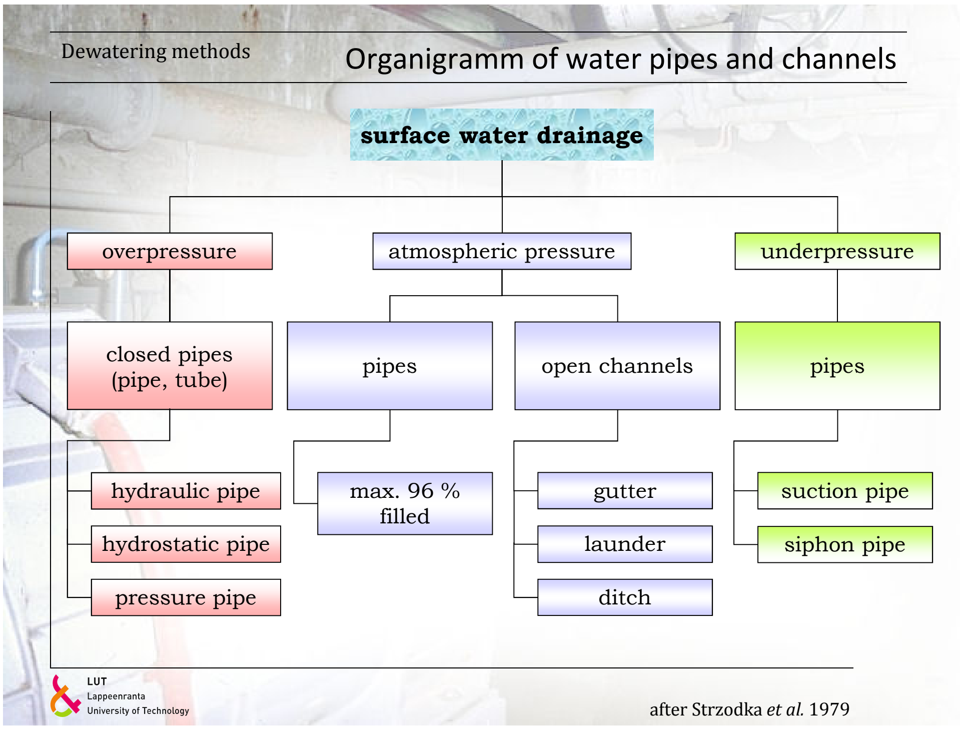
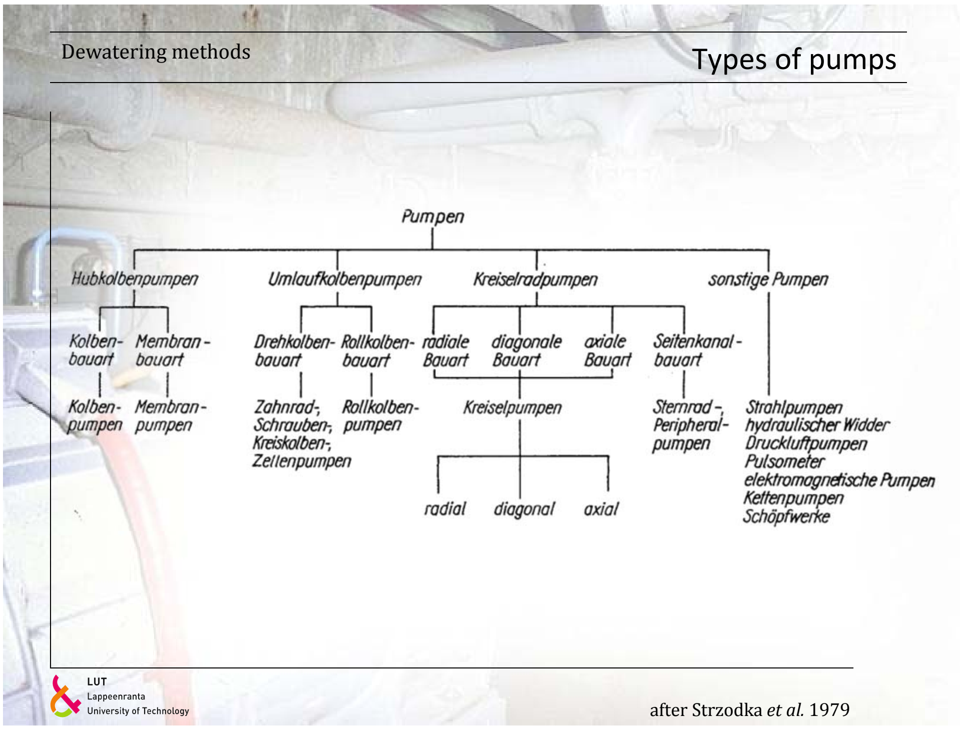
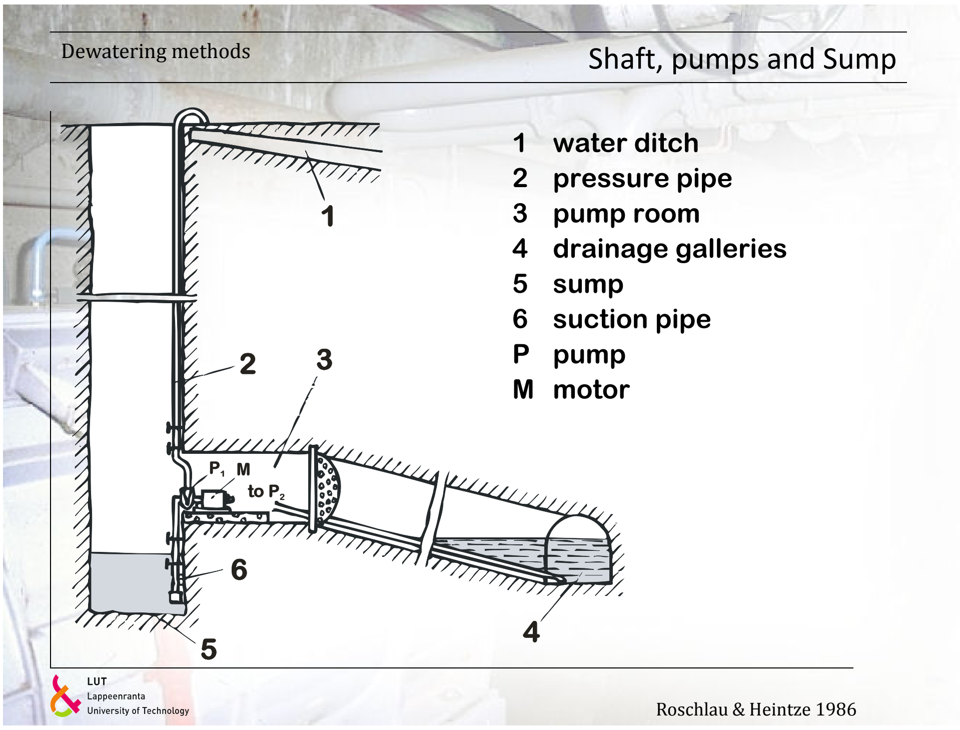
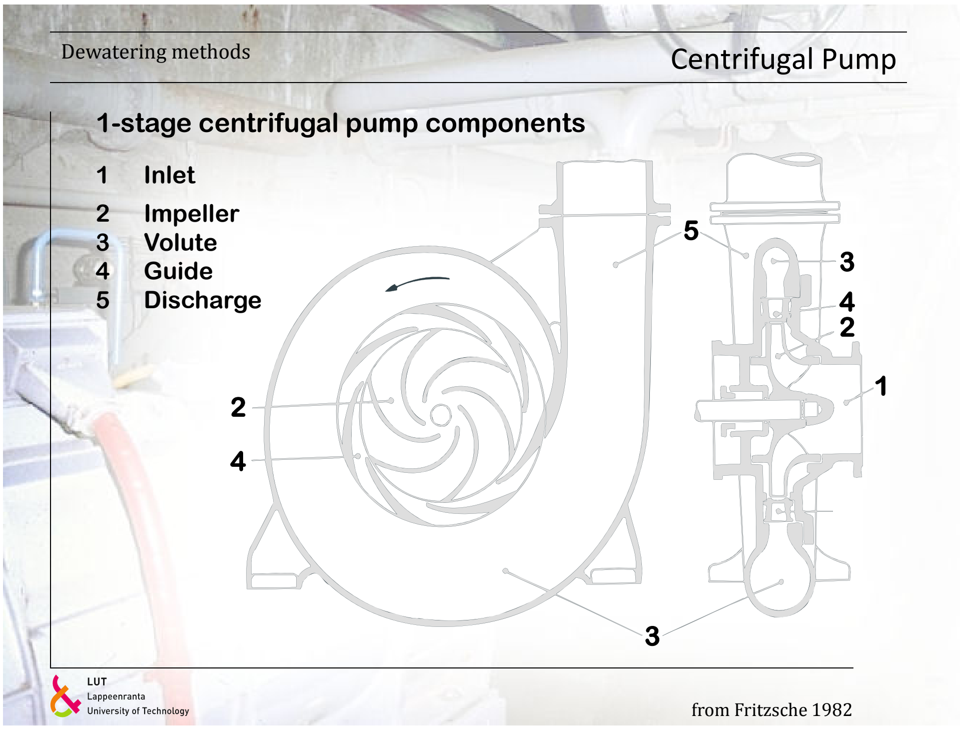

Dewatering methods
Organigramm of water pipes and channels
surface water drainage
overpressure
atmospheric pressure
underpressure
closed pipes (pipe, tube)
pipes
open channels
pipes
hydraulic pipe
hydrostatic pipe
pressure pipe
max. 96 % filled
gutter
launder
ditch
suction pipe
siphon pipe
LUT Lappeenranta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

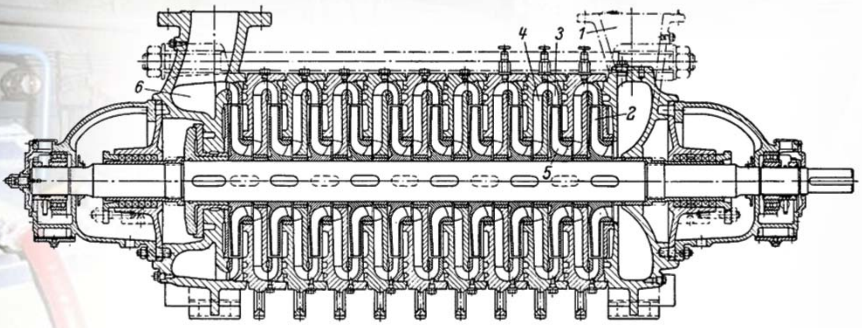

Dewatering methods
Types of pumps
Pumpen
Hubkolbenpumpen
Umlaufkolbenpumpen
Kreiselradpumpen
sonstige Pumpen
Kolben- bauart
Membran- bauart
Drehkolben- bauart
Rollkolben- bauart
radiale Bauart
diagonale Bauart
axiale Bauart
Seitenkanal- bauart
Kolben- pumpen
Membran- pumpen
Zahnrad-, Schrauben-, Kreiskolben-, Zellenpumpen
Rollkolben- pumpen
Kreiselpumpen
Sternrad-, Peripheral- pumpen
Strahlpumpen
hydraulischer Widder
Druckluftpumpen
Pulsometer
elektromagnetische Pumpen
Kettenpumpen
Schöpfwerke
radial
diagonal
axial
LUT Lappeenranta University of Technology
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
LUT Lappeenranta University of Technology
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
LUT Lappeenranta University of Technology
from Fritzsche 1982

Dewatering methods

Centrifugal Pump



10-stage centrifugal pump

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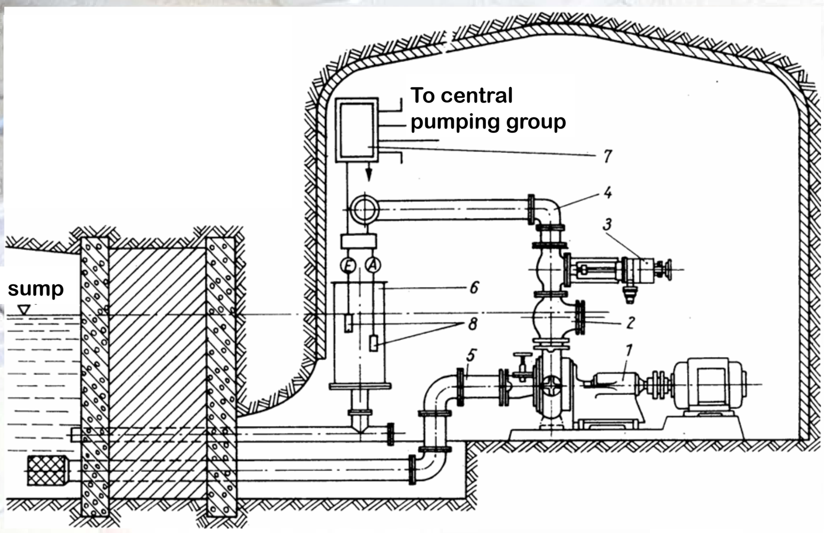
from Fritzsche 1982

Dewatering methods

Automatic Pumping Station



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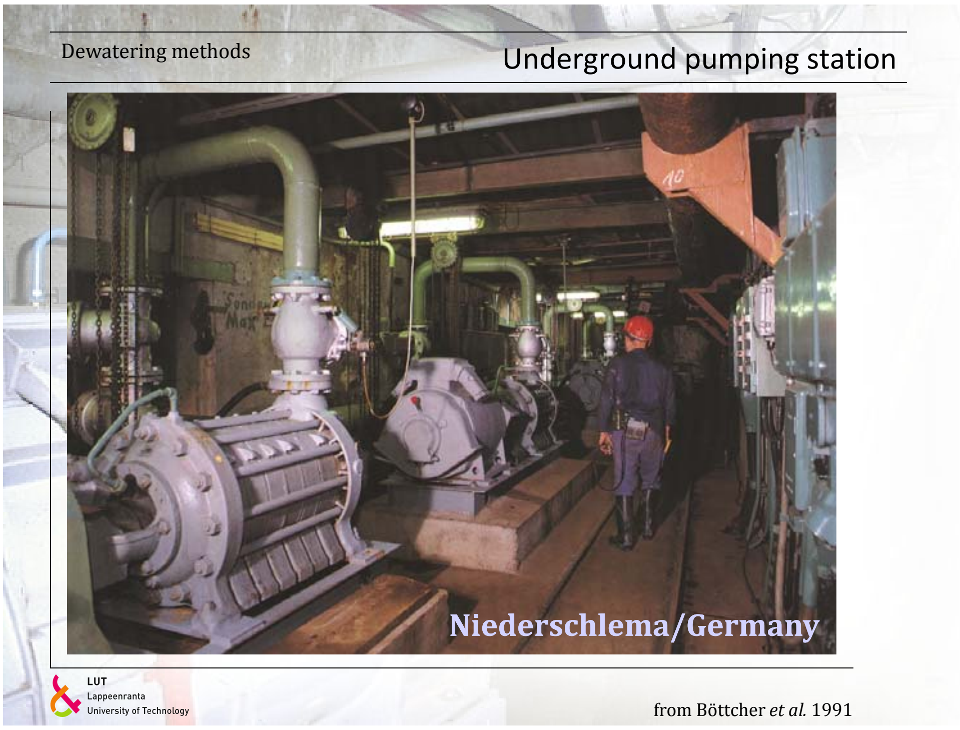
from Fritzsche 1982


Dewatering methods
Underground pumping station
Niederschlema/Germany
LUT
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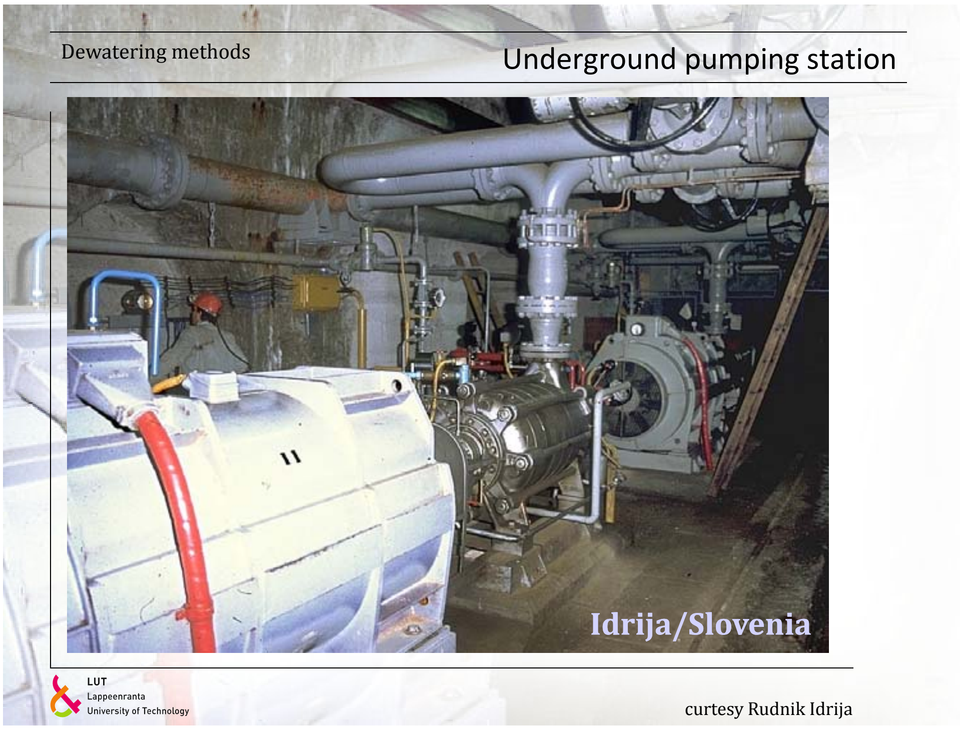
University of Technology
from Böttcher *et al.* 1991


Dewatering methods
Underground pumping station
Idrija/Slovenia
LUT
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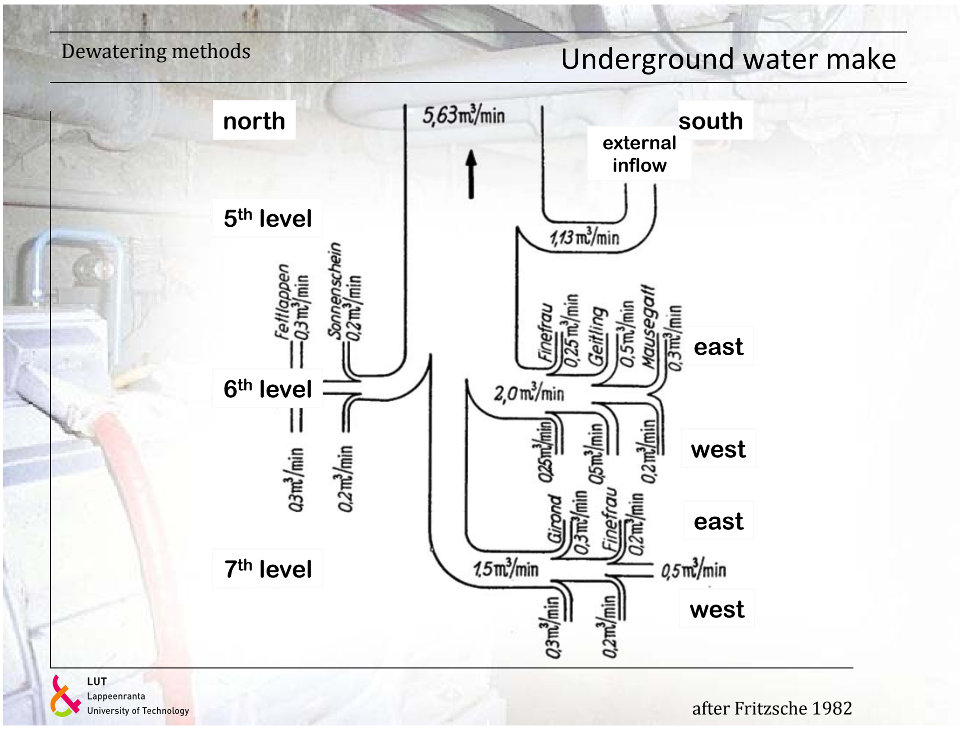
University of Technology
curtesy Rudnik Idrija


Dewatering methods
Underground water make
north
south
external inflow
5,63 m³/min
5th level
6th level
7th level
1,13 m³/min
Feltlappen
0,3 m³/min
Sonnenschein
0,2 m³/min
Finefrau
0,25 m³/min
Geitling
0,5 m³/min
Mausegatt
0,3 m³/min
east
west
east
west
2,0 m³/min
1,5 m³/min
0,5 m³/min
Girond
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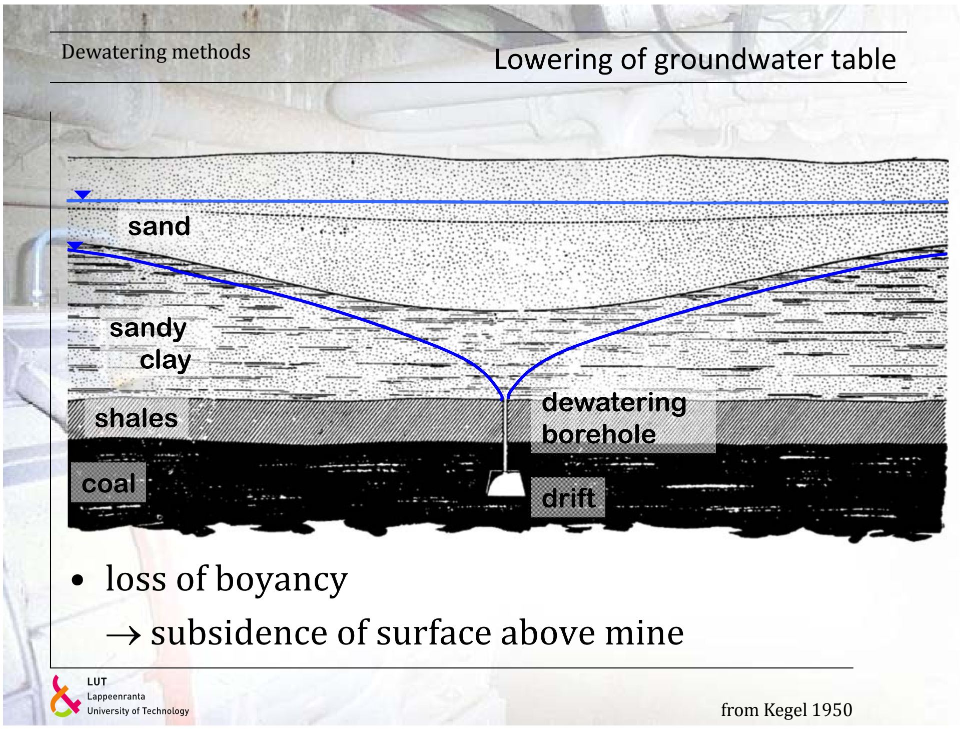
University of Technology
after Fritzsche 1982


Dewatering methods
Lowering of groundwater table
sand
sandy
clay
shales
coal
dewatering
borehole
drift
• loss of boyancy
→ subsidence of surface above mine
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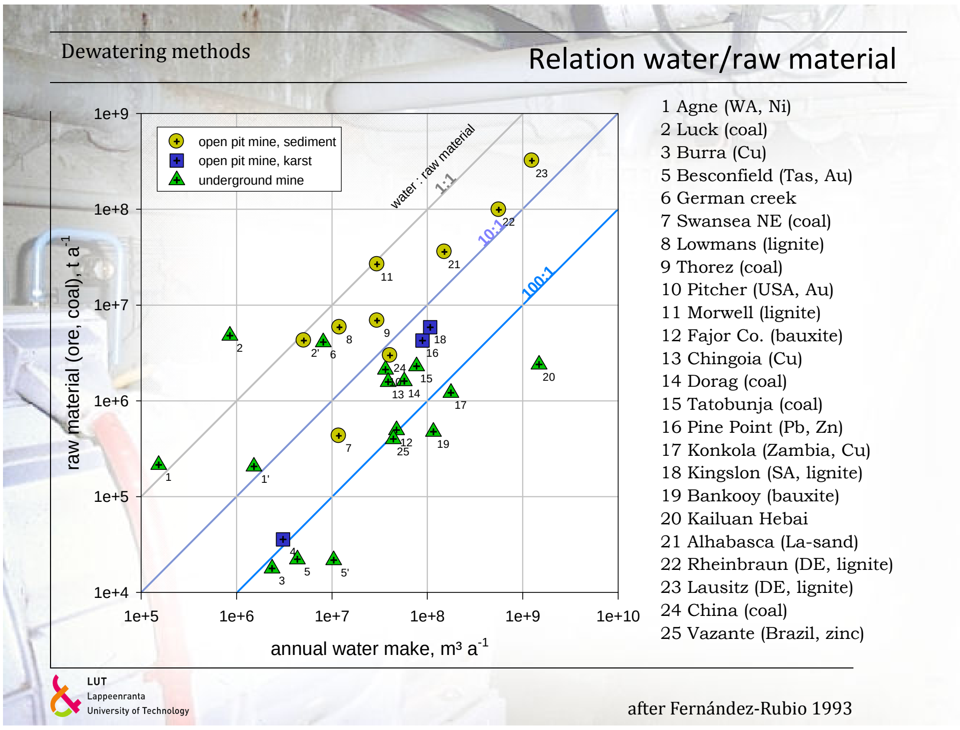
University of Technology
from Kegel 1950


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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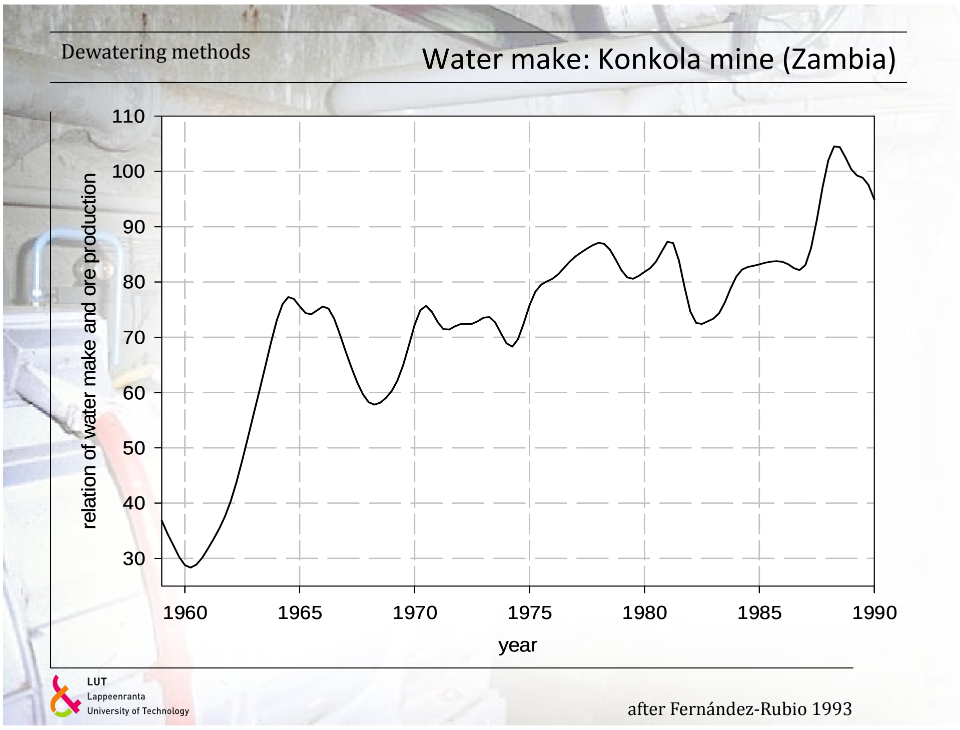
after Fernández-Rubio 1993


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
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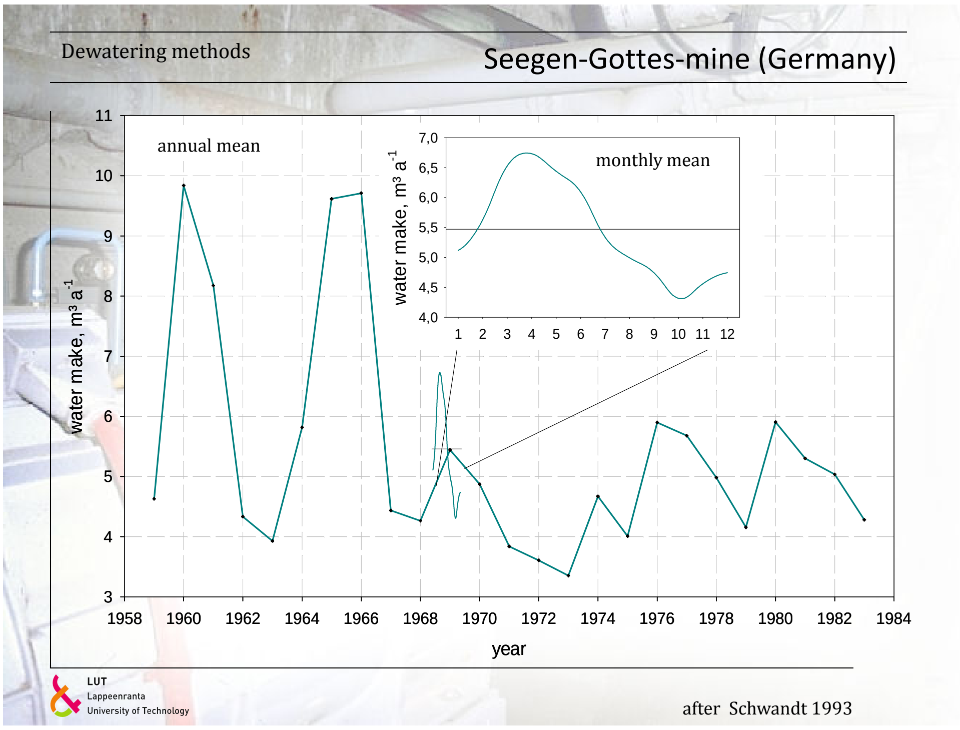
after Fernández-Rubio 1993


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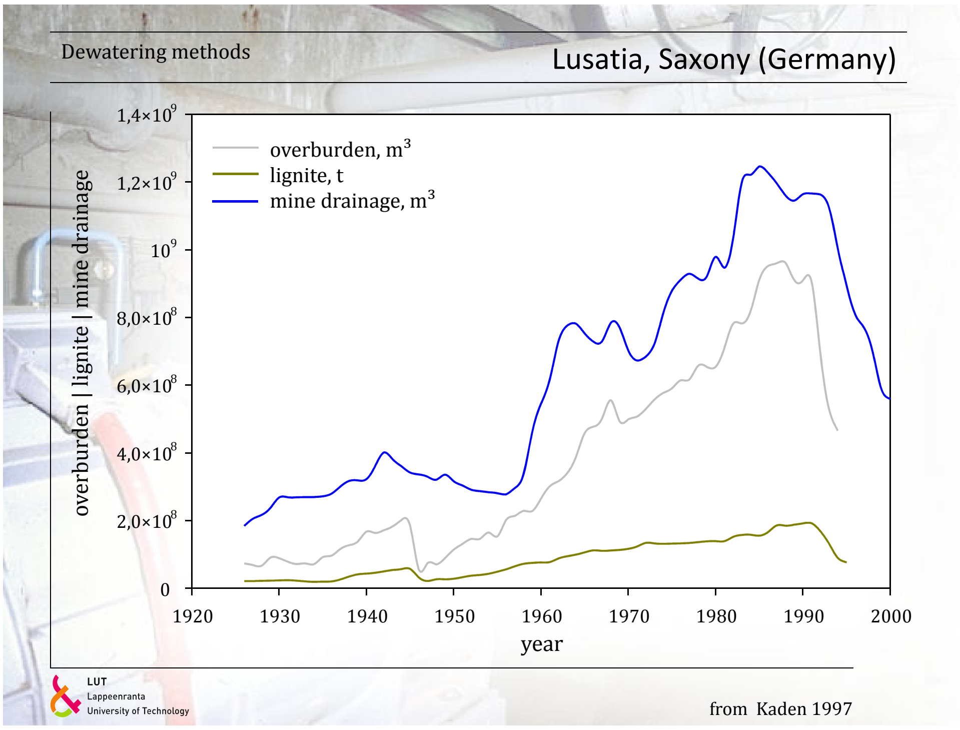
after Schwandt 1993


Dewatering methods
Lusatia, Saxony (Germany)
overburden, m³
lignite, t
mine drainage, m³
overburden | lignite | mine drainage
year
LUT
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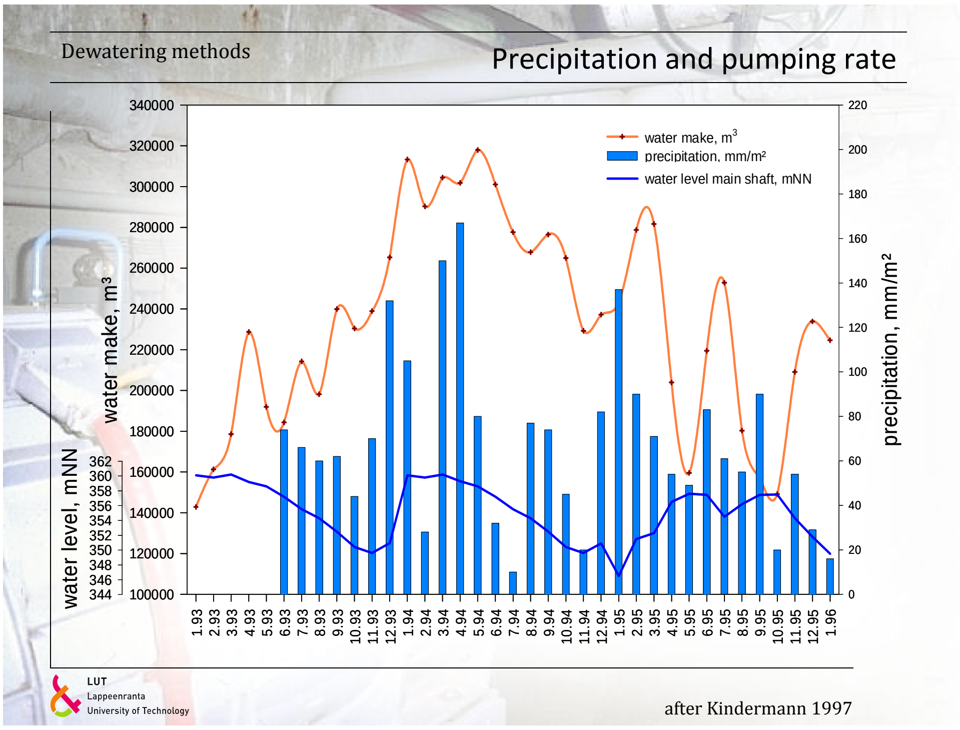
University of Technology
from Kaden 1997


Dewatering methods
Precipitation and pumping rate
water make, m³
precipitation, mm/m²
water level main shaft, mNN
water level, mNN
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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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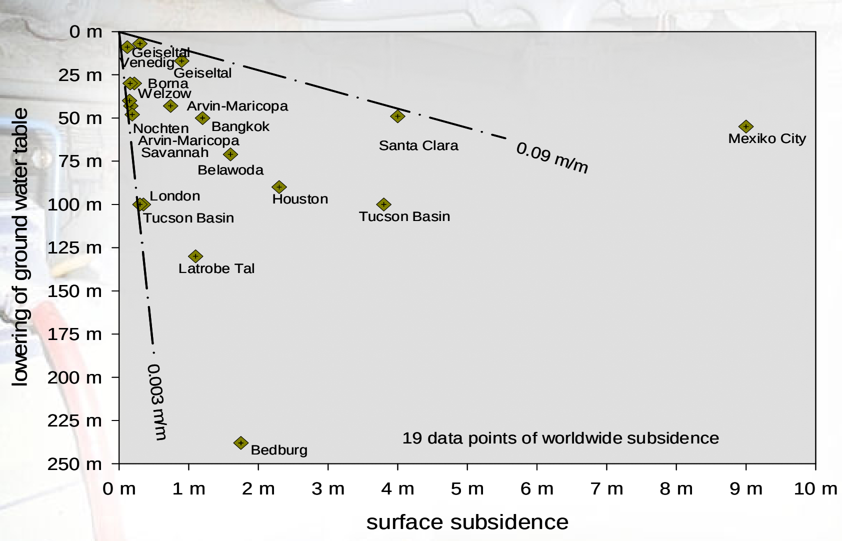
Roncourt/Lorraine 2005

Subsidence

Worldwide subsidence



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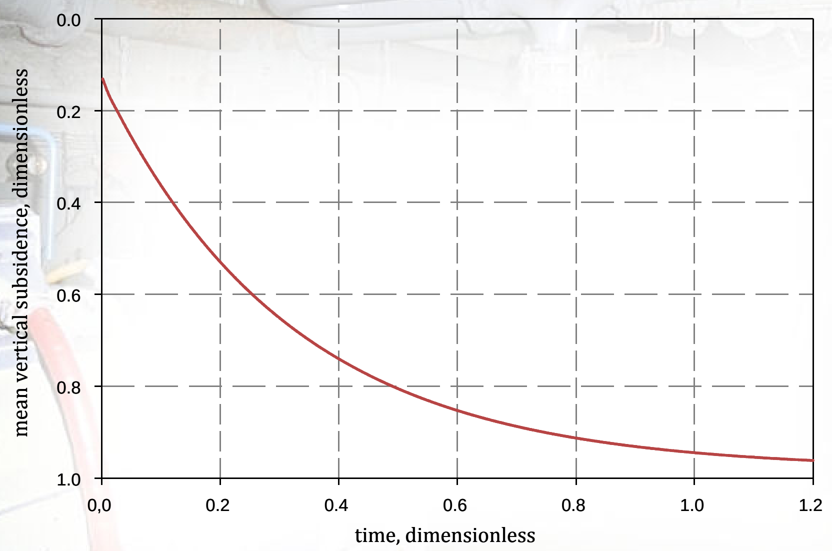
Wolkersdorfer & Thiem 1999

Subsidence

Terzaghi's Consolidation Theory



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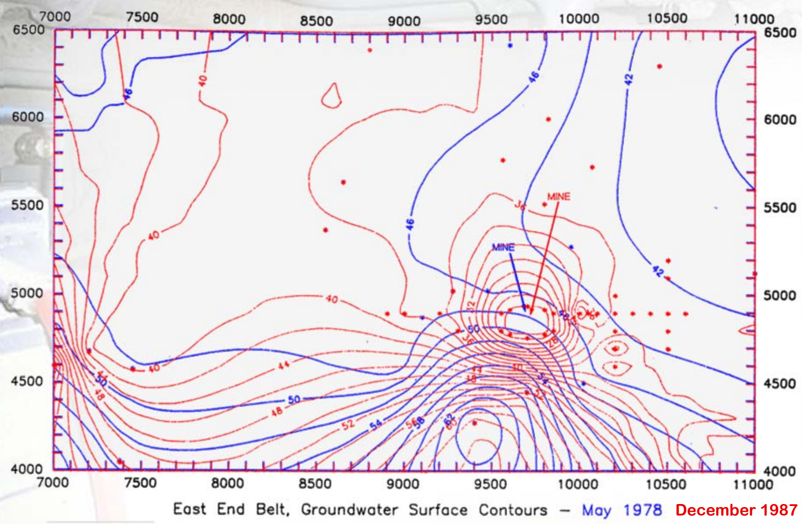
Terzaghi 1929

Subsidence

Open cast mine: ground water withdrawal



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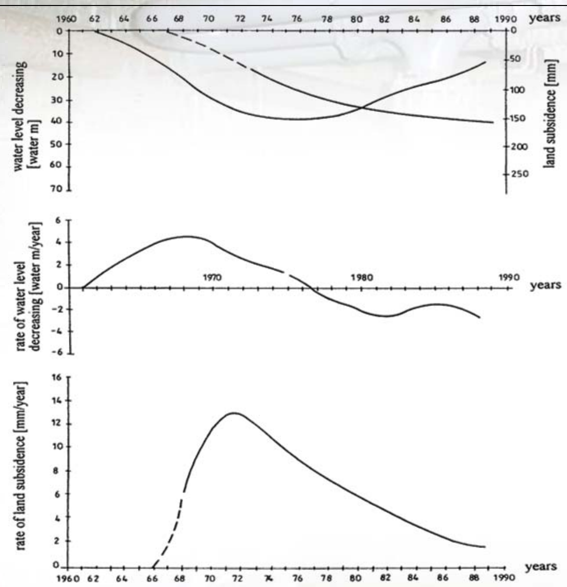
after Dudgeon 1994

Subsidence

Matraalia: Ground Water Withdrawal



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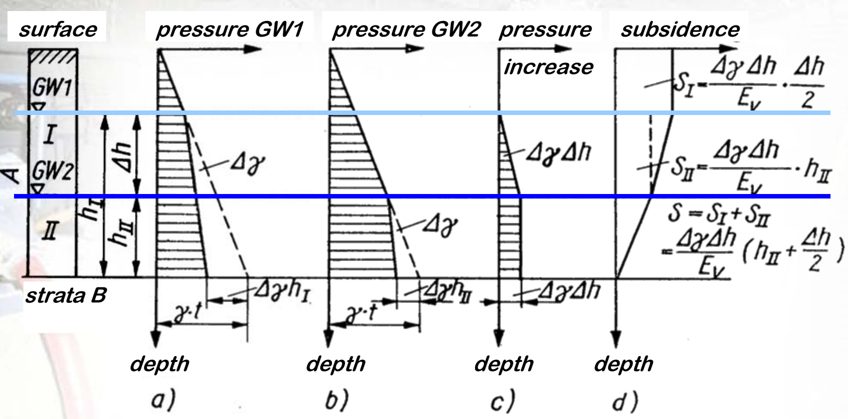
from Jambrik 1995

Subsidence

Ground Water Withdrawal: Subsidence



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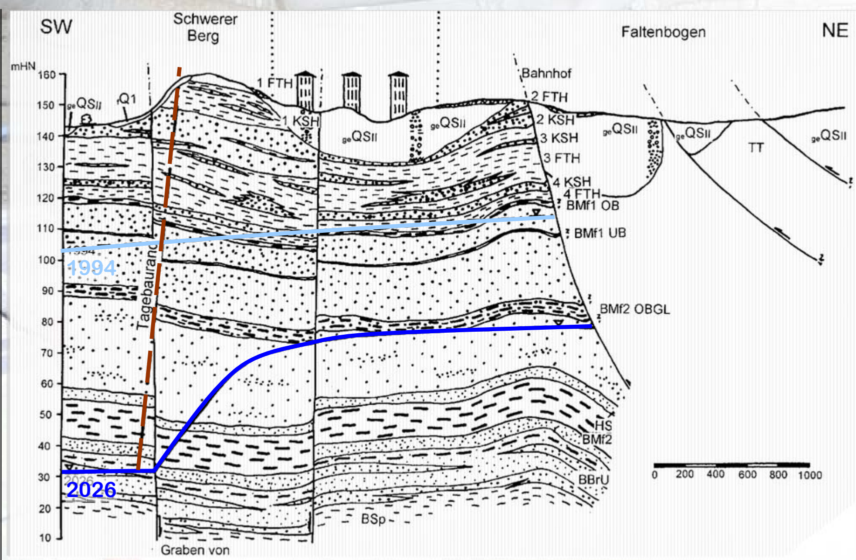
after Strzodka *et al.* 1979

Subsidence

Nochten/Lusatia: Geological Cross Section



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Subsidence

Nochten/Lusatia: Soil Parameters

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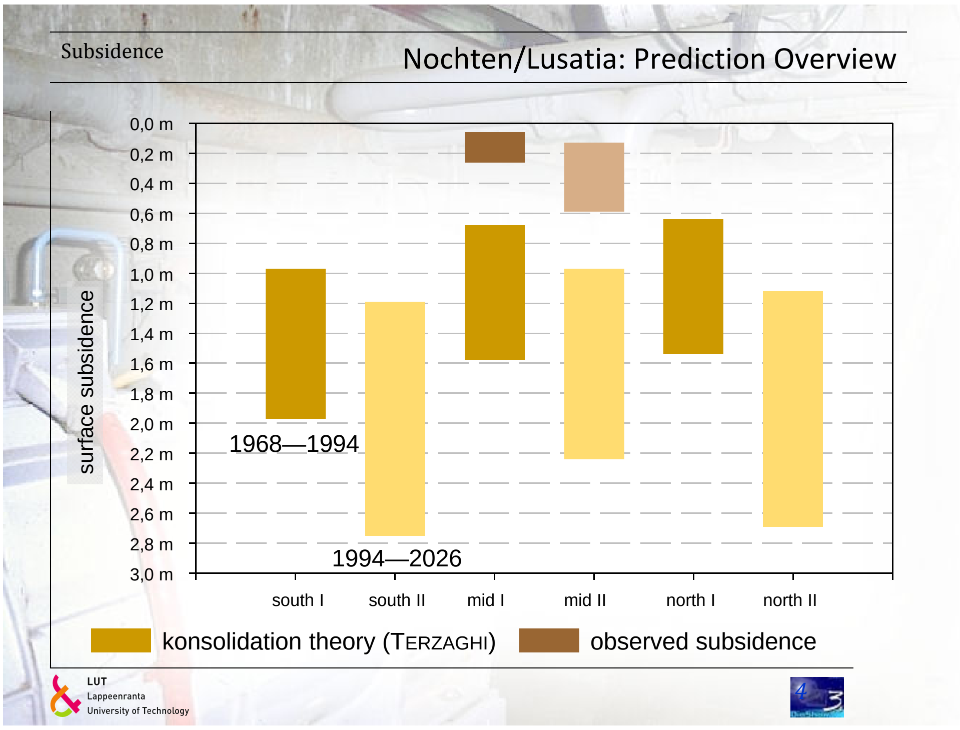
Subsidence
Nochten/Lusatia: Prediction Overview
surface subsidence
0,0 m
0,2 m
0,4 m
0,6 m
0,8 m
1,0 m
1,2 m
1,4 m
1,6 m
1,8 m
2,0 m
2,2 m
2,4 m
2,6 m
2,8 m
3,0 m
1968—1994
1994—2026
south I
south II
mid I
mid II
north I
north II
konsolidation theory (TERZAGHI)
observed subsidence
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From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

Environmental Hydrogeology in Mining

Mine Flooding

Prof. Dr. Christian Wolkersdorfer

IMWA – General Secretary

From Ground Water to Mine Water

Contents

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Mine Flooding

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

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
  - Laminar flow
- Numerical (partly geochemical)
  - GRAM
  - SHETRAN
  - Monte Carlo
  - CFD
  - FEFLOW
  - MODFLOW
  - EPA NET
  - CE-QUAL-W2
  - GOLDSIM
  - VULCAN

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Mine Flooding

Catastrophical mine water inundations

1815
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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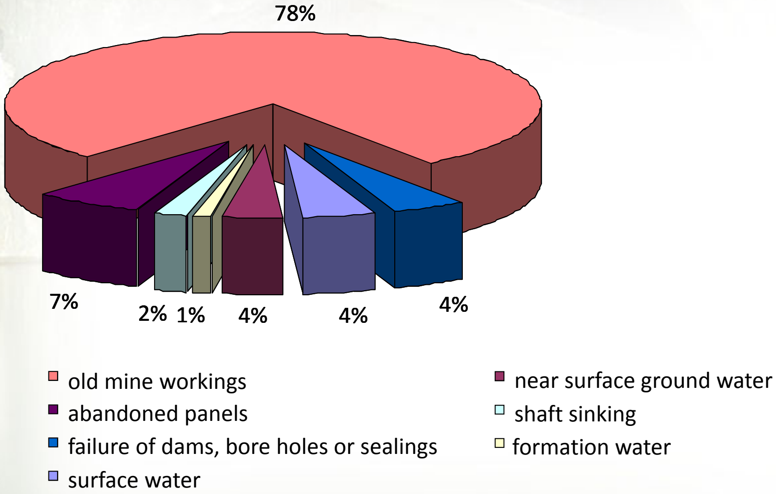
Vutukuri & Singh 1995

Mine Flooding

Reasons for mine inundation



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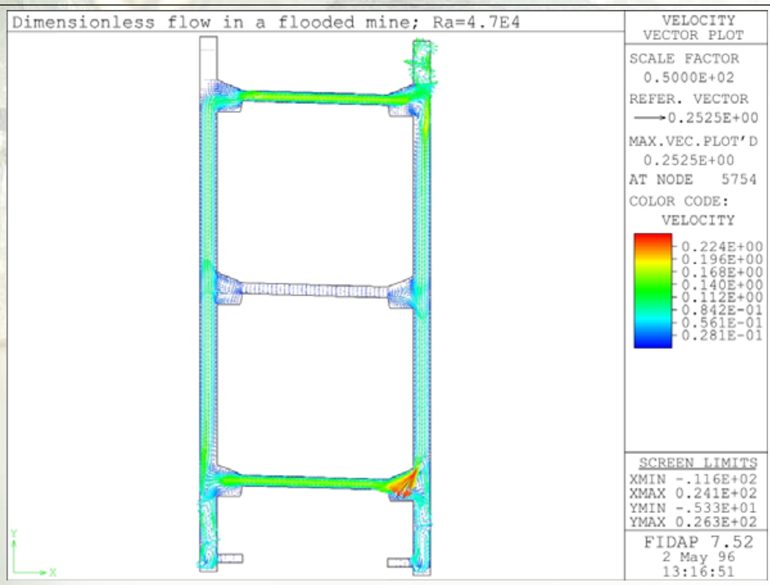
Job 1987; Vutukuri & Singh 1995

Mine Flooding

CFD-Modell (Velocity Plot)



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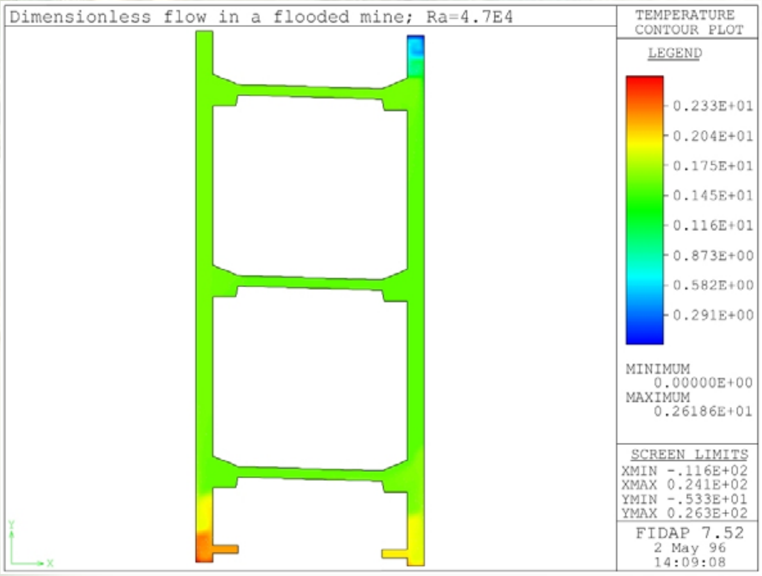
Wolkersdorfer & Trebušak

Mine Flooding

CFD-Modell (Temperature Plot)



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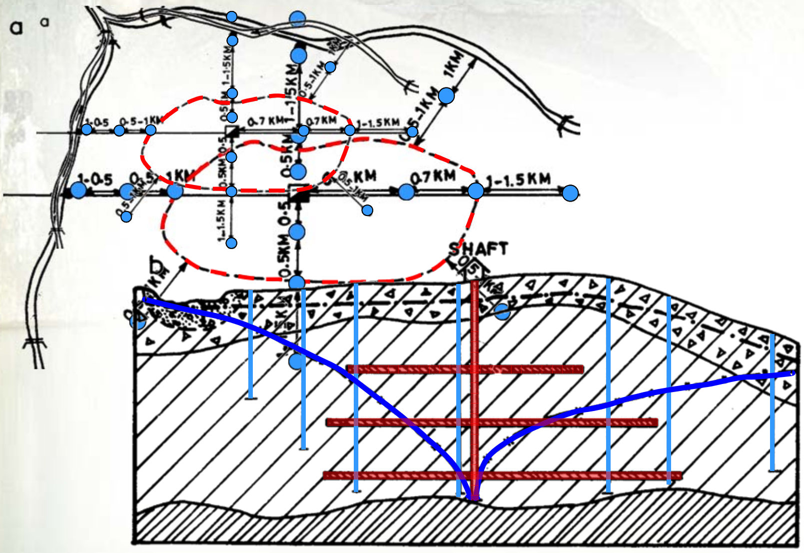
Wolkersdorfer & Trebušak

Mine Flooding

Monitoring Bore Holes around a Mine



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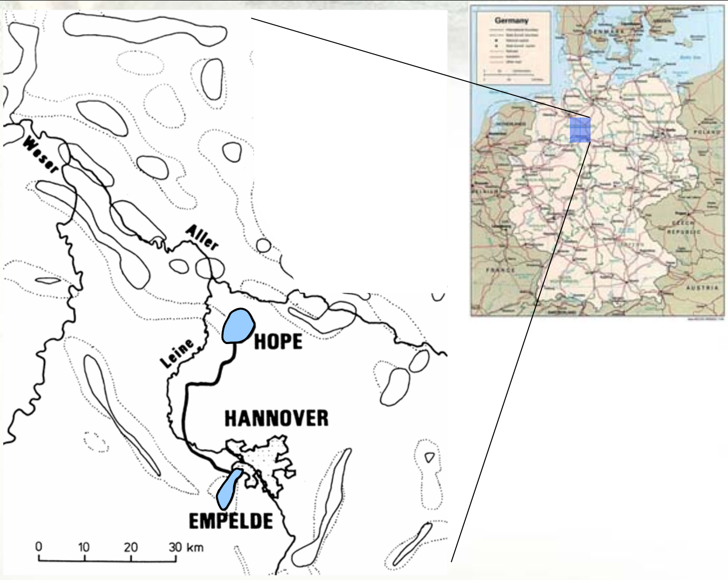
Plotnikov & Rogintes 1989

Mine Flooding

Hope/Germany: Topography



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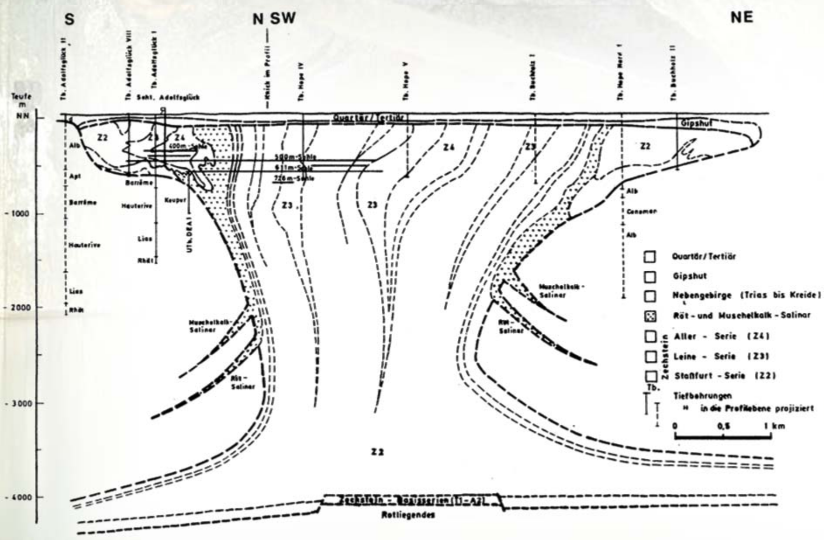
from GSF 1985

Mine Flooding

Hope/Germany: Geological Profile



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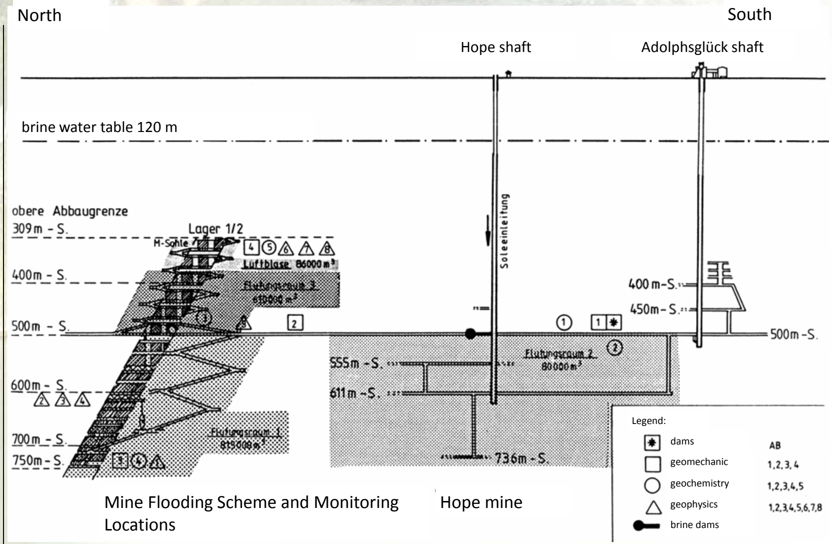
from GSF 1985

Mine Flooding

Hope/Germany: Flooding Scheme



Mine Flooding Scheme and Monitoring Locations

Hope mine

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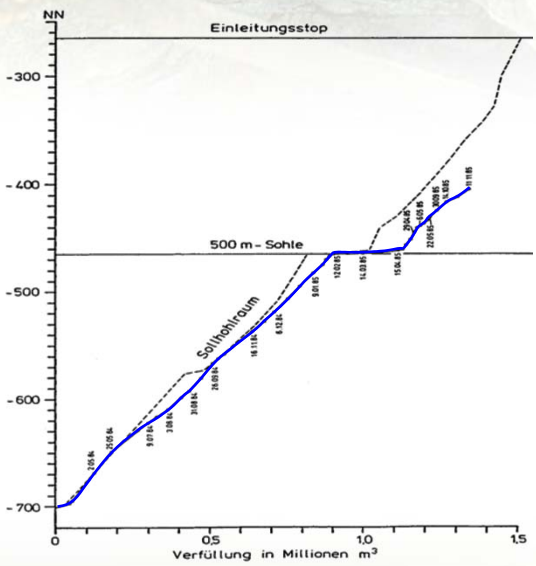
from Flach & Heick 1986

Mine Flooding

Hope/Germany: Raise of Mine Water Table



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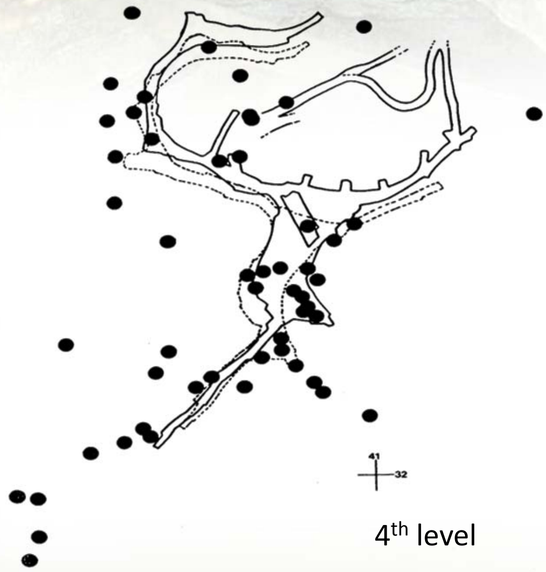
from GSF 1986

Mine Flooding

Hope/Germany: Rockbursts



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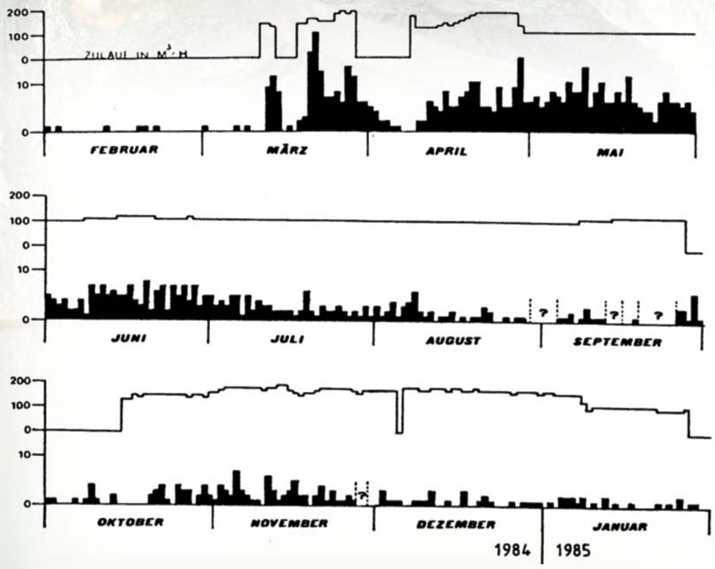
from Flach & Heick 1986

Mine Flooding

Hope/Germany: Rock Bursts



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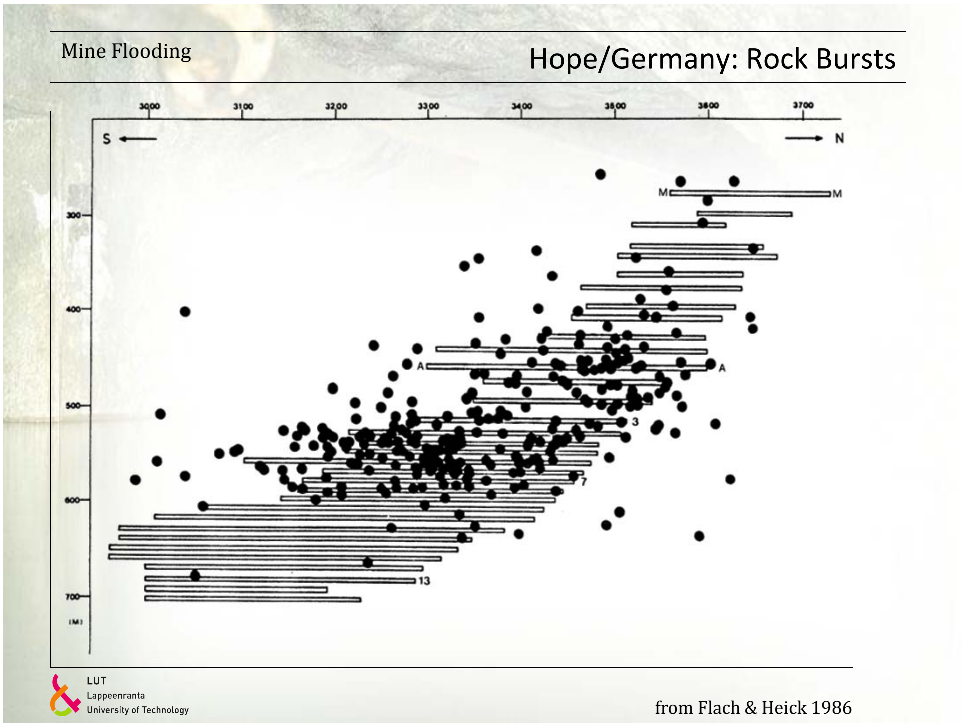
from Flach & Heick 1986


Mine Flooding
Hope/Germany: Rock Bursts
3000
3100
3200
3300
3400
3500
3600
3700
S
N
300
400
500
600
700
(M)
M
A
3
7
13
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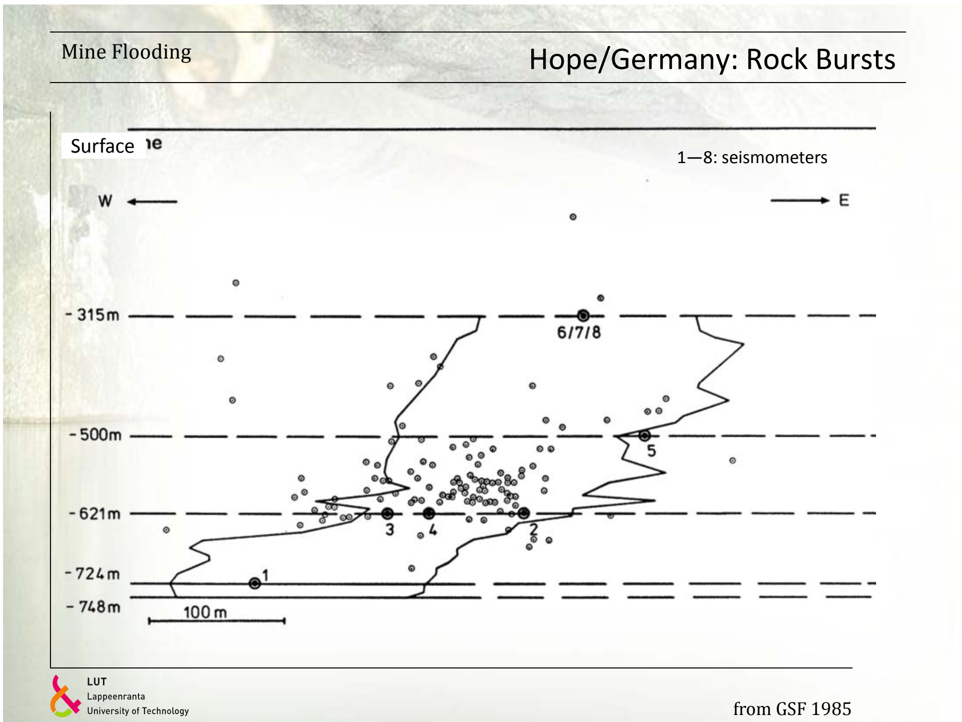
University of Technology
from Flach & Heick 1986


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
LUT
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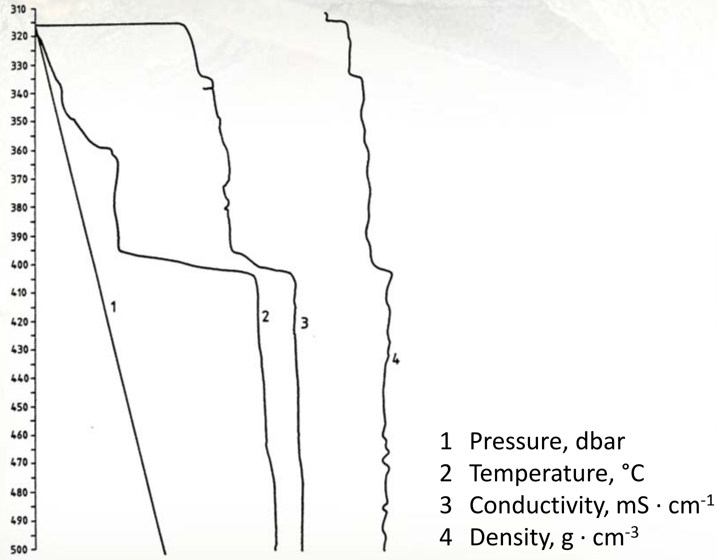
University of Technology
from GSF 1985

Mine Flooding

Hope/Germany

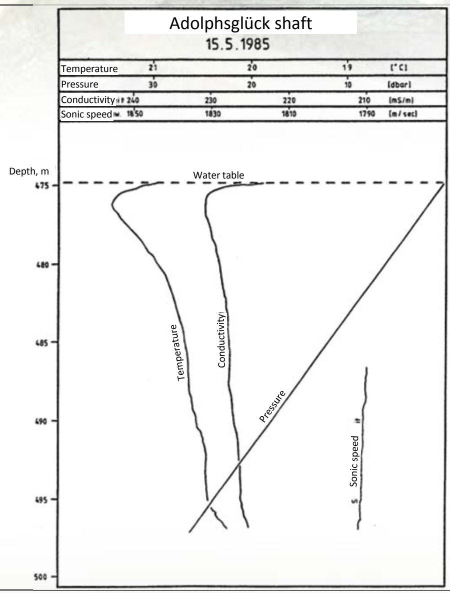


LUT Lappeenranta University of Technology

from Herbert 1989

Mine Flooding

Hope/Germany



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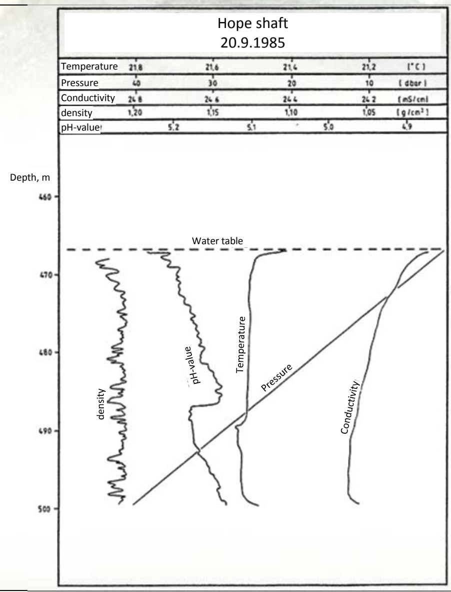
from GSF 1986

Mine Flooding

Hope/Germany



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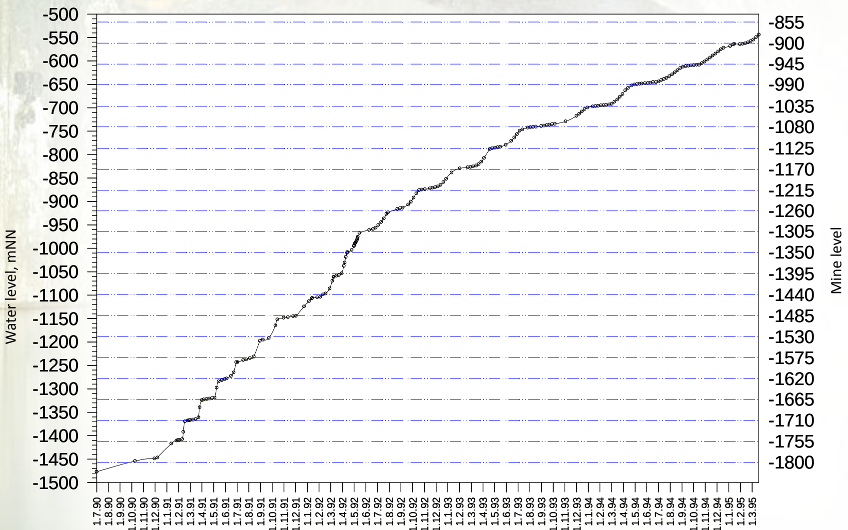
from GSF 1986

Mine Water Rebound

Niederschlema: Raise of Mine Water Table



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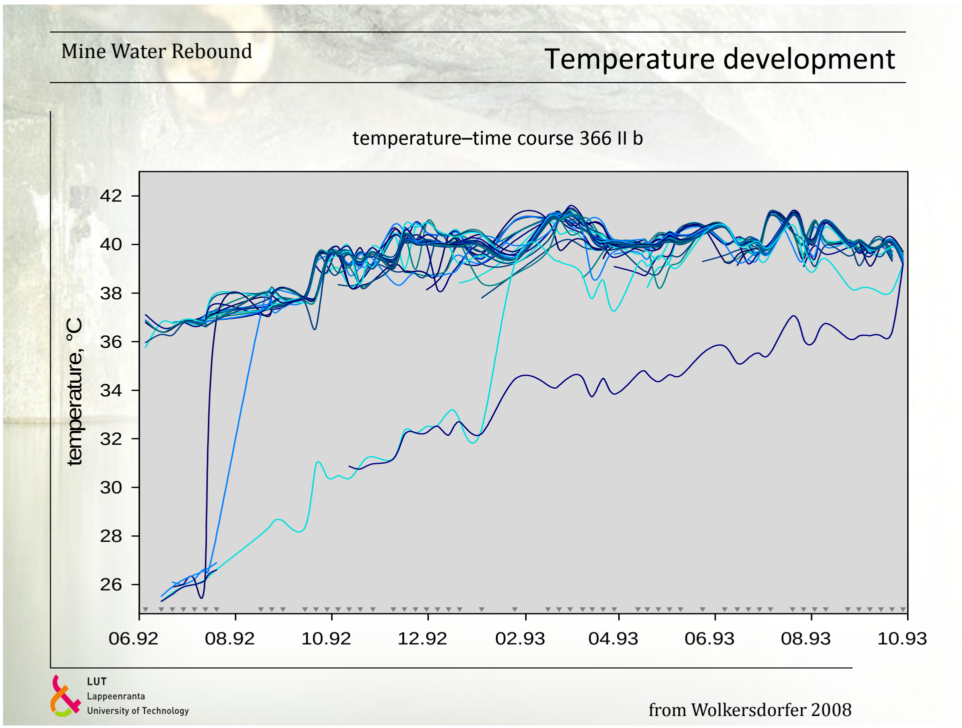
from Wolkersdorfer 1995


Mine Water Rebound
Temperature development
temperature–time course 366 II b
temperature, °C
42
40
38
36
34
32
30
28
26
06.92
08.92
10.92
12.92
02.93
04.93
06.93
08.93
10.93
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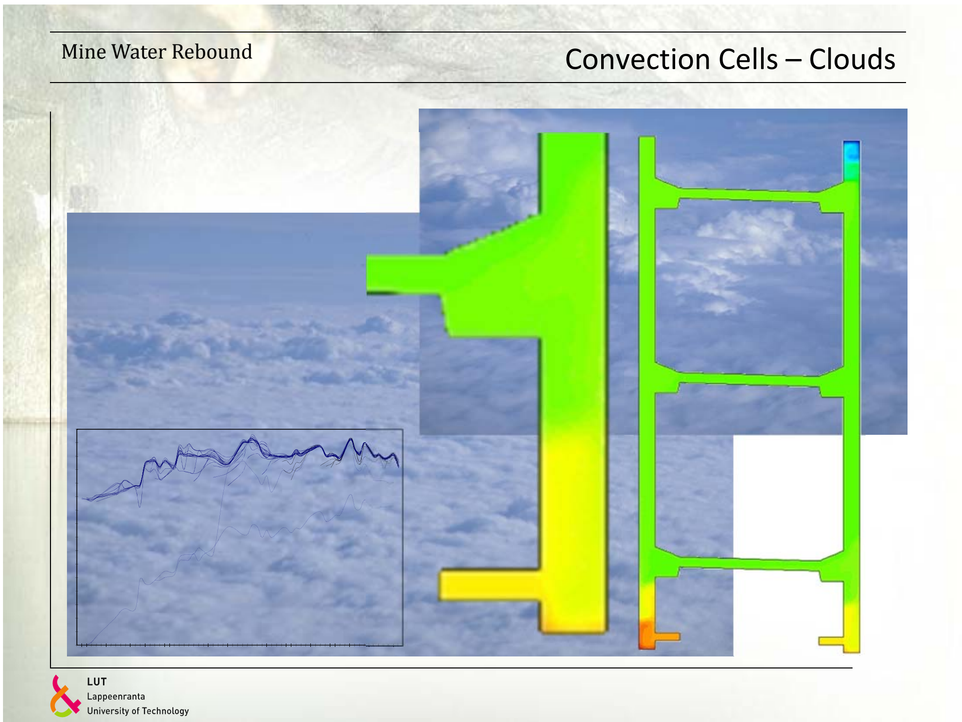
from Wolkersdorfer 2008


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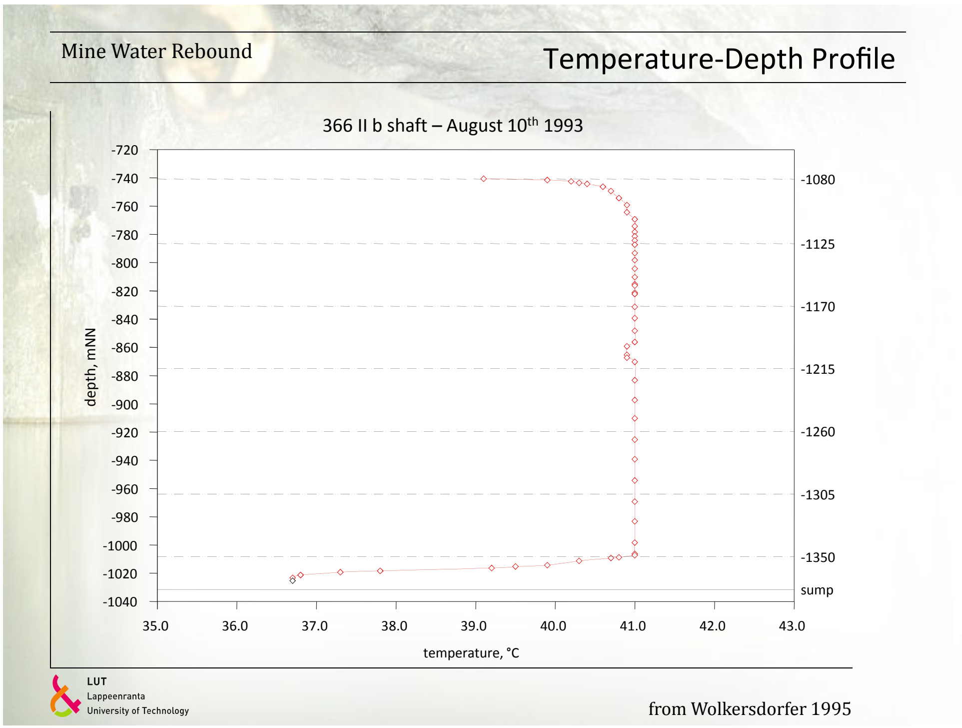
Mine Water Rebound
Temperature-Depth Profile
366 II b shaft – August 10th 1993
depth, mNN
-720
-740
-760
-780
-800
-820
-840
-860
-880
-900
-920
-940
-960
-980
-1000
-1020
-1040
-1080
-1125
-1170
-1215
-1260
-1305
-1350
sump
35.0
36.0
37.0
38.0
39.0
40.0
41.0
42.0
43.0
temperature, °C
LUT
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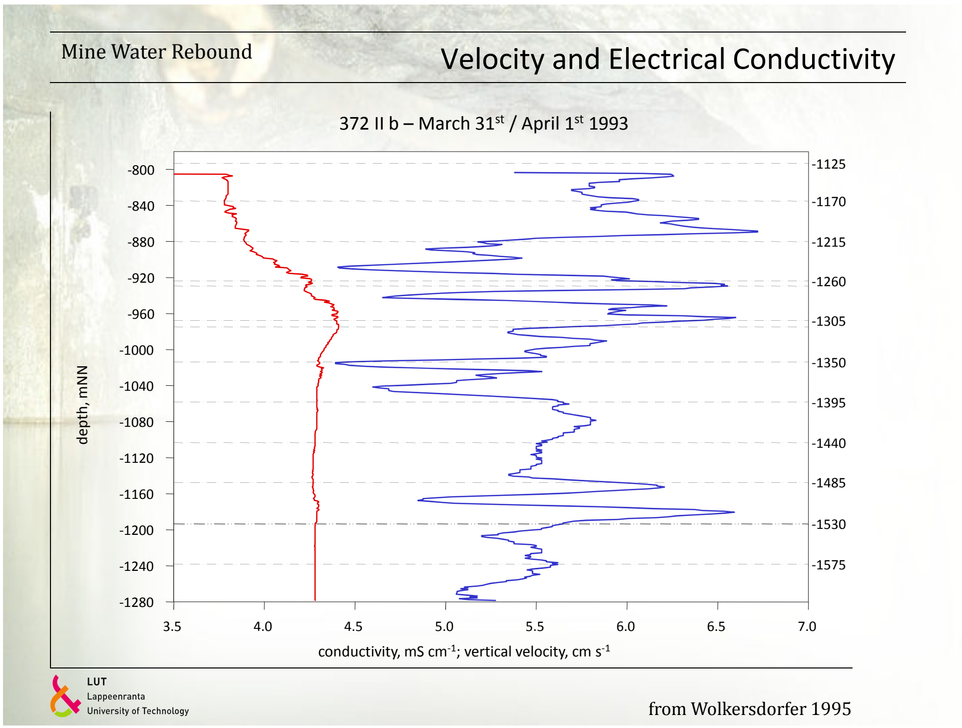
from Wolkersdorfer 1995


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
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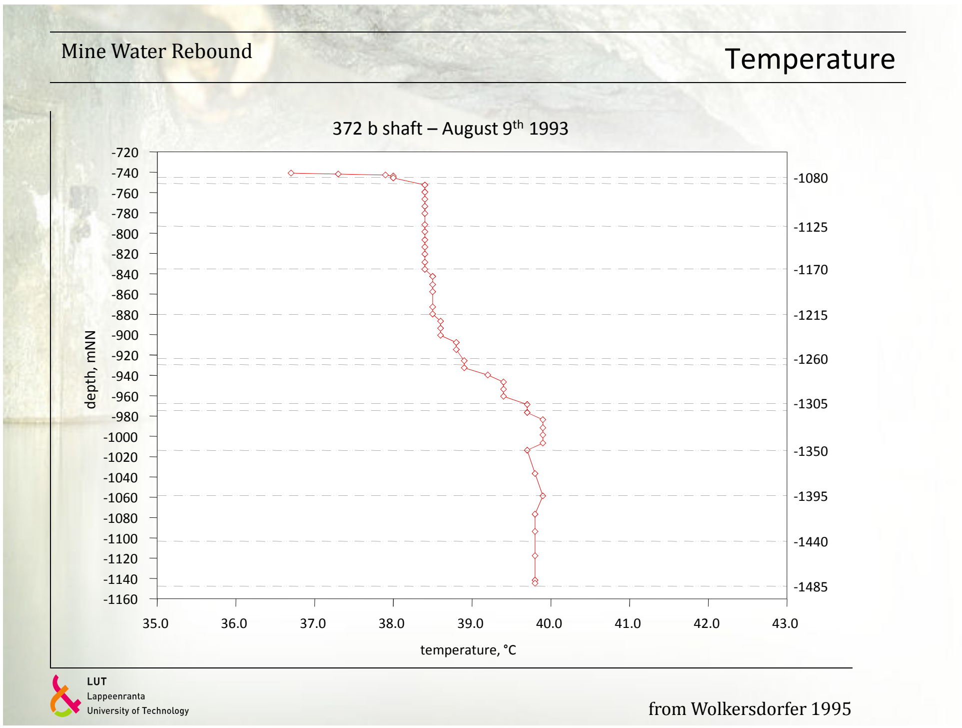
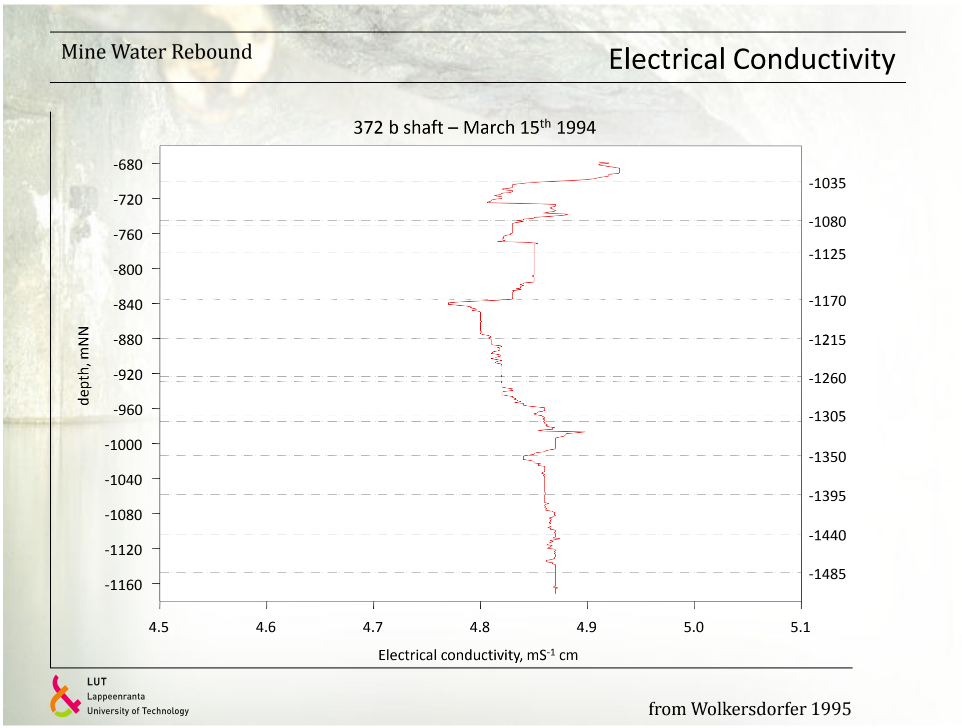
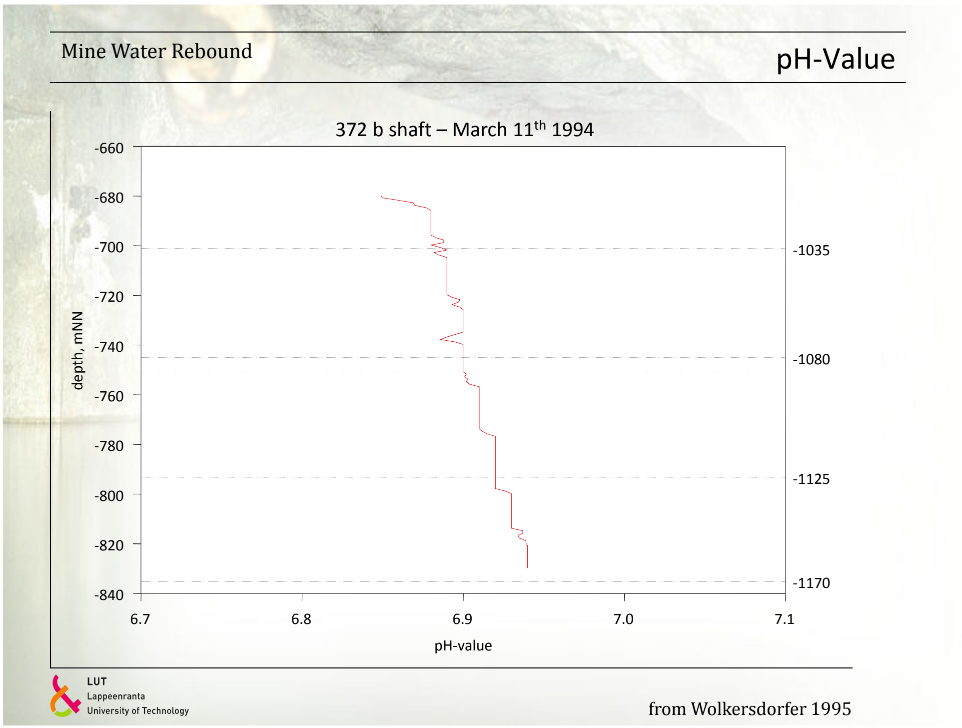
from Wolkersdorfer 1995


Mine Water Rebound
Temperature
372 b shaft – August 9th 1993
depth, mNN
temperature, °C
LUT Lappeenranta University of Technology
from Wolkersdorfer 1995


Mine Water Rebound
Electrical Conductivity
372 b shaft – March 15th 1994
depth, mNN
Electrical conductivity, mS-1 cm
LUT Lappeenranta University of Technology
from Wolkersdorfer 1995


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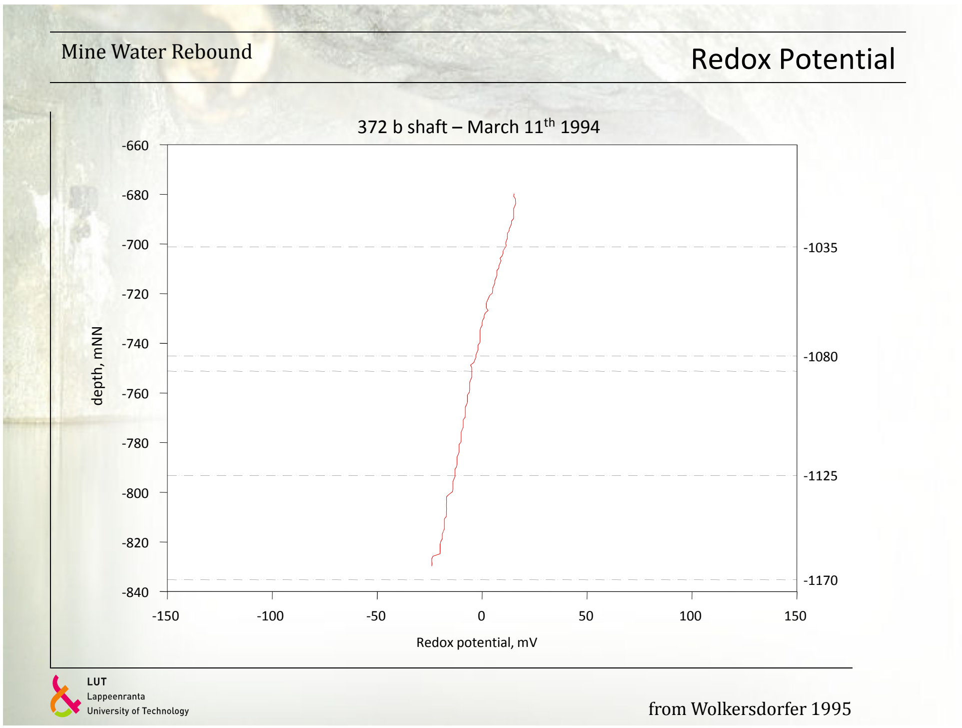
Mine Water Rebound
Redox Potential
372 b shaft – March 11th 1994
-660
-680
-700
-720
-740
-760
-780
-800
-820
-840
depth, mNN
-1035
-1080
-1125
-1170
-150
-100
-50
0
50
100
150
Redox potential, mV
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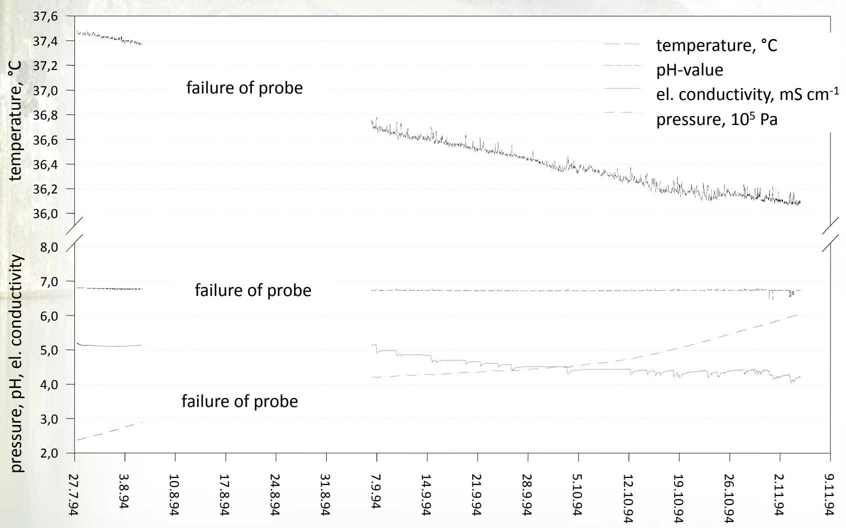
from Wolkersdorfer 1995

Mine Water Rebound

Raise of Mine Water Table



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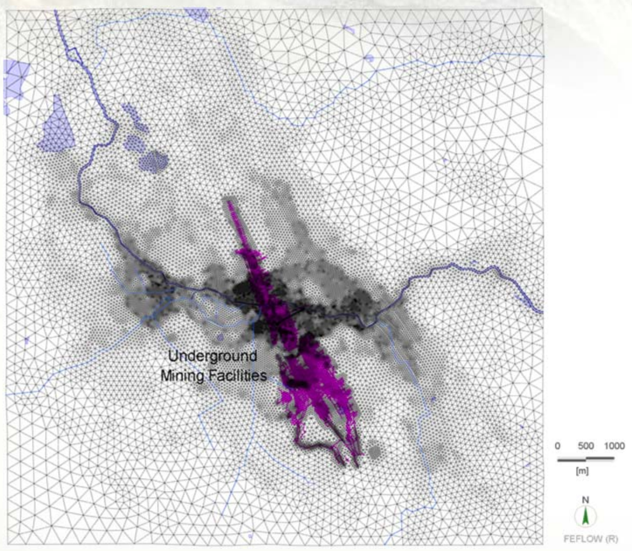
from Wolkersdorfer 1995

Mine Water Rebound

Modelling with FEFLOW



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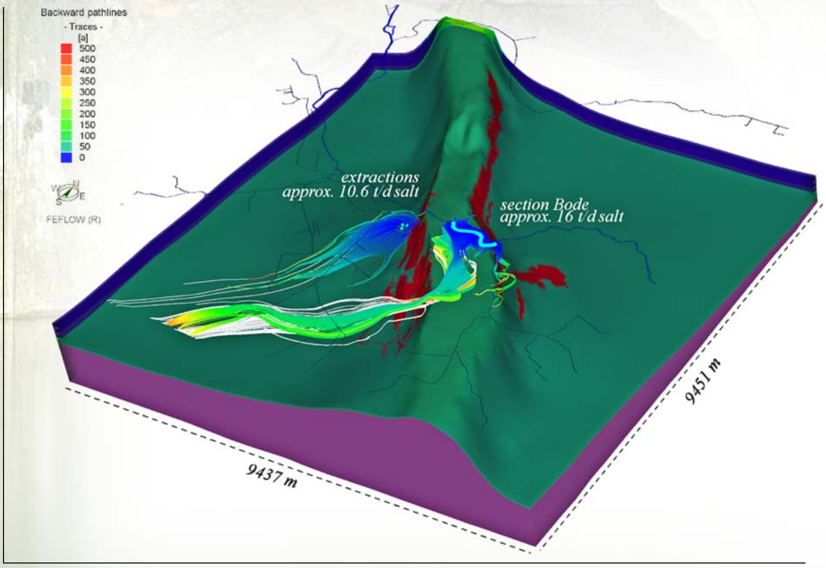
from Luo *et al.* 2012: 3D Modeling of Saline Groundwater Flow and Transport in a Flooded Salt Mine in Stassfurt, Germany. – "Mine Water and the Environment"

Mine Water Rebound

Modelling with FEFLOW



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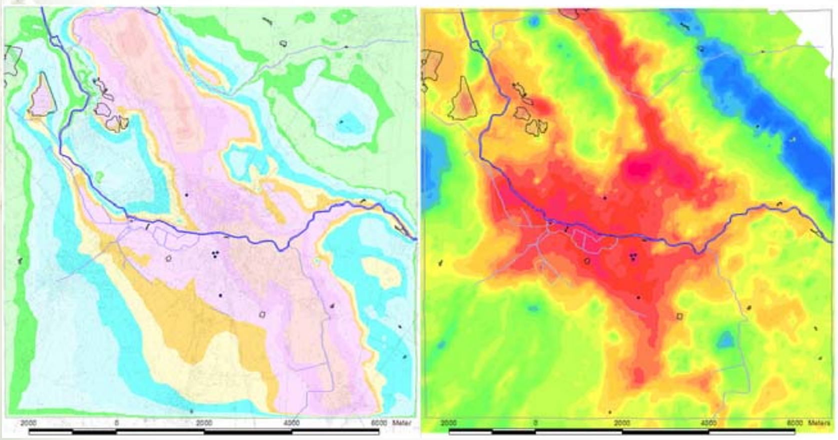
from Luo *et al.* 2012

Mine Water Rebound

Modelling with FEFLOW

Comparison of calculated salt concentrations in the Quaternary aquifer (left) with results of measured electrical conductivity by helicopter electro-magnetics (right)



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from Luo *et al.* 2012

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 (云村)

IMWA – General Secretary

From Ground Water to Mine Water

Contents

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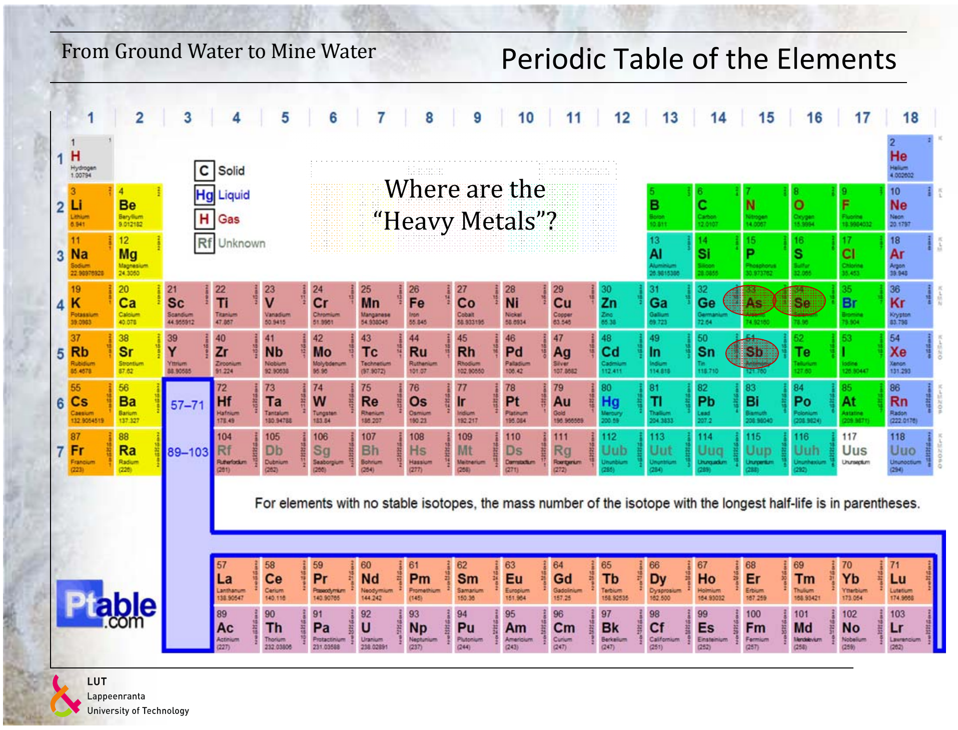
From Ground Water to Mine Water
Periodic Table of the Elements
Where are the
"Heavy Metals"?
C Solid
Hg Liquid
H Gas
Rf Unknown
57–71
89–103
For elements with no stable isotopes, the mass number of the isotope with the longest half-life is in parentheses.
Ptable.com
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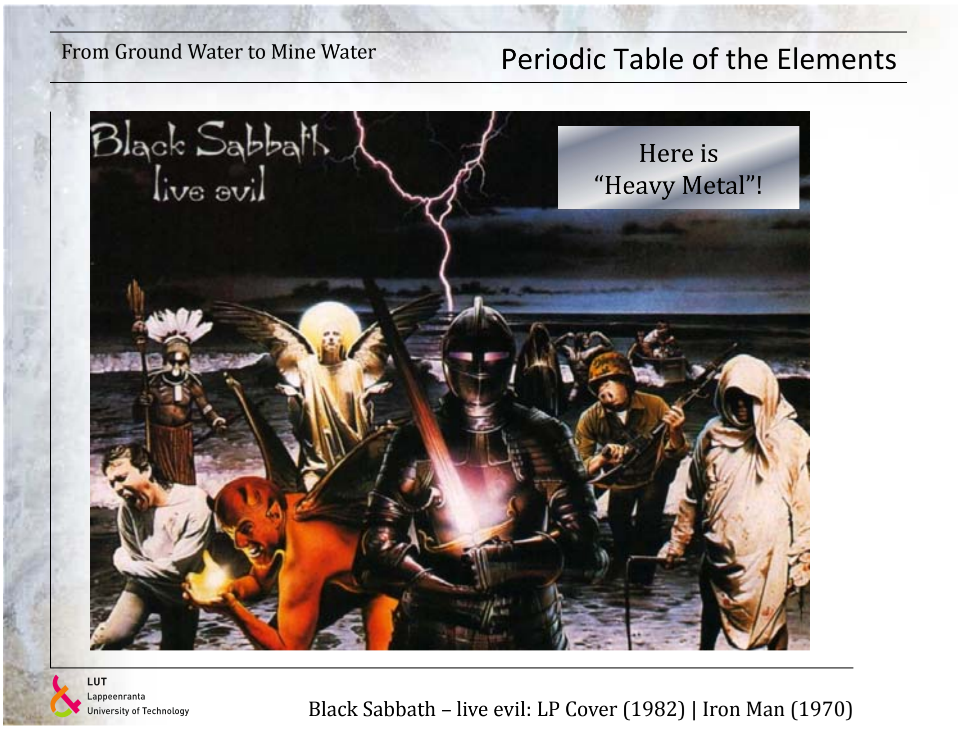
From Ground Water to Mine Water
Periodic Table of the Elements
Black Sabbath
live evil
Here is
"Heavy Metal"!
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Black Sabbath – live evil: LP Cover (1982) | Iron Man (1970)

Mine Water Geochemistry

Why to deal with mine water chemistry?

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Cape Breton Island/Canada: Mine Water Outfall

Mine Water Geochemistry

Why to deal with mine water chemistry?

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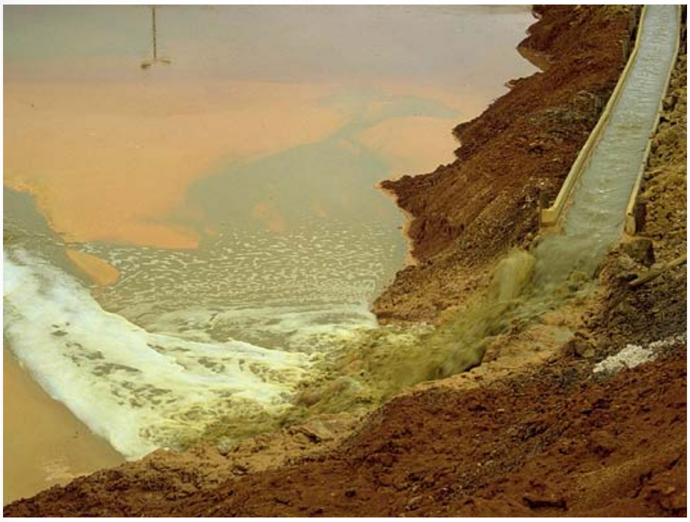
Eagle Picher Superfund Site/USA: Mark R. Boardman

Mine Water Geochemistry

Why to deal with mine water chemistry?



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Former Königstein Uranium Mine / Saxony

Mine Water Geochemistry

Why to deal with mine water chemistry?

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Pfunderer Berg/Southern Tyrol: Armin Hanneberg

Mine Water Geochemistry

Why to deal with mine water chemistry?

Georgi Unterbau / Tyrol

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Mine Water Geochemistry

Why to deal with mine water chemistry?

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

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Mine Water Geochemistry

Factors to be taken into Account

- Source — Pathway — Target-Concept
- Type of mine water
  - AMD: acid mine drainage (< ≈ pH 6)
  - ND: neutral mine drainage (> ≈ pH 6)
  - SD: saline mine drainage (> ≈ 1000 mgL^{-1})
- Pyrite weathering
  - pH-dependence of metal dissolution
- Natural attenuation of contaminants
- Buffer reactions
- Microbiological processes
- Control of the source ("*in-situ*-methods")
- Evaluation on a case-to-case basis: every site is unique

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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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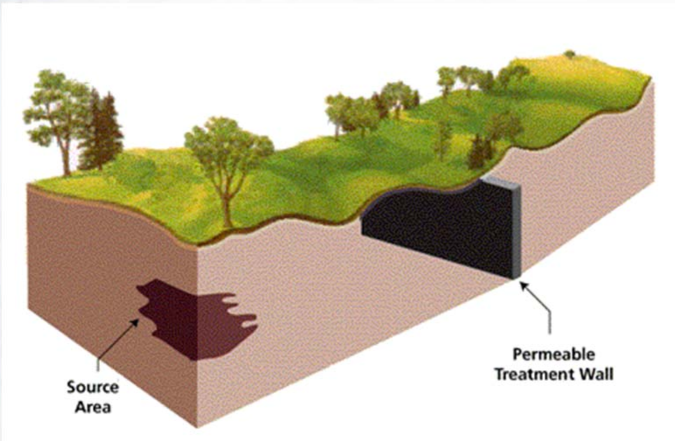
Mine Water Geochemistry

Source—Pathway—Target-Concept



Source → **Pathway** → **Target**

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From US EPA

Mine Water Geochemistry

Source—Pathway—Target-Concept

Sources

- Tailings
- Waste rock stockpiles
- Ore stockpiles
- Heap leach material
- Pit walls
- Underground workings
- Processing wastes

Pathways

- Infiltration through mine waste
- Infiltration through soil/vadose zone
- Movement of mine waters
- Uptake by biota
- Groundwater
- Surface Water
- Runoff
- Air

Targets

- Groundwater
- Surface water
- Sediment
- Air
- Soil

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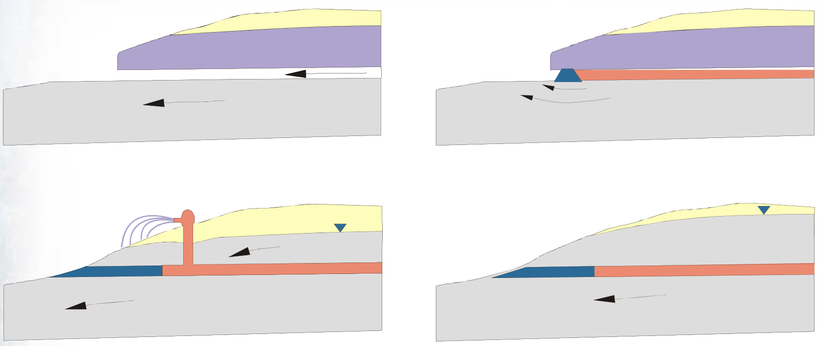
modified from GARD guide

Mine Water Geochemistry

Mine Closure Systems



Soil cover	Mine water
Impermeable rock	Damm or backfill
Permeable rock	Ground water flow direction
Ground water table	

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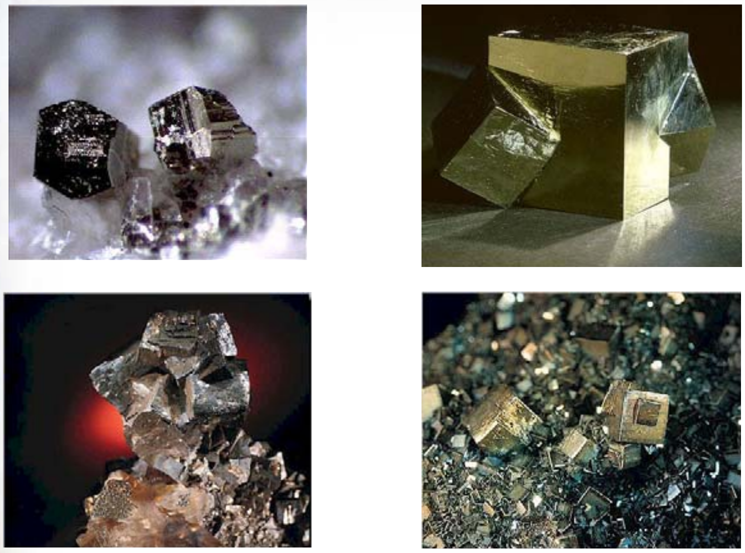
Fernandez-Rubio 1987

Mine Water Geochemistry

Pyrite Weathering Processes



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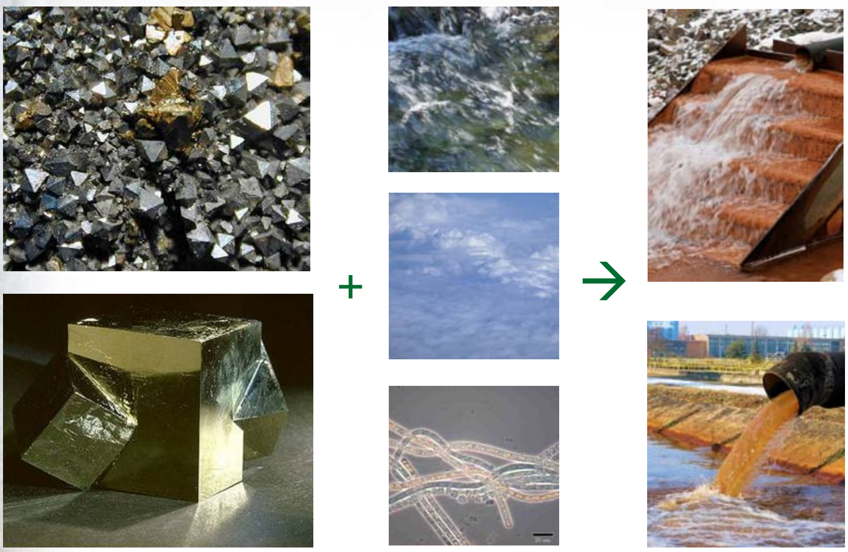
Mine Water Geochemistry

Pyrite Weathering Processes



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Mine Water Geochemistry

Pyrite Weathering Processes (½)

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

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

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

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

(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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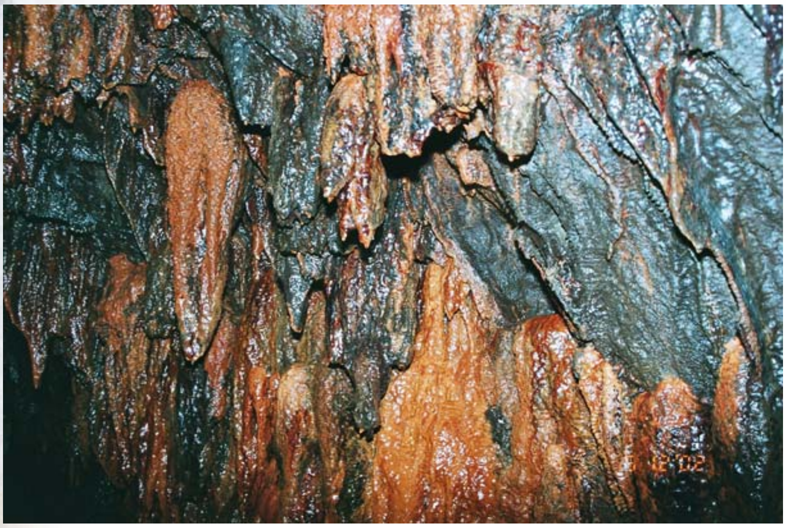
Mine Water Geochemistry

Pyrite Weathering Processes (²⁄₂)



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Weyer 2002

Mine Water Geochemistry

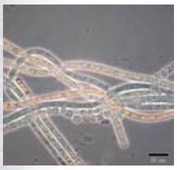
Bacterial Processes

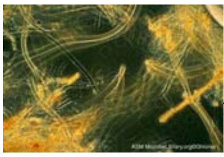
Acidithiobacillus thiooxidans, Gallionella, Beggiatoa and *Thiothrix* increase the reaction speed 10^6-fold

$$ADP + P^- \leftrightarrow ATP \qquad \Delta G°' = +32\ kJ$$

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

$$2\ S + 6\ H_2O + 3\ O_2 \leftrightarrow 2\ SO_4^{2-} + 4\ H_3O^+ \qquad \Delta G°' = -498\ kJ$$





	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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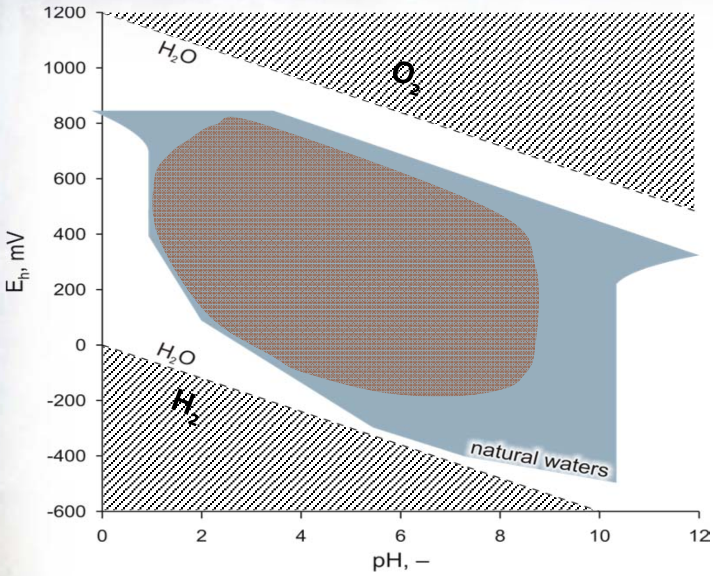
Mine Water Geochemistry

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 potentially 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 Germany	6.3	359	31		6	0.9	0.08
abandoned coal mine	6.3	210	11	< 0.05	2	< 0.007	
abandoned coal mine	6.3	83	5	0.08	0.4	0.05	0.005
metal mine	6.5	124	15	0.1	2	0.003	
Niederschlema Germany	7.1	1138	3	0.4	3	0.1	0.03
mine water (coal)	8.2	7	<0.01	< 0.02	0.004	0.055	< 0.005

concentrations in mg L^{-1}

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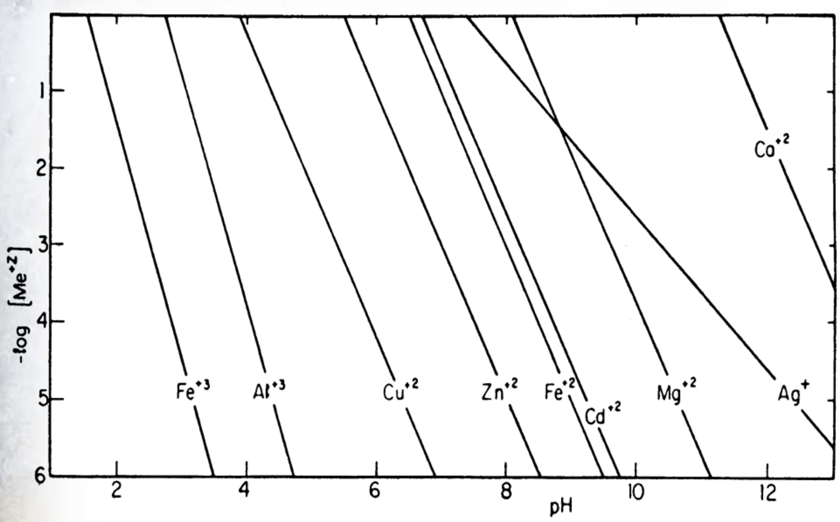
Mine Water Geochemistry

pH-Dependency of Metal Solubility



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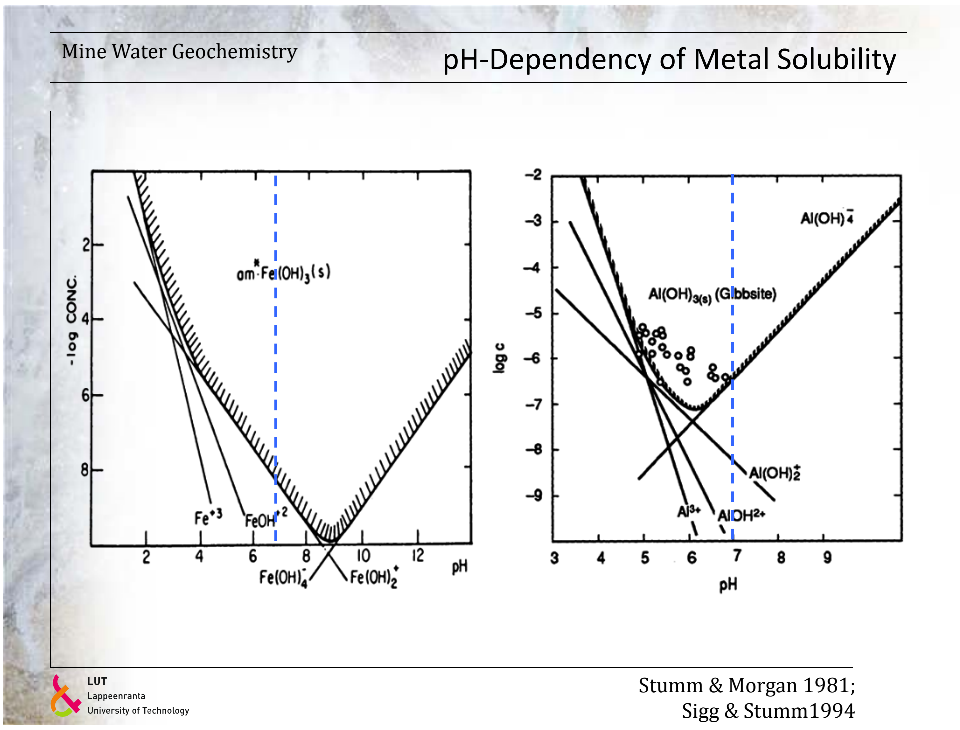
Stumm & Morgan 1981



Mine Water Geochemistry
pH-Dependency of Metal Solubility
-log CONC.
am Fe(OH)3(s)
Fe+3
FeOH+2
Fe(OH)4-
Fe(OH)2+
pH
log c
Al(OH)4-
Al(OH)3(s) (Gibbsite)
Al(OH)2+
Al3+
AlOH2+
pH
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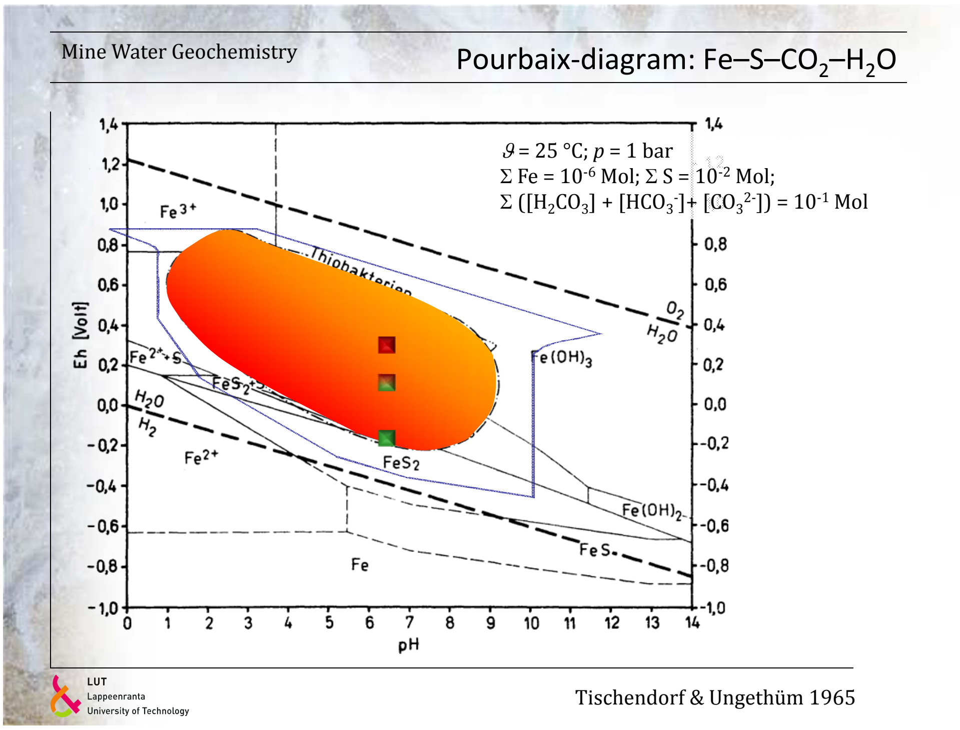
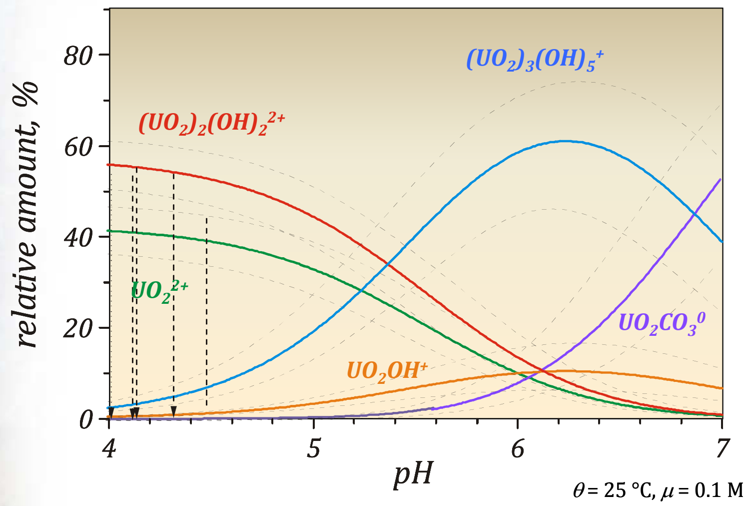
Stumm & Morgan 1981;
Sigg & Stumm1994



Mine Water Geochemistry
Pourbaix-diagram: Fe–S–CO2–H2O
ϑ = 25 °C; p = 1 bar
Σ Fe = 10-6 Mol; Σ S = 10-2 Mol;
Σ ([H2CO3] + [HCO3-]+ [CO32-]) = 10-1 Mol
Eh [Volt]
Fe3+
Thiobakterien
O2
H2O
Fe(OH)3
Fe2++S
FeS2+S
H2O
H2
Fe2+
FeS2
Fe(OH)2
FeS
Fe
pH
LUT Lappeenranta University of Technology
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)
  - $FeCO_3 + H^+ \leftrightarrow Fe^{2+} + HCO_3^-$
  - $Fe^{2+} + ¼\ O_2 + {}^5/_2\ H_2O \rightarrow Fe(OH)_3 + 2\ H^+$

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Natural Attenuation

Weathering Processes

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

  $KAlSi_3O_8 + H^+ + {}^9/_2\ H_2O \rightarrow 2\ H_4[SiO_4] + ½\ Al_2Si_2O_5(OH)_4$
- Anorthite

  $CaAl_2Si_2O_8 + H^+ + H_2O \rightarrow Ca^{2+} + 2\ H_4[SiO_4] + ½\ Al_2Si_2O_5(OH)_4$
- Albite

  $NaAlSi_3O_8 + H^+ + {}^9/_2\ H_2O \rightarrow Na^+ + 2\ H_4[SiO_4] + ½\ Al_2Si_2O_5(OH)_4$

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Natural Attenuation

Weathering Processes

- *Mica*
- Biotite

  $KMg_{3/2}Fe_{3/2}[AlSi_3O_{10}](OH)_2 + 7\ H^+ + ½\ H_2O \rightarrow$
  $K^+ + {}^3/_2\ Mg^{2+} + {}^3/_2\ Fe^{2+} + 2\ H_4[SiO_4] + ½\ Al_2Si_2O_5(OH)_4$
- Muscovite

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

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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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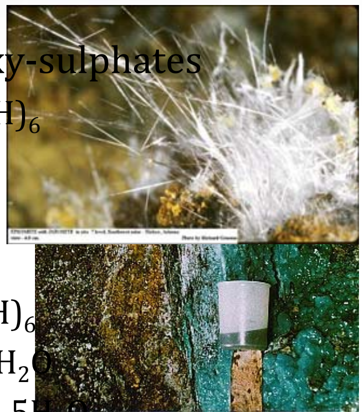
Immobilisation of Metals

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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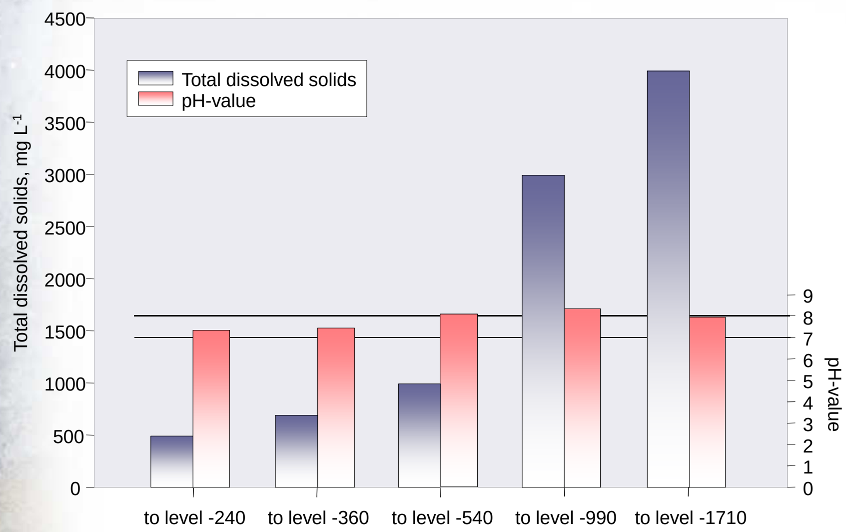
Mine Water Geochemistry

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” k_B
  Alkalinity: “acid capacity” k_A

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Mine Water Geochemistry

Acidity – Alkalinity

- Acidic waters have a pH-value < 5.6
- Alkaline waters have a pH-value > 5.6

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

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Mine Water Geochemistry

Acidity – Alkalinity

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

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Acidity – Alkalinity

Strong Acids and Bases

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

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

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

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

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

$$\underset{\text{(gaseos)}}{CO_2}$$

$$\uparrow\downarrow$$

$$\underset{\text{(aqueous)}}{CO_2} + H_2O \leftrightarrow H_2CO_3 \leftrightarrow H^+ + HCO_3^-$$

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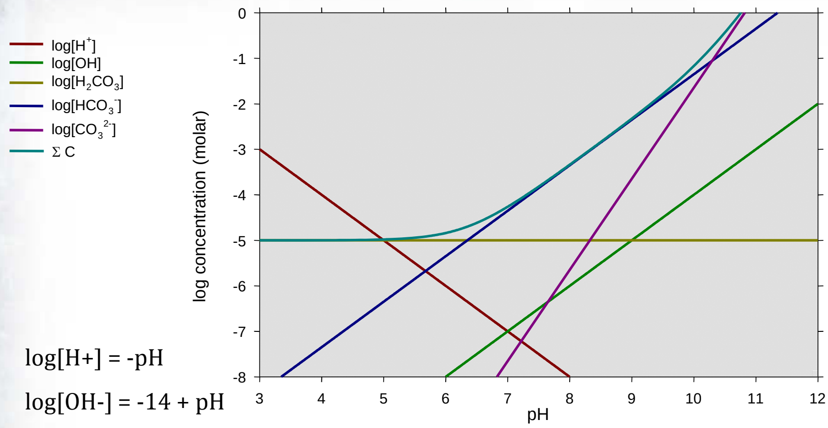
Acidity – Alkalinity

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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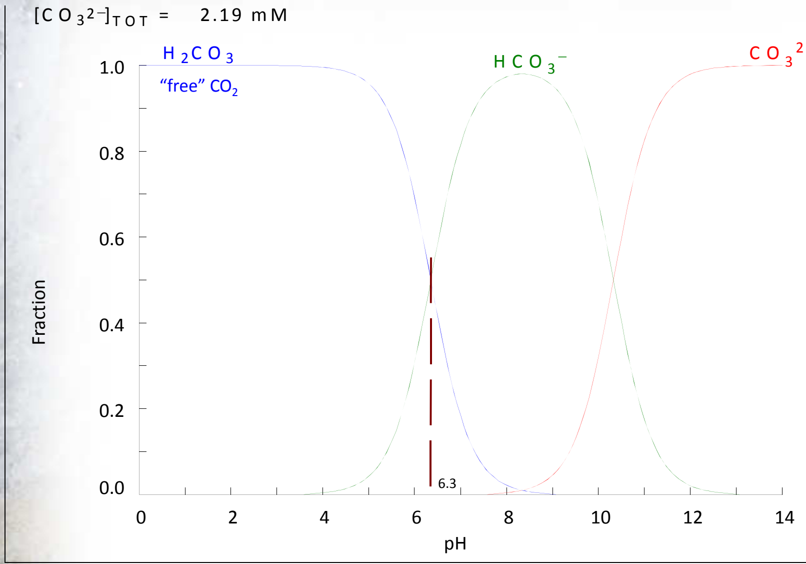
Acidity – Alkalinity

Distribution of Carbon Species



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Medusa Hydra Geochemical Software; Ignasi Puigdomenech: 2010 – 2013

Aqueous Solutions

Mass and charge balance

- Ground water is always electro-neutral:

  Σ_{eq}[positive charged ions] = Σ_{eq}[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:

$$[Alk] = \frac{pCO_2\,(g)\,K_1}{[H^+]} + \frac{[HCO_3^-]K_2}{[H^+]} + \frac{K_W}{[H^+]} - [H^+]$$

- 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:

$$[Alk] \cong \frac{[H_2CO_3]K_1}{[H^+]} - [H^+] \quad \text{mol L}^{-1} \quad (\text{pH} < 8.3)$$

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

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

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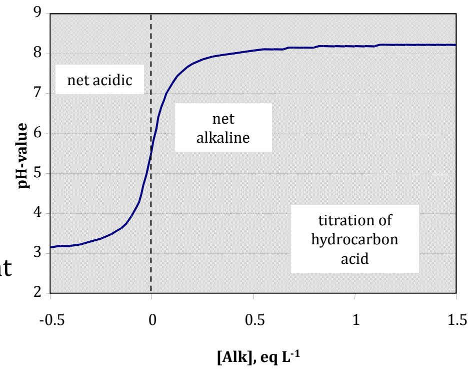
Acidity – Alkalinity

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 dissolve
- High mobility and bioavailability



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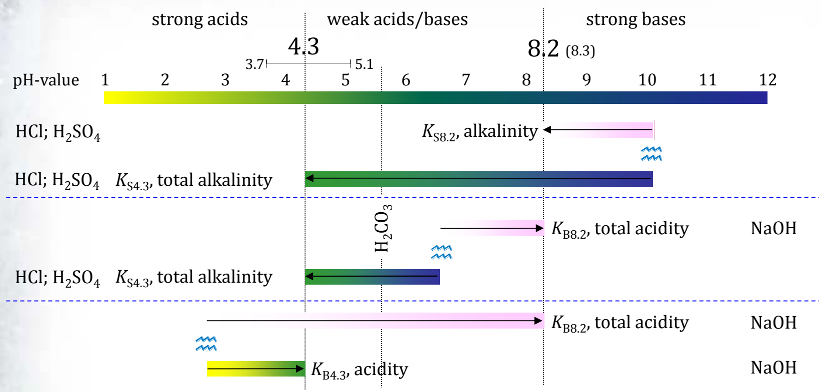
Acidity – Alkalinity

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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Models

Chemical-Thermodynamic ("Geochemical") Models

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

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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 $CaCO_3$

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

$$[Alk] \cong \frac{[H_2CO_3^-]K_1}{[H^+]} - [H^+] \quad mol\ L^{-1} \quad (pH < 8.3)$$

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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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From Ground Water to Mine Water

Environmental Hydrogeology in Mining

Prediction of Mine Flooding

Prof. Dr. Christian Wolkersdorfer

IMWA – General Secretary

Contents

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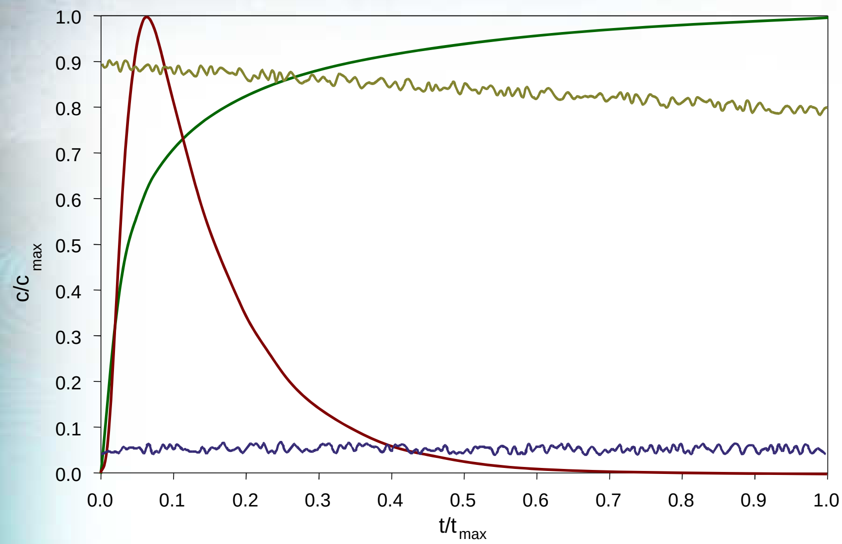
Prediction of Mine Flooding

Scenarios of pollution development



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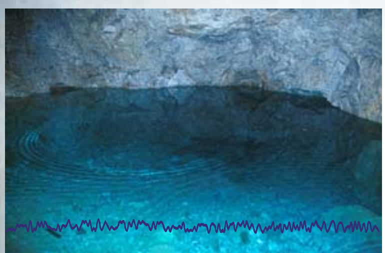
Scenarios of pollution development

Typical Cases



Georgi Unterbau, Brixlegg, Tyrol

Shilbottle, Great Britain

Lehesten, Thuringia

Straßberg, Saxony-Anhalt

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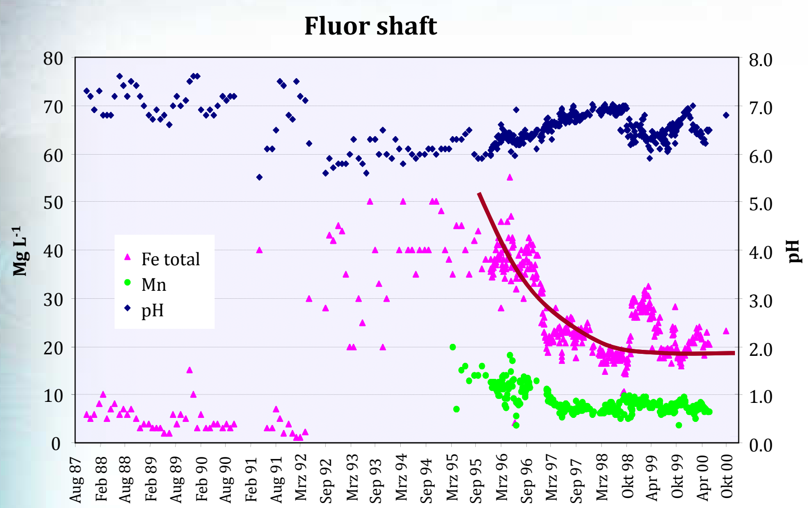
Scenarios of pollution development

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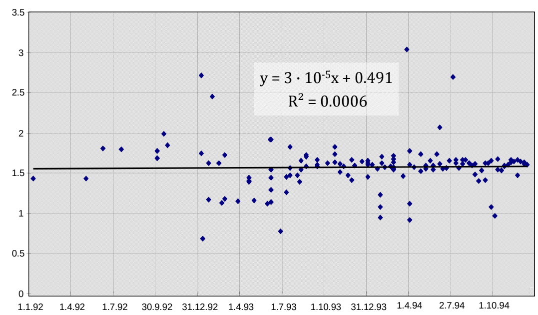
Lapakko 1990, Lapakko *et al.* 1995, Wolkersdorfer 1995

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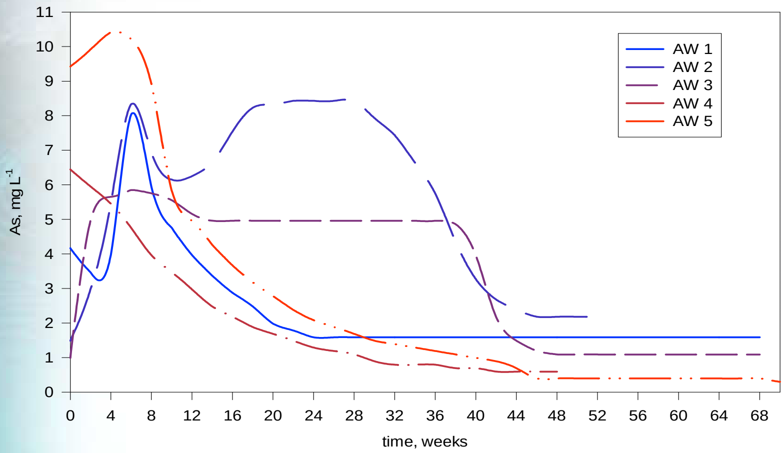
Voigt 1990, Jacks *et al.* 1984, Norberg 1985

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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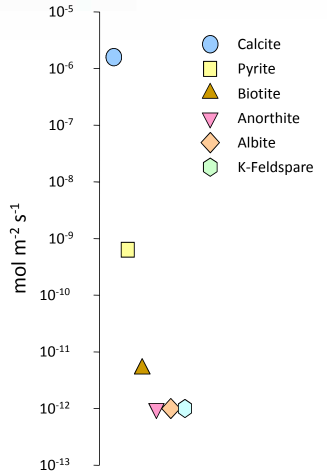
Prediction of Mine Flooding

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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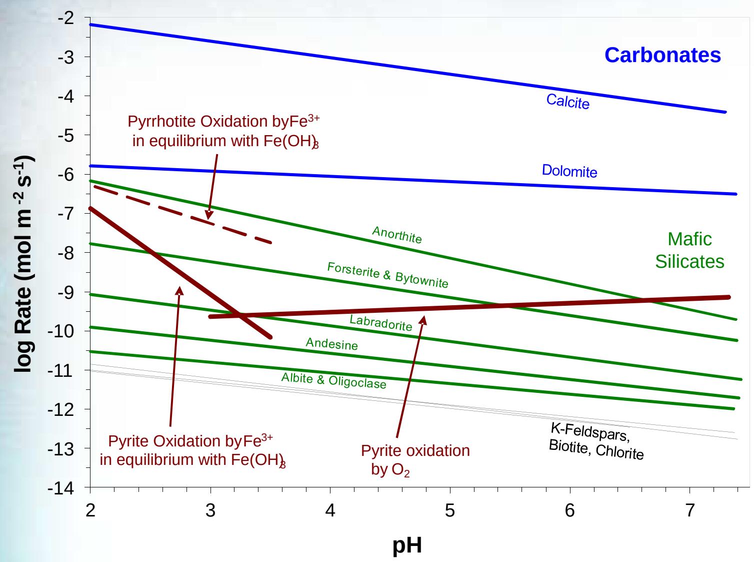
Prediction of Mine Flooding

Weathering Kinetics



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from Geller *et al.* 2013; data from Williamson & Rimstidt (1994: pyrite); Palandri & Karaka (2004: pyrrhotite, carbonates, silicates)

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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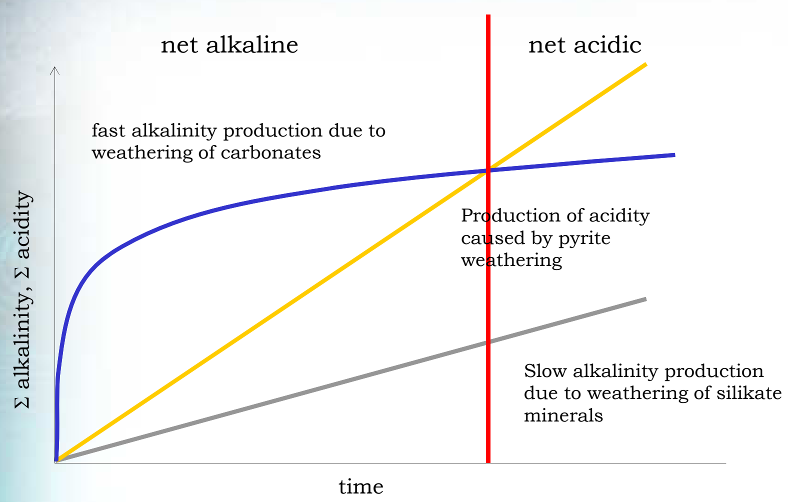
Prediction of Mine Flooding

Weathering Kinetics



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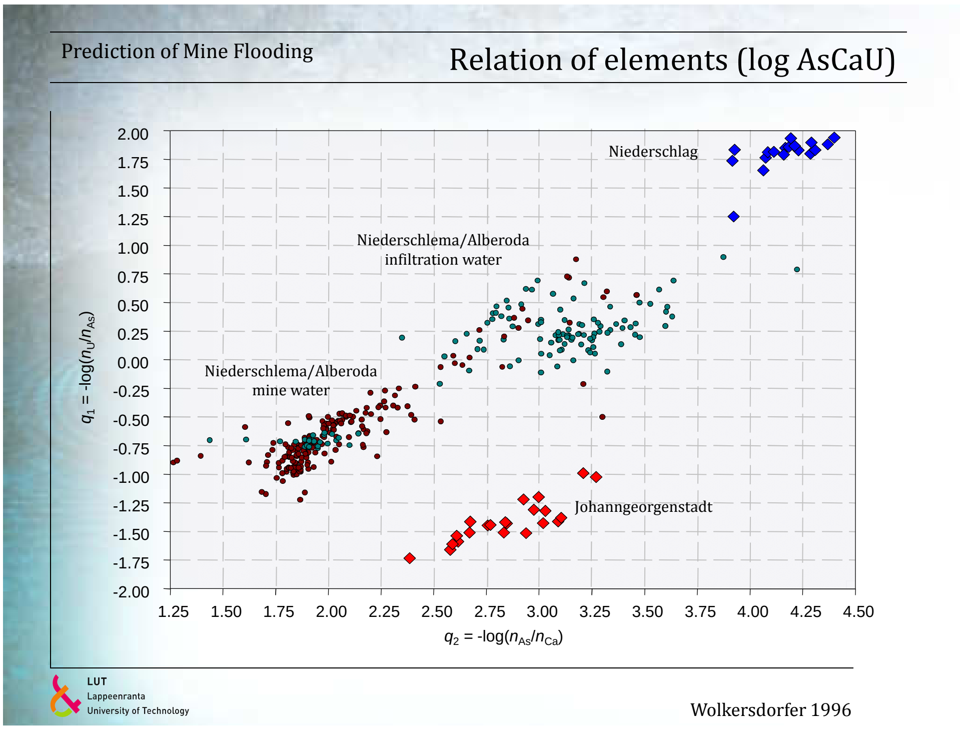
Prediction of Mine Flooding
Relation of elements (log AsCaU)
Niederschlag
Niederschlema/Alberoda infiltration water
Niederschlema/Alberoda mine water
Johanngeorgenstadt
q_1 = -log(n_U/n_{As})
q_2 = -log(n_{As}/n_{Ca})
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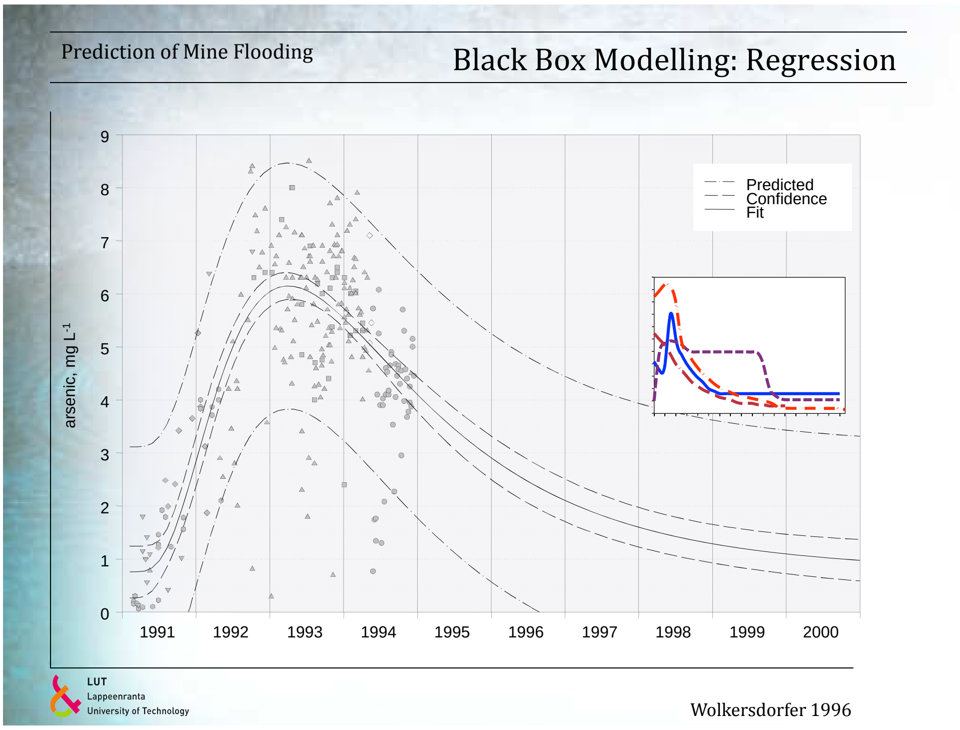
Wolkersdorfer 1996


Prediction of Mine Flooding
Black Box Modelling: Regression
Predicted
Confidence
Fit
arsenic, mg L-1
1991
1992
1993
1994
1995
1996
1997
1998
1999
2000
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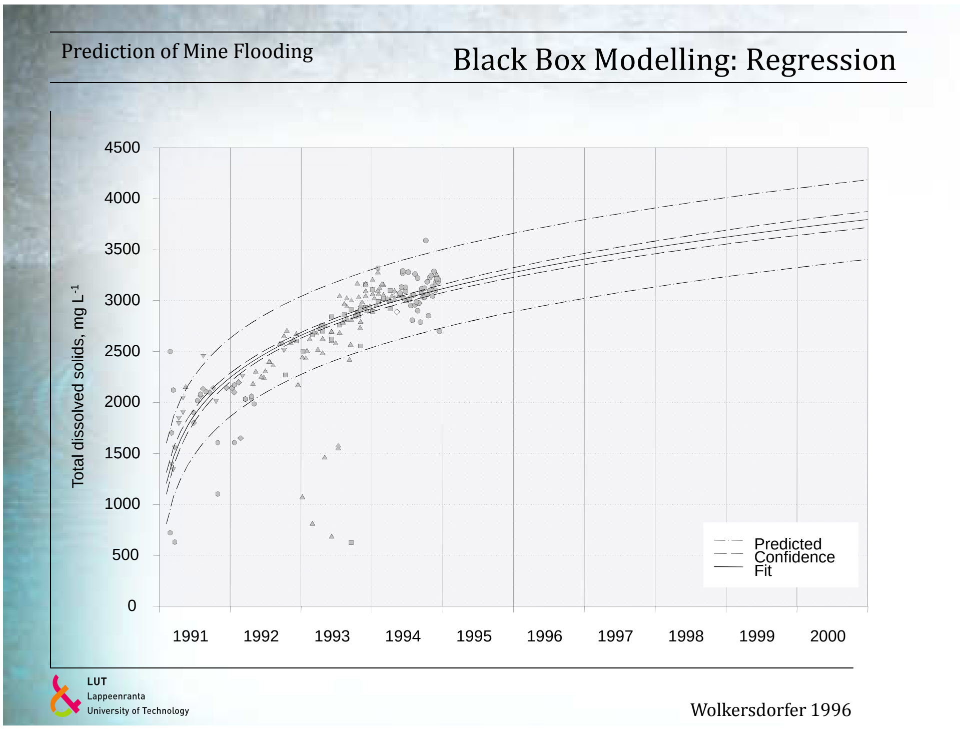
Wolkersdorfer 1996


Prediction of Mine Flooding
Black Box Modelling: Regression
4500
4000
3500
3000
2500
2000
1500
1000
500
0
Total dissolved solids, mg L-1
1991
1992
1993
1994
1995
1996
1997
1998
1999
2000
Predicted
Confidence
Fit
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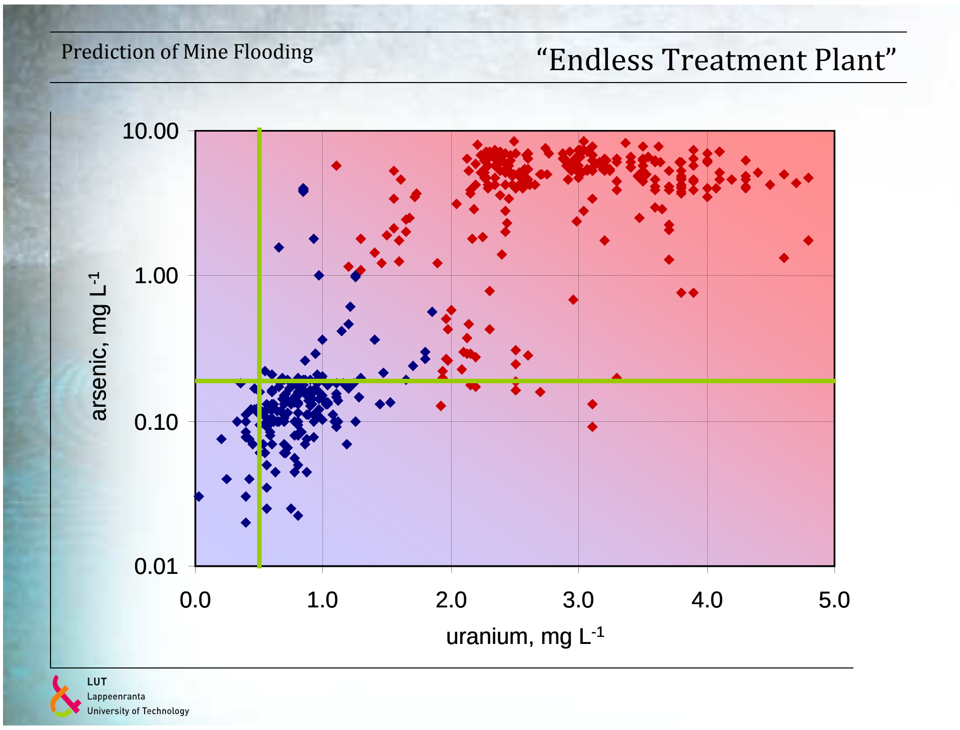
University of Technology
Wolkersdorfer 1996


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 ρ_m = 2500 kg m^3
- Density of coal ρ_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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Prediction of Mine Flooding

Calculation Example (1/8)

- Lifetime for Generation and Attenuation of contamination loads from an underground coal mine
- Discharge
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- Mine water constituents, mg L^{-1}

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Prediction of Mine Flooding

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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

$$V = 1.22\ \text{m} \times 3{\cdot}10^6\ \text{m}^2 \times 40\% = 1.464\cdot10^6\ \text{m}^3$$

$$M = 1.464{\cdot}10^6\ \text{m}^3 \times 1260\ \text{kg m}^{-3} = 1.845\cdot10^9\ \text{kg}$$

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Prediction of Mine Flooding

Calculation Example (5/8)

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

$V = 1.22\ \text{m} \times 3{\cdot}10^6\ \text{m}^2 \times 60\% \times 0.6 = 1.318 \cdot 10^6\ \text{m}^3$

$M = 1.318 \cdot 10^6\ \text{m}^3 \times 2500\ \text{kg m}^{-3} = 3.294 \cdot 10^9\ \text{kg}$

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Prediction of Mine Flooding

Calculation Example (6/8)

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

$M_{S/coal} = 1.845 \cdot 10^9\ \text{kg} \times 0.3\% = 5.53 \cdot 10^6\ \text{kg}$

$M_{S/coal} = 5.53 \cdot 10^6\ \text{kg} / 32.07\ \text{g mol}^{-1} = 172.4 \cdot 10^6\ \text{mol}$

$M_{pyrite/coal} = 172.4 \cdot 10^6\ \text{mol} \times 119.97\ \text{g mol}^{-1} / 2 = 10.3 \cdot 10^6\ \text{kg}$

$M_{py/mud} = 3.294 \cdot 10^9\ \text{kg} \times 2.5\% = 82.4 \cdot 10^6\ \text{kg}$

$M_{py} = (10.3 + 82.4) \cdot 10^6\ \text{kg} = 92.7 \cdot 10^6\ \text{kg}$

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Prediction of Mine Flooding

Calculation Example (7/8)

4. Calculate sulphate flux in discharge and pyrite lifetime

$L_{sulphate}$ =	$0.460\ \text{g L}^{-1} \times 2.6 \cdot 10^{6}\ \text{L day}^{-1} = 1196\ \text{kg day}^{-1}$
$L_{sulphate}$ =	$1196\ \text{kg day}^{-1} / 96.06\ \text{g mol}^{-1} = 12450\ \text{mol day}^{-1}$
M_{py} =	$92.7 \cdot 10^{6}\ \text{kg} / 119.97\ \text{g mol}^{-1} = 773 \cdot 10^{6}\ \text{mol}$
t =	$773 \cdot 10^{6}\ \text{mol} / 12450\ \text{mol day}^{-1} = 62088\ \text{days}$
t =	$62088\ \text{days} / 365.25\ \text{days year}^{-1} = 170\ \text{years}$

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Prediction of Mine Flooding

Calculation Example (8/8)

5. Calculate lifetime of calcite in the mudstone

$M_{calcite}$ =	$3.294 \cdot 10^{9}\ \text{kg} \times 3\ \% = 98.8 \cdot 10^{6}\ \text{kg}$
L_{ca} =	$0.127\ \text{g L}^{-1} \times 2.6 \cdot 10^{6}\ \text{L day}^{-1} = 330\ \text{kg day}^{-1}$
L_{ca} =	$330\ \text{kg day}^{-1} / 40.08\ \text{g mol}^{-1} = 8233\ \text{mol day}^{-1}$
$M_{calcite}$ =	$98.8 \cdot 10^{6}\ \text{kg} / 100.09\ \text{g mol}^{-1} = 987 \cdot 10^{6}\ \text{mol}$
t =	$987 \cdot 10^{6}\ \text{mol} / 8233\ \text{mol day}^{-1} = 120 \cdot 10^{3}\ \text{days}$
t =	$120 \cdot 10^{3}\ \text{days} / 365.25\ \text{days year}^{-1} = 330\ \text{years}$

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From Ground Water to Mine Water

Environmental Hydrogeology in Mining

Mine Water Treatment

Prof. Dr. Christian Wolkersdorfer (云村)

IMWA – General Secretary

Contents

Mine Water Treatment

Treatment Technology Categories (1/2)

- Neutralisation
  - Lime based
  - Sodium-based
  - Ammonia
  - Biological sulphate reduction
  - Constructed wetlands
- Metals Removal
  - Precipitation
    - Hydroxides
    - Carbonates
    - Sulphates
  - Constructed wetlands

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Mine Water Treatment

Treatment Technology Categories (2/2)

- Desalination
  - Biological Sulphate Removal
  - Ettringite Process
  - Membrane Processes
  - Ion Exchange
  - Constructed wetlands
- Special Treatment Options
  - Cyanide removal
  - Radioactive compounds
  - Arsenic removal
- *In-situ* treatment

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From Ground Water to Mine Water

Mine Water Treatment: Overview

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

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Mine Water Treatment

General issues

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

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Mine Water Treatment

General issues

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

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Mine Water Treatment

General issues

- To choose the appropriate treatment technology, the following points have to be considered
  - Existing or available processes
  - Cost-benefit analyses of alternative methods

    Keep in mind: passive methods can be expensive in the first place, but maintenance is usually of lower cost whereas in active systems it is often vise-versa
  - Possible changes of mine water quality: “longevity of mine water pollution”

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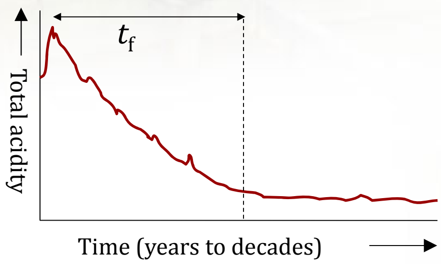
Mine Water Treatment

First Flush

- The time of mine water pollution depends on
  - Acidity removal or reduction rate ("first flush"): buffering
  - Rate at 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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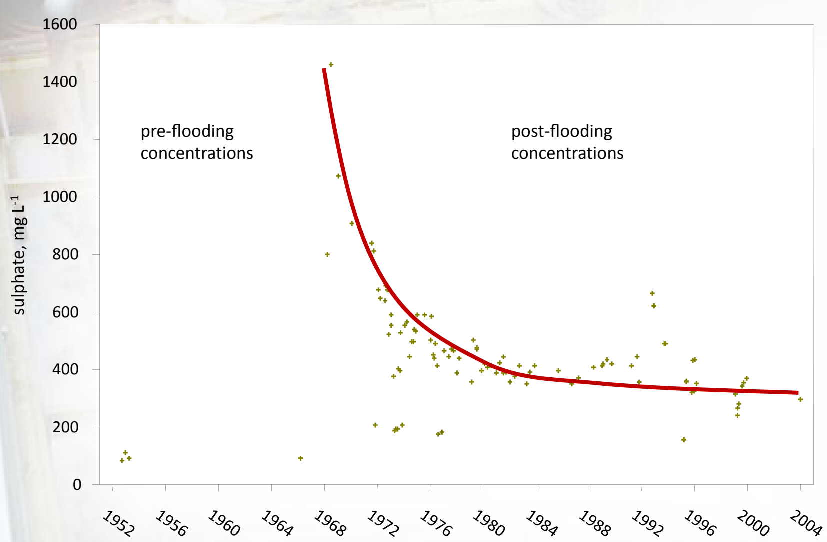
Mine Water Treatment

First Flush



Reiche Zeche Freiberg Germany (Wolkersdorfer 2008)

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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 hydraulic 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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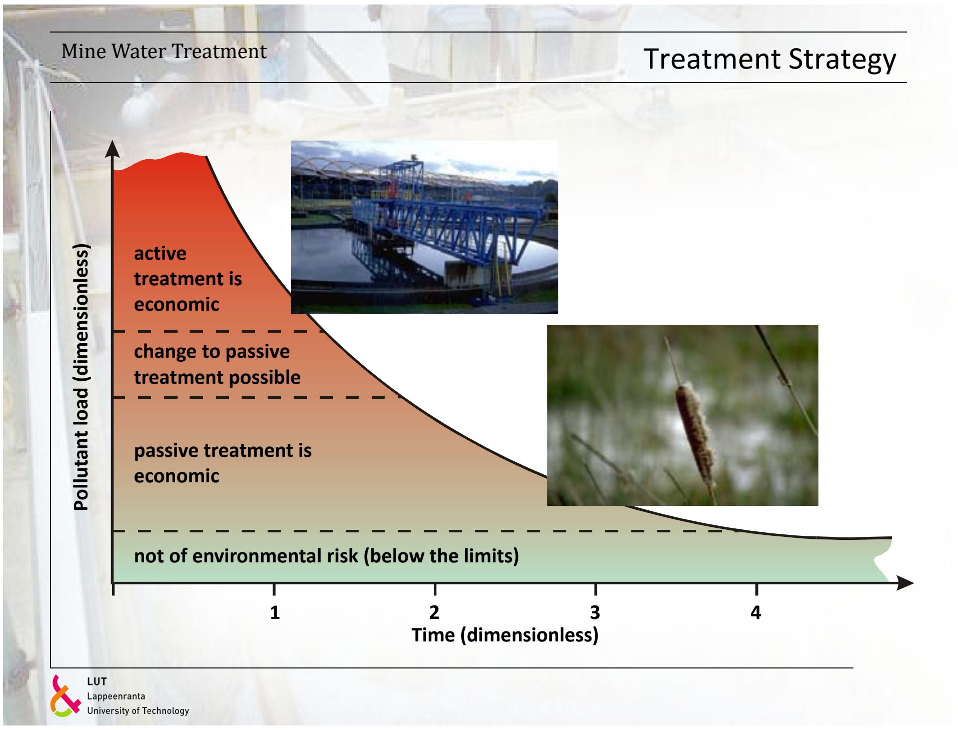
Mine Water Treatment
Treatment Strategy
active treatment is economic
change to passive treatment possible
passive treatment is economic
not of environmental risk (below the limits)
Pollutant load (dimensionless)
1
2
3
4
Time (dimensionless)
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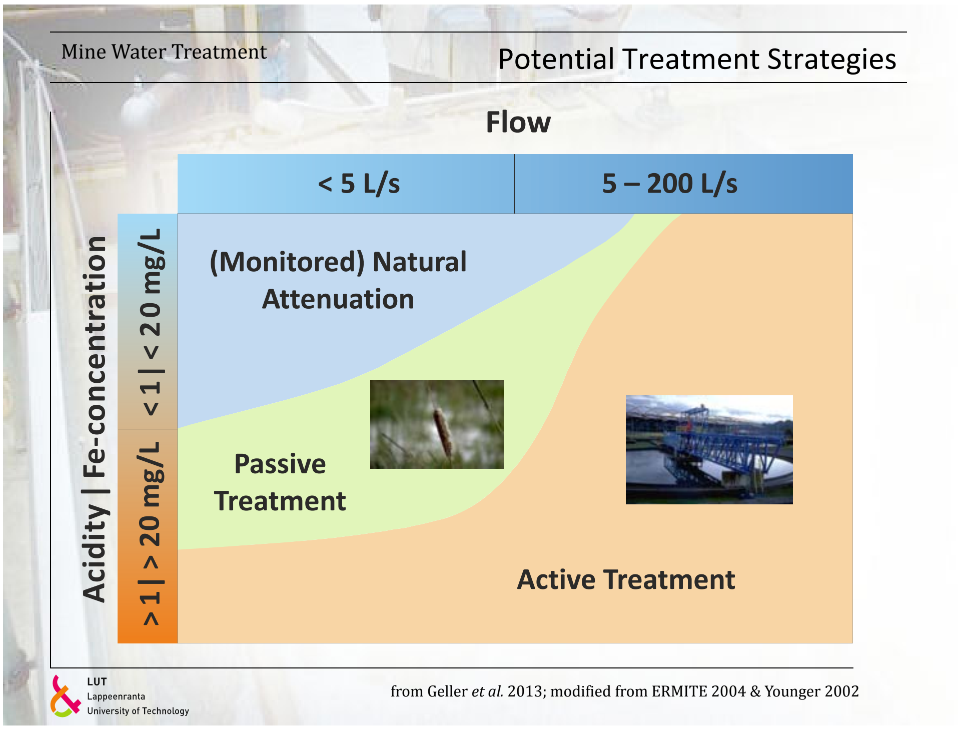
Mine Water Treatment
Potential Treatment Strategies
Flow
< 5 L/s
5 – 200 L/s
Acidity | Fe-concentration
< 1 | < 20 mg/L
> 1 | > 20 mg/L
(Monitored) Natural Attenuation
Passive Treatment
Active Treatment
from Geller et al. 2013; modified from ERMITE 2004 & Younger 2002
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Mine Water Treatment

Treatment Strategy

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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
- Freeze separation

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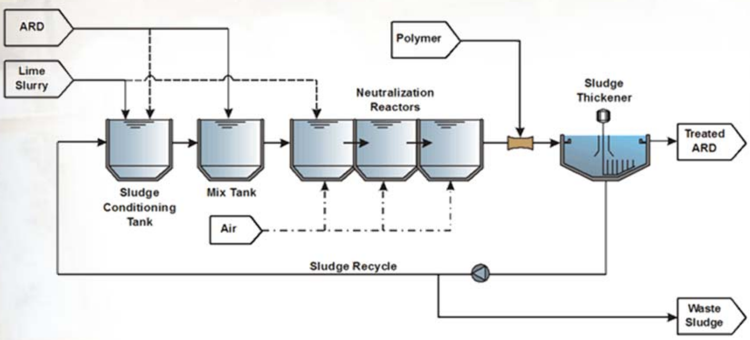
Mine Water Treatment

High Density Treatment



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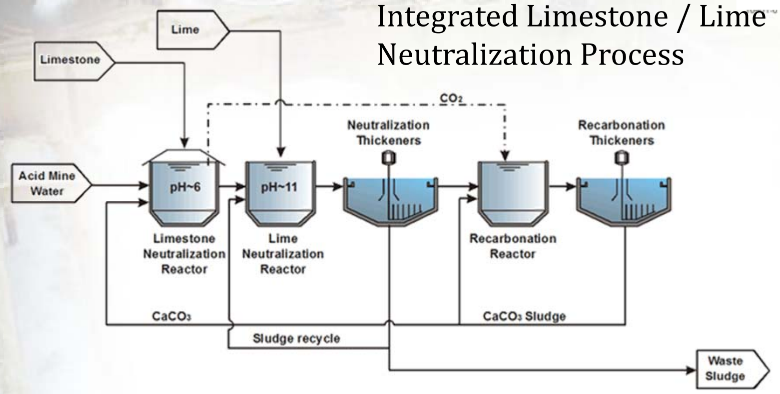
adapted from GARD Guide

Mine Water Treatment

Neutralization Process

Integrated Limestone / Lime Neutralization Process



- Pre-neutralization: relatively inexpensive limestone
- Lime neutralization to a pH target (metal dependent)
- Re-carbonation and pH adjustment
  CO_2 generated in the first process step

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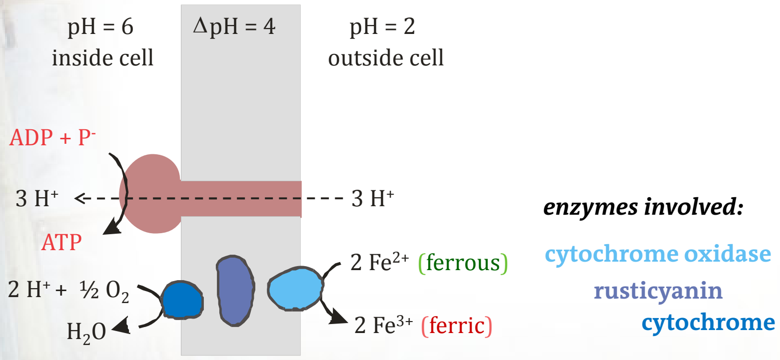
adapted from GARD Guide

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:

$$Fe^{2+} + \frac{1}{4} O_2 + H^+ \rightarrow Fe^{3+} + \frac{1}{2} H_2O$$

$$Fe^{3+} + 3 H_2O \rightarrow Fe(OH)_3 + 3 H^+$$

- 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

Neutralisation: Alkali materials

Alkali Compound/ Material	Alkali Requirements ton/ton of acidity	Neutralisation Efficiency % of applied alkali used	Relative Cost € / tonnes bulk
Limestone, $CaCO_3$	1.00	30 – 50	8 – 12
Hydrated Lime, $Ca(OH)_2$	0.74	90	50 – 80
Un-hydrated (quick) Lime, CaO	0.56	90	60 – 190
Soda Ash, Na_2CO_3	1.06	60 – 80	150 – 270
Caustic Soda, NaOH	0.80	100	500 – 700
Magna Lime, MgO	0.4	90	project specific
Fly ash	material specific	–	project specific
Kiln dust	material specific	–	project specific
Slag	material specific	–	project specific

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adapted from GARD Guide

Mine Water Treatment

Liming

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

$$Ca(OH)_2 + H_2SO_4 \rightarrow CaSO_4 \cdot 2H_2O$$

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

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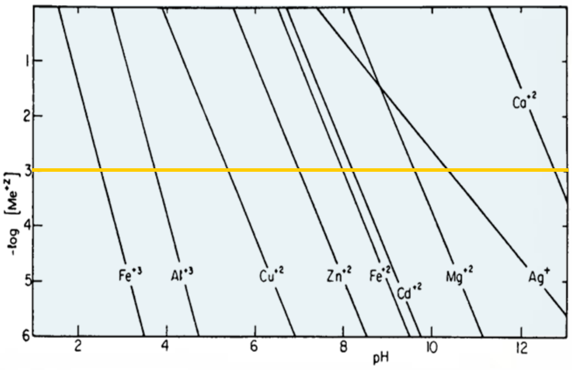
Mine Water Treatment

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}) + $[(1000 \times 10^{-pH_t}) - 10^{-3}]\} \times 37$

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Mine Water Treatment

Flocculation/Coagulation

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

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Mine Water Treatment

Settlement and Sludge Management

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

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Mine Water Treatment

Plate Filter Press

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Žirovski Vrh/Slovenia (Kovinarska Industrija/Ajdovščina)

Mine Water Treatment

Sludge Disposal

- High amounts of metals (*e.g.* Pb, Zn, Cd) could cause the sludge to be classified as hazardous waste
- HDS or Fe-rich sludge might be used as pigments or in brick industry
- Experience has shown (“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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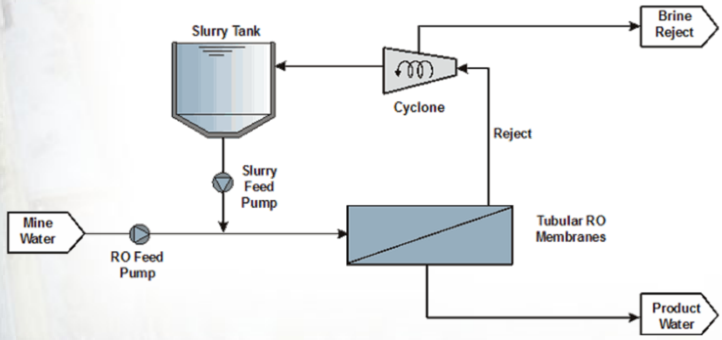
Mine Water Treatment

Sulphate Removal

- Barium sulphate process (pilot scale)
- Ettringite precipitation process (pilot scale)
  - SAVMIN™
  - $Ca_6Al_2(SO_4)_3(OH)_{12} \cdot 26H_2O$



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adapted from GARD Guide

Mine Water Treatment

Ion exchange

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

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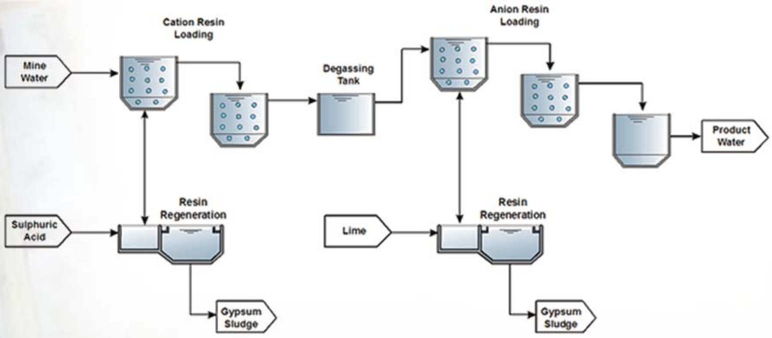
Mine Water Treatment

Ion exchange

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



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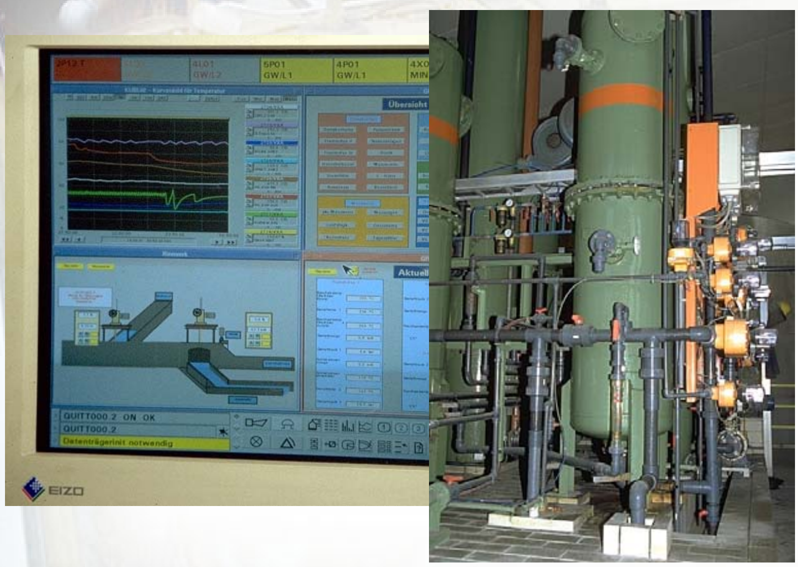
Mine Water Treatment

Brixlegg/Tyrol, Ion Exchange Reactor



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Mine Water Treatment

Burgfey/Eifel: Pilot Plant

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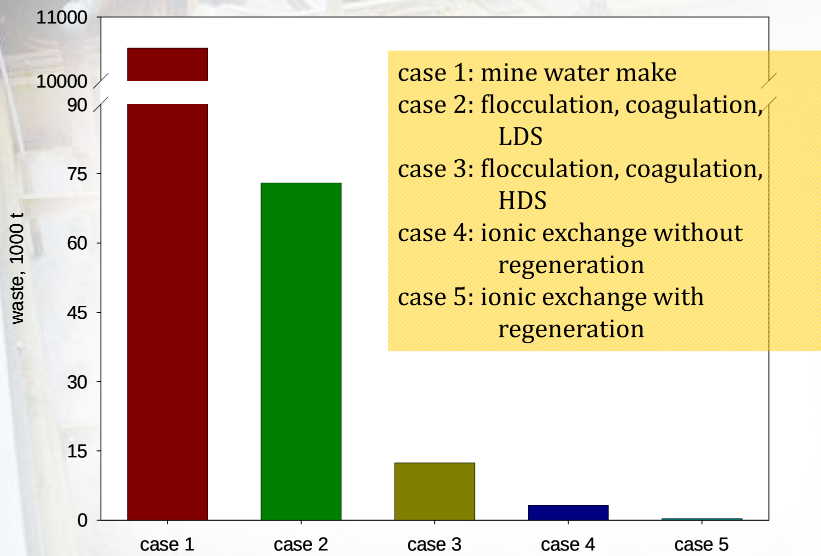
Mine Water Treatment

Burgfey/Eifel: Ion Exchange Effectiveness



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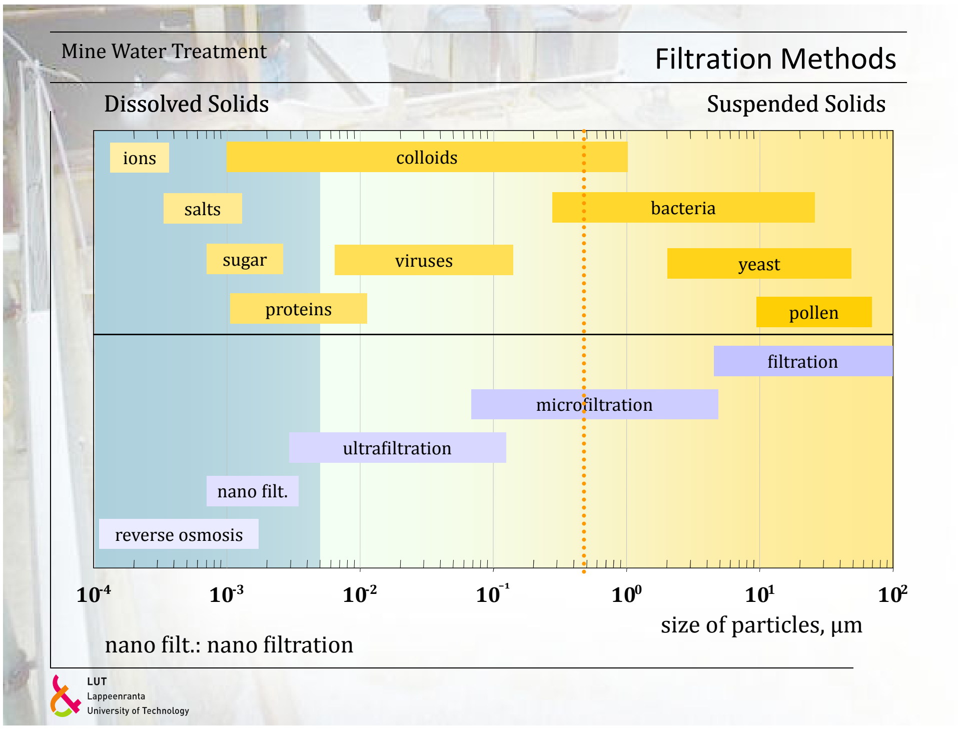
Mine Water Treatment
Filtration Methods
Dissolved Solids
Suspended Solids
ions
colloids
salts
bacteria
sugar
viruses
yeast
proteins
pollen
filtration
microfiltration
ultrafiltration
nano filt.
reverse osmosis
10-4
10-3
10-2
10-1
100
101
102
size of particles, µm
nano filt.: nano filtration
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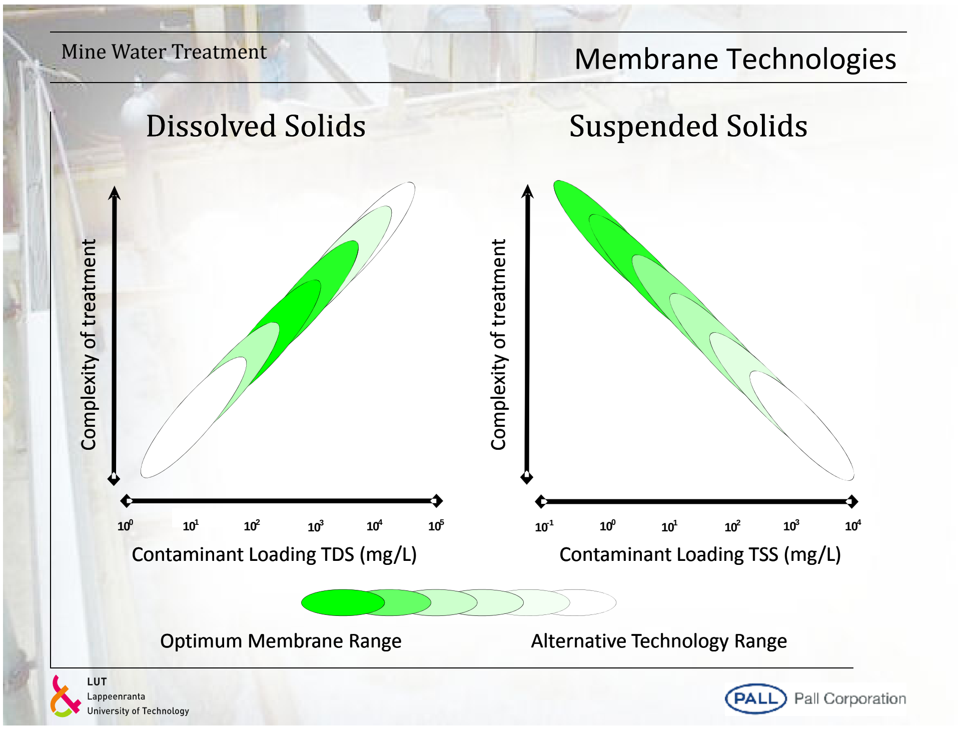
Mine Water Treatment
Membrane Technologies
Dissolved Solids
Suspended Solids
Complexity of treatment
100
101
102
103
104
105
Contaminant Loading TDS (mg/L)
Complexity of treatment
10-1
100
101
102
103
104
Contaminant Loading TSS (mg/L)
Optimum Membrane Range
Alternative Technology Range
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University of Technology
PALL Pall Corporation

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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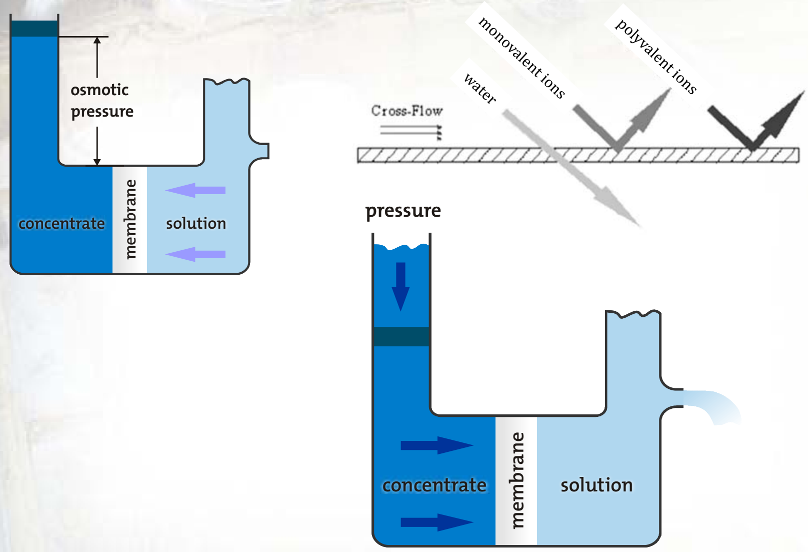
Mine Water Treatment

Osmosis/Reverse Osmosis



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Mine Water Treatment

Osmosis/Reverse Osmosis: Example

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

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Wilson & Brown 1997; ACWA Services Limited

Mine Water Treatment

Reverse Osmosis

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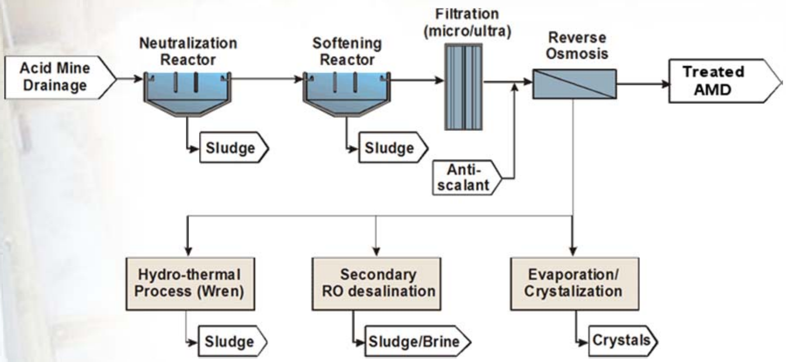
Emalahleni/South Africa

Mine Water Treatment

Reverse Osmosis

Conceptual High Recovery Membrane Desalination Process



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adapted from GARD Guide

The rising importance of desalination and raw sea water

- Currently Reverse Osmosis because
  - Reduced membrane costs
  - Reduced energy consumption
- Viable source of water supply for mining
- Reliable operation
- Experienced and skilled operators needed
- Holistic approach case to case based
  - *e.g.* Ultrafiltration more expensive in investments, but less for operation costs in Reverse Osmosis plant

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The rising importance of desalination and raw sea water

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

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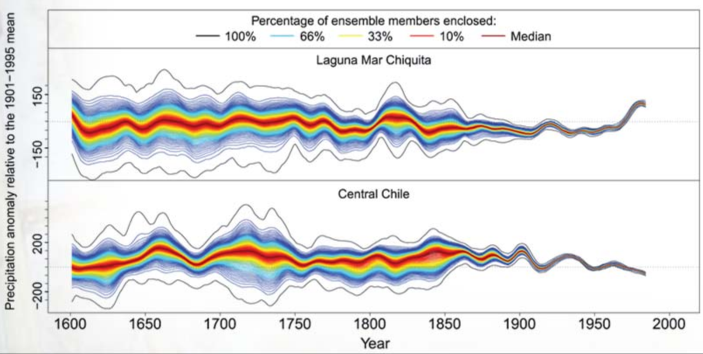
The rising importance of desalination and raw sea water

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



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The rising importance of desalination and raw sea water

- Concurrent water use of two industries
  - Mining
  - Agriculture



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

Desalination: Pre-treatment

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

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Pre-treatment: Dissolved air flotation

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

Northland Engineering MN

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Pre-treatment: Dual Media Filters

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

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Pre-treatment: Ultrafiltration

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

Knops et al. 2012

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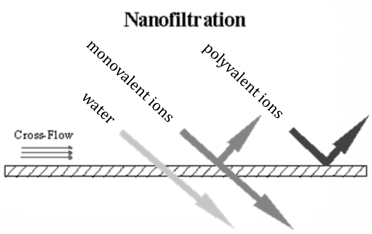
Mine Water Treatment

Nanofiltration

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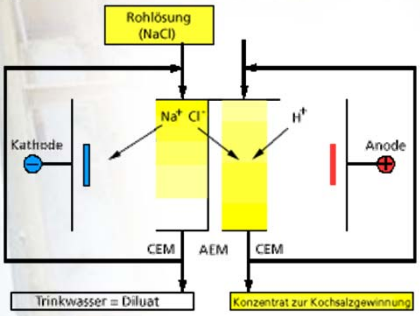
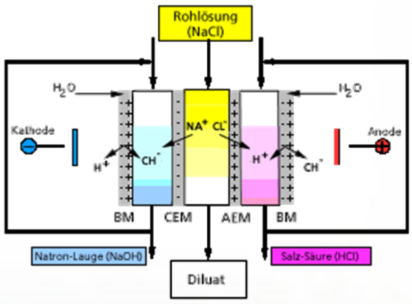
Mine Water Treatment

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

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

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Pulles, Coetser, Heath & Muhlbauer 2004

Mine Water Treatment

Passive Treatment Methods

- Reactive barrier/wall ("funnel-and-gate")
- Anoxic limestone drains
- Aerobic constructed wetlands
- Anaerobic constructed wetlands
- SAPS (RAPS, VFL)
  - **S**uccessive **A**lkalinity **P**roducing **S**ystems
  - **V**ertical **F**low **R**eactors
- Settlement lagoons

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Mine Water Treatment

Reactive Barriers

- Ground water has to flow through a permeable reactive barrier
- Barrier has to bind into impermeable strata
- The whole pollutant plume must flow through barrier
- Not too close at source of contamination (wide reaction front)
- Short cuts must be avoided
- costs: € 100 — € 700/m^2

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Mine Water Treatment

Reactive Barriers

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

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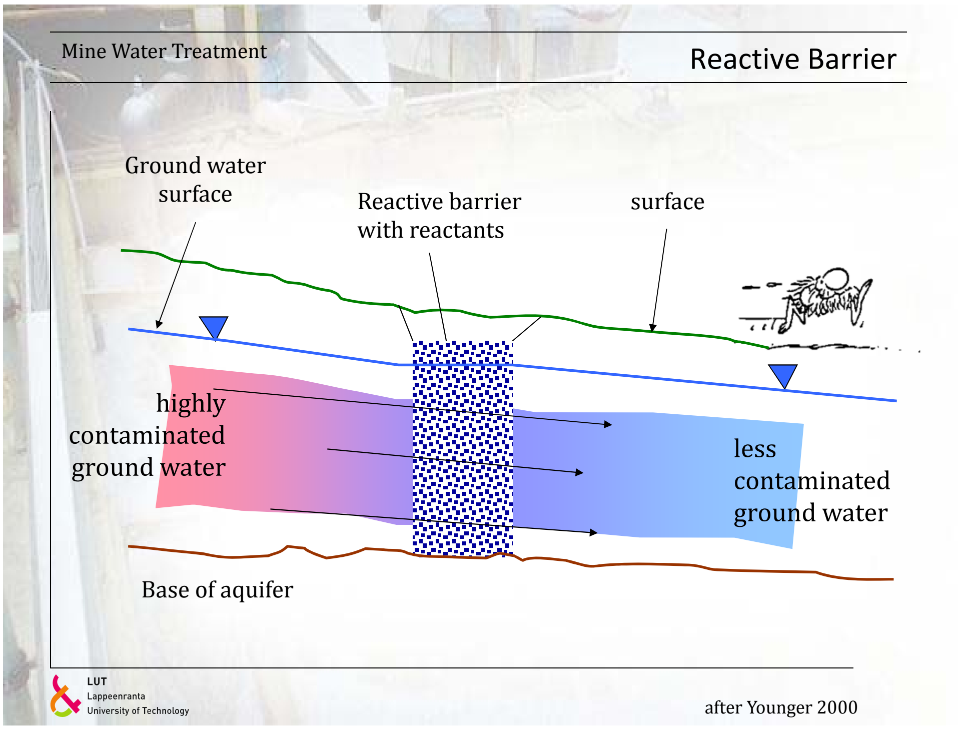
Mine Water Treatment
Reactive Barrier
Ground water surface
Reactive barrier with reactants
surface
highly contaminated ground water
less contaminated ground water
Base of aquifer
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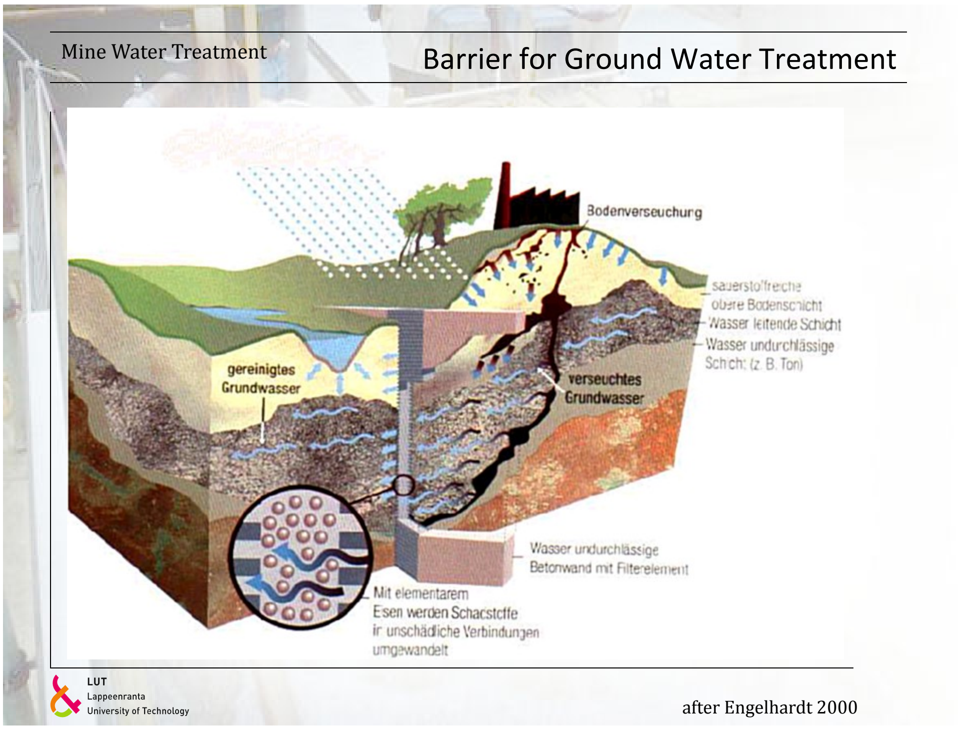
after Younger 2000


Mine Water Treatment
Barrier 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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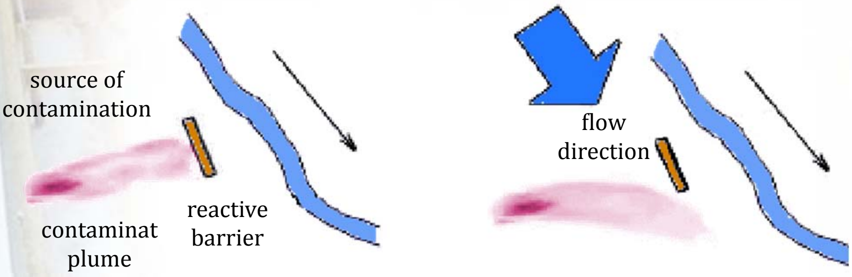
after Engelhardt 2000

Mine Water Treatment

Reactive Barrier: Construction Pitfalls



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

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after Kansy 2000

Mine Water Treatment

Uranium Mine Fry Canyon, Utah

Filling of reactive barrier with reactive material

Completed reactive barrier before soil covering

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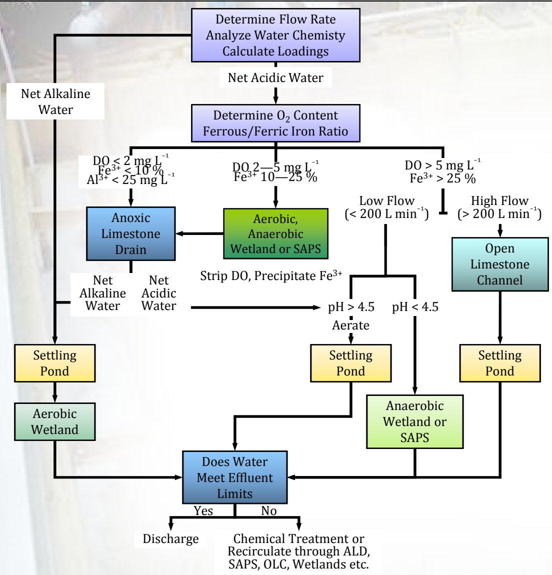
from USGS ("Fry Canyon Reactive Barrier Installation")

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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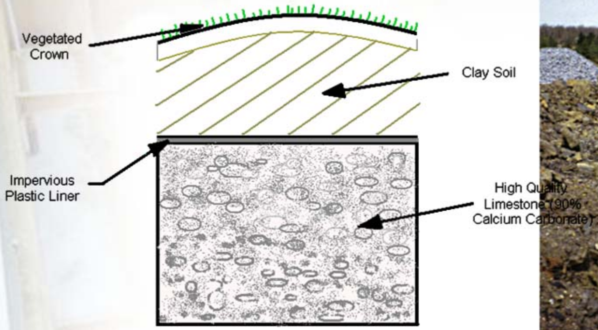
Anoxic carbonate drain

Cross Section and Construction



Cross section of anoxic carbonate drain

Tributary of Swatara Creek, PA

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Mine Water Treatment

Anoxic Limestone Drain (ALD)

- Failed ALD, because
  - Al-concentration relatively high (8 – 20 mgL^{-1} filtered)
  - O_2-concentration: never determined
  - Fe^{2+}/Fe^{3+}-ratio: never determined

Lehesten/Germany

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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:

$^1/_{50\%}$ · 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 · m^{-2} · d^{-1}

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Aerobic Wetlands

Cross Section and Plants

Typha

Phragmites

Juncus

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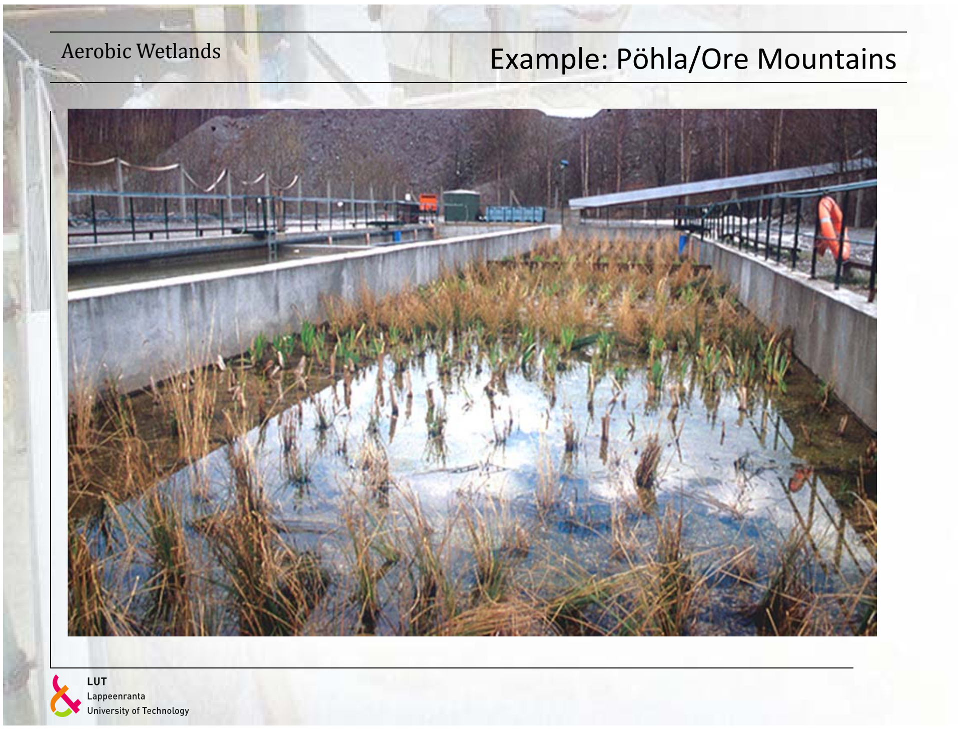
Aerobic Wetlands
Example: Pöhla/Ore Mountains
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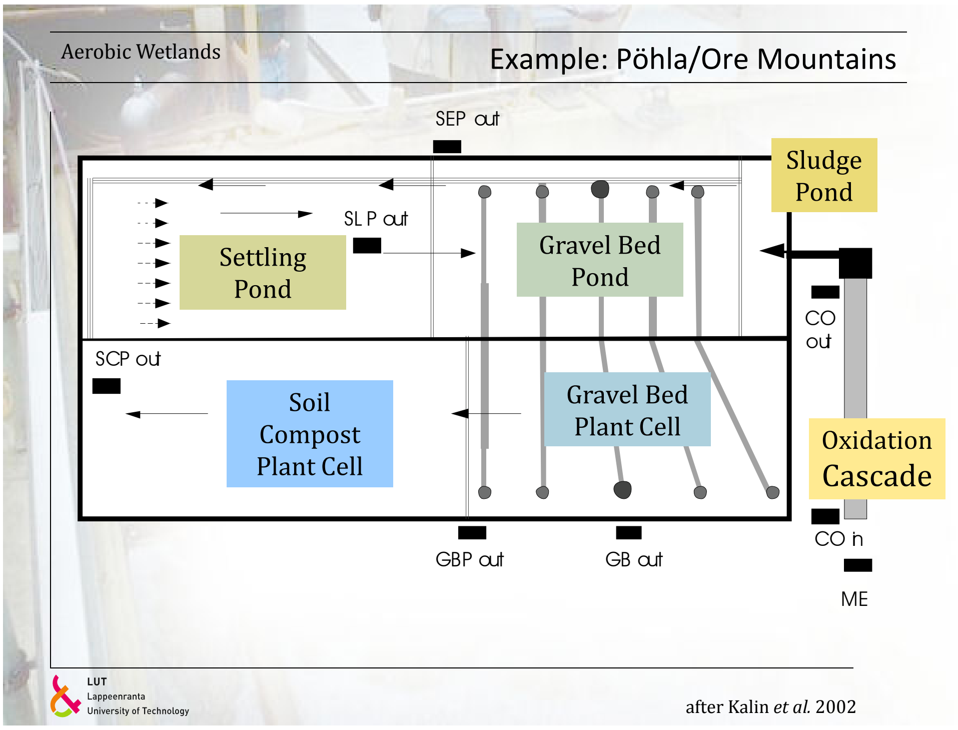
Aerobic Wetlands
Example: Pöhla/Ore Mountains
SEP out
Sludge Pond
SL P out
Settling Pond
Gravel Bed Pond
CO out
SCP out
Soil Compost Plant Cell
Gravel Bed Plant Cell
Oxidation Cascade
CO in
GBP out
GB out
ME
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University of Technology
after Kalin *et al.* 2002

Aerobic Wetlands

Example: Straßberg/Harz

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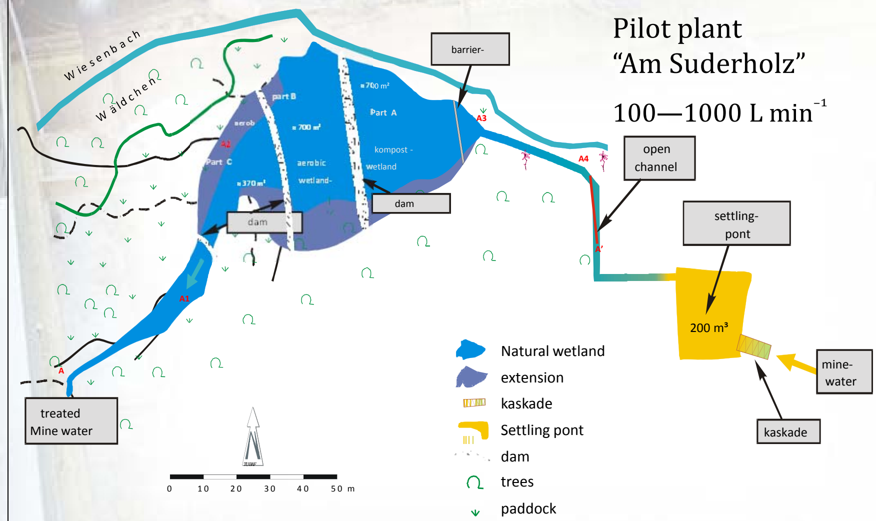
Aerobic Wetlands

Example: Straßberg/Harz



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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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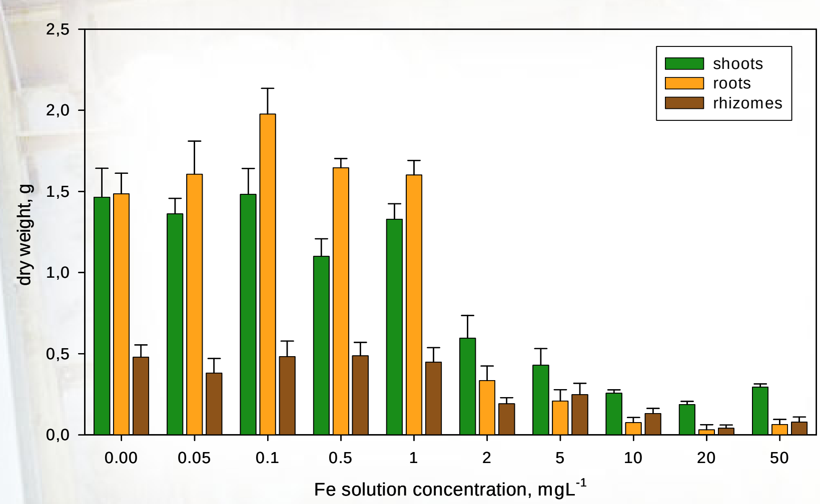
Passive Treatment

Aerobic Wetlands: Plants' Iron Removal (2/4)

Phragmites australis: healthy growth



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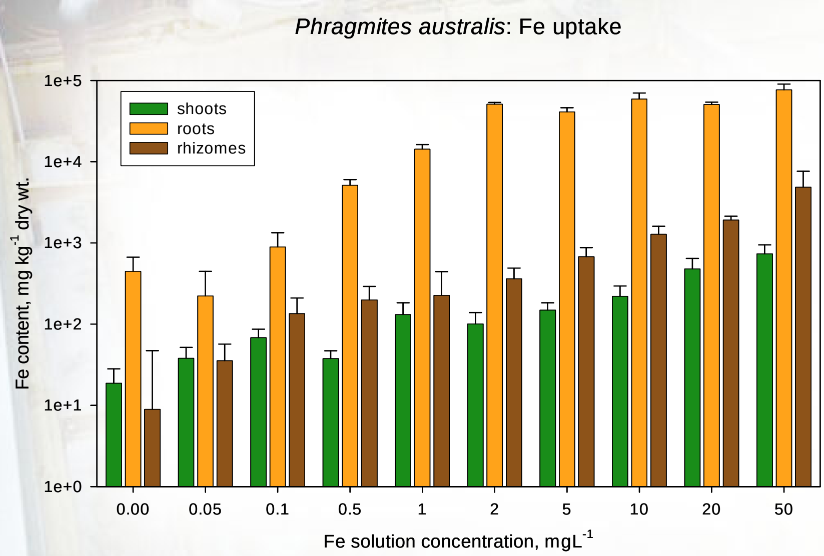
Passive Treatment

Aerobic Wetlands: Plants' Iron Removal (3/4)



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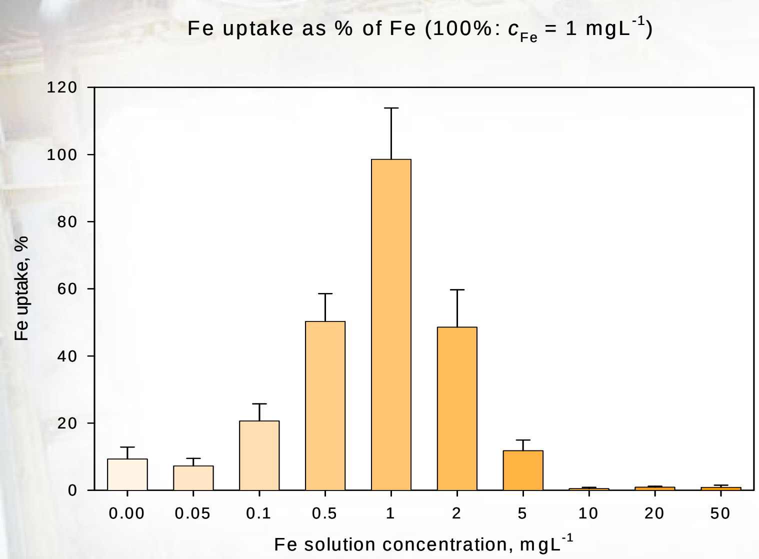
Passive Treatment

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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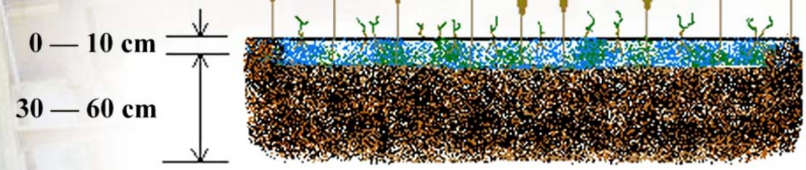
Passive Treatment

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

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	144	$\mu g\ L^{-1}$
Copper	28	$\mu g\ L^{-1}$
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
el. Conductivity	4,856	$\mu S\ cm^{-1}$

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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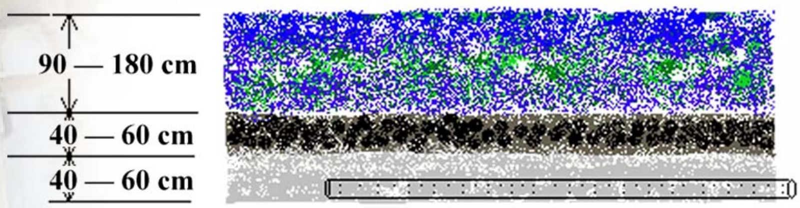
SAPS: Systems

Cross Section and Scheme



- The system ***never*** must fall dry (precipitation of Fe-oxihydrates)
- Compost: 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 reducing 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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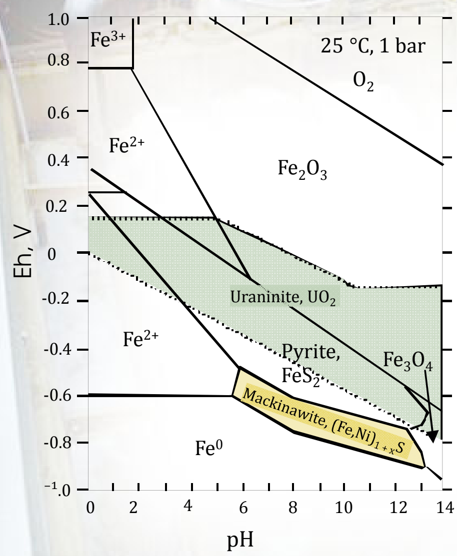
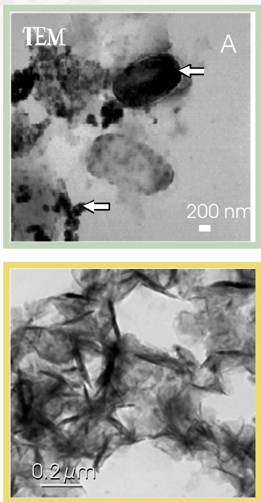
Functional Aspects

Passive Uranium Removal





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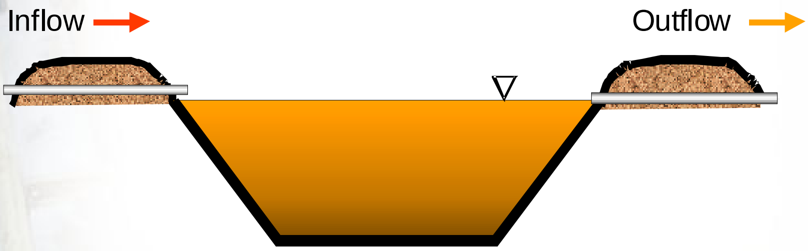
Lutze *et al.* 2002

Settling Lagoons

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



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Tar Creek Superfund Task Force 2000

Mine Water Treatment

Strategic insights into leading technology

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

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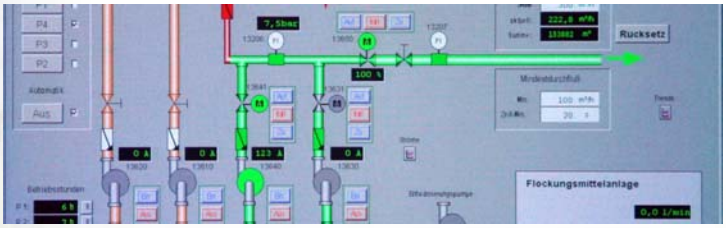
Mine Water Treatment

Strategic insights into leading technology

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



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Mine Water Treatment

Strategic insights into leading technology

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

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Mine Water Treatment

Strategic insights into leading technology

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


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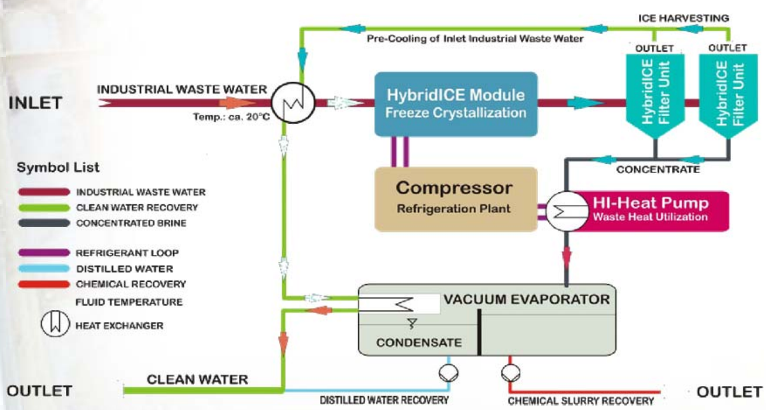
itrcweb.org, Soudan Mine | ionteching.com, Adit 93 Kremitkovtzi, Bulgaria | ionteching.com Assarel-Medet, Bulgaria

Mine Water Treatment

Strategic insights into leading technology

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



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e.g. Reddy & Lewis 2010

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