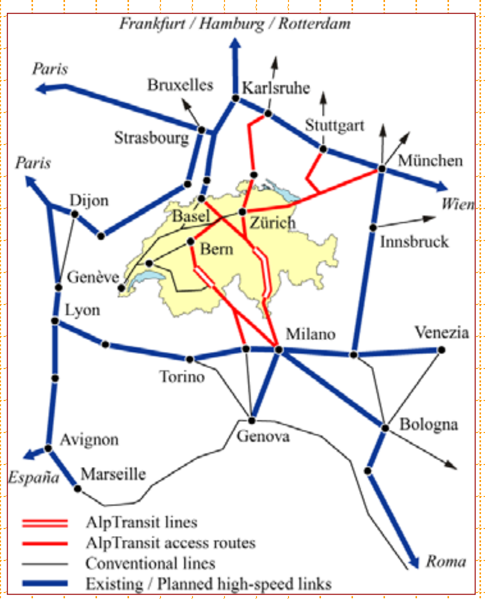
EOSC547: Tunnelling & Underground Design

Topic 2:
Geological Uncertainty

Geotechnical Challenges of the Gotthard Base Tunnel:
The Known Knowns, Known Unknowns,
& Unknown Unknowns

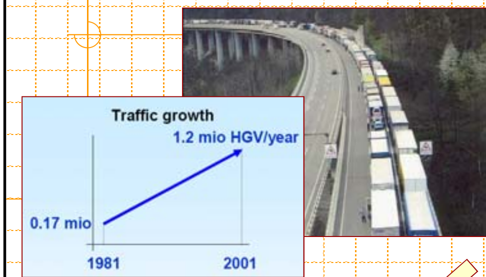


AlpTransit

In 1994 the Swiss voted an alpine protection article into their constitution, forbidding the expansion of road capacity in alpine regions. This forced the government to shift heavy goods traffic from road to rail.

To accommodate this, voters approved the "Alptransit" project to build new tunnels through the Gotthard and the Lötschberg.

Reasons for the Base Tunnels



Increasing Population Demands & Commercial Traffic

- The Gotthard Road Tunnel, is the main north-south route through the Alps, between Switzerland and Italy.
- 18,000 vehicles/day pass through the Gotthard Road Tunnel.

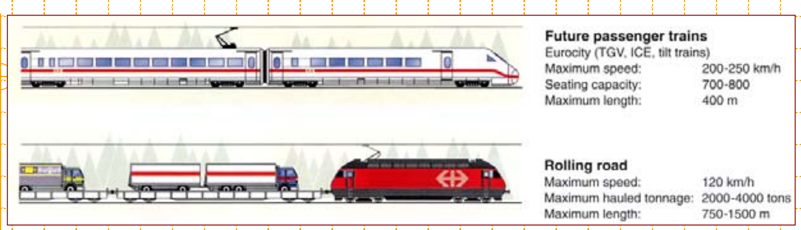
Safety

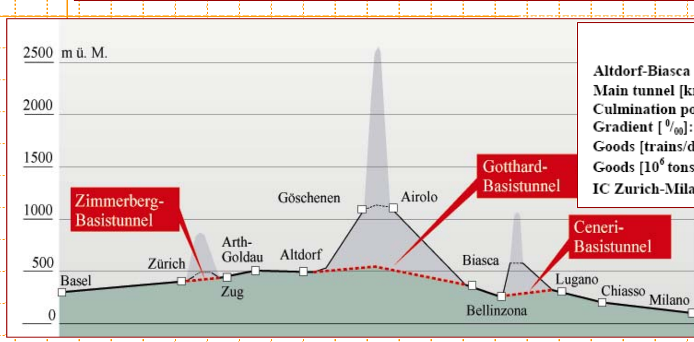
Gotthard Road Tunnel Fire (2001) – 11 people killed

Pollution

Drivers going through the Gotthard Road Tunnel inhale as many pollutants as if they smoked up to eight cigarettes.

AlpTransit Base Tunnels





	current line	new line
Altdorf-Biasca [km]:	96	65
Main tunnel [km]:	15	57
Culmination point [m]:	1151	550
Gradient [‰]:	26	12/17
Goods [trains/day]:	140	220
Goods [10^6 tons/year]:	20	42
IC Zurich-Milan:	4h10	2h40

Tunnelling & Geology – The Swiss Base Tunnels

World's Longest Transportation Tunnels

Tunnel	Length (km)	Completion Date
Gotthard Base (CH)	57.1	2018*
Brenner Base (AU)	55.4	2025
Sei-kan (Japan)	53.9	1988
Chunnel (ENG-FR)	50.5	1994
Loetschberg (CH)	34.6	2007

#30 Mount MacDonald (CAN) @ 14.6 km
#43 New Cascade (USA) @ 12.5 km

Gotthard Road Tunnel (CH) = 16.9 km

Canada = 5 rail tunnels > 2 km
USA = 4 rail tunnels > 2 km

Switzerland = 42 rail tunnels > 2 km

Tunnelling & Geology – The Swiss Base Tunnels

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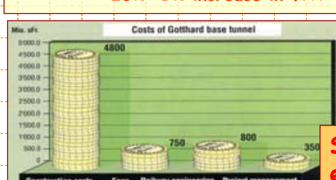
COST:

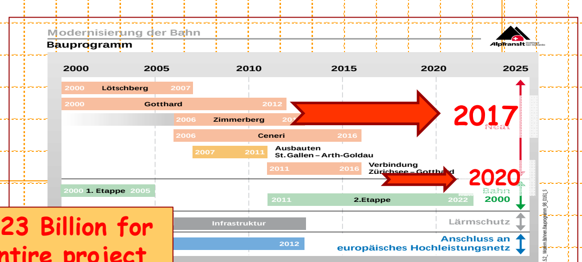
1998: $7.2 Billion
2016: $12.3 Billion

1998: $3.2 Billion
2007: $4.3 Billion

Financing: *10% Oil Tax*
15% Loans
55% Heavy Vehicle Tax
20% 1% increase in VAT

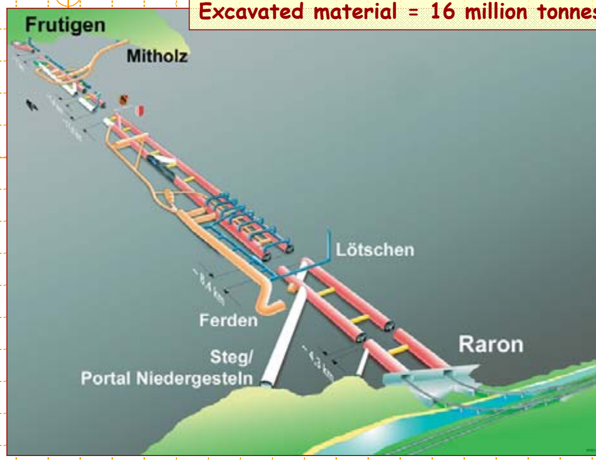


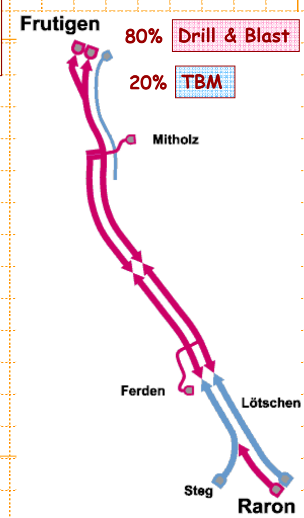
$23 Billion for entire project



Lötschberg Base Tunnel

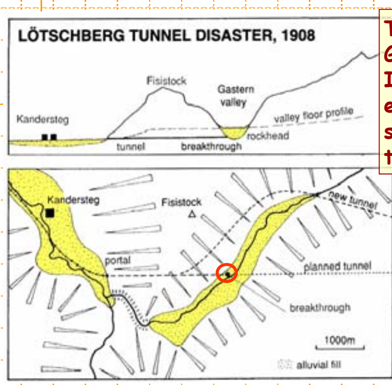
Length = 34.6 km
Total tunnel system = 88.1 km
Excavated material = 16 million tonnes





Geological Challenges: Lötschberg Base Tunnel

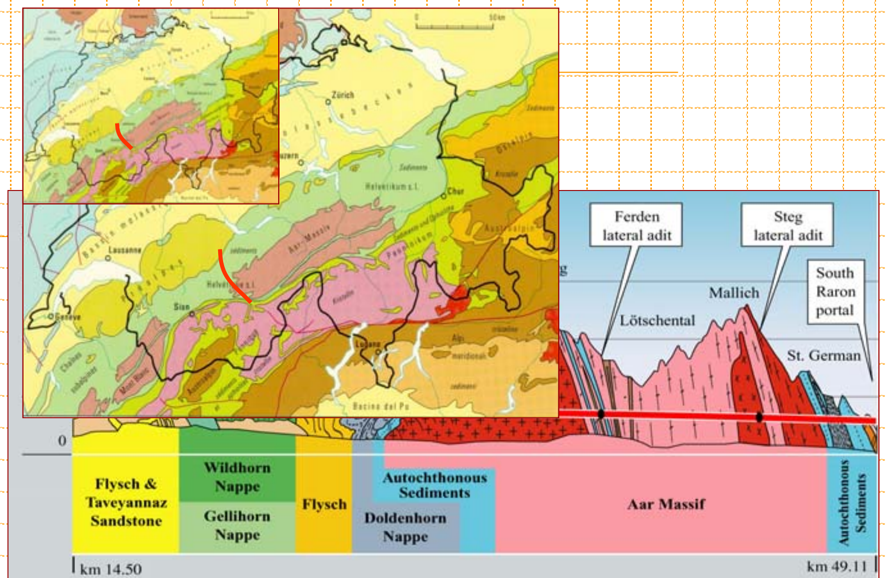
Buried Valleys: burial is the consequence of glacial down cutting and alluvial deposition. Buried valleys are a major concern in tunnelling as they are often deep (!!), with unknown thicknesses, and filled with water saturated sediments under high water pressures.



The path of the Lötschberg passed under the Gästern Valley, 200 m below the valley floor. It was estimated that the alluvial sediments extended 100 m below surface leaving 100 m of strong limestone to form the roof of the tunnel.

In actuality, the buried valley reached depths of more than 185 m. By July 24, 1908, the tunnel had advanced such that only a thin wall of rock divided the working-face from the buried valley. Within seconds of that morning's blast, 40,000m^3 of water saturated sediments swept into the tunnel killing 25 men and filling the tunnel for a distance 1.25 km.

Lötschberg Base Tunnel: Geological Prognosis

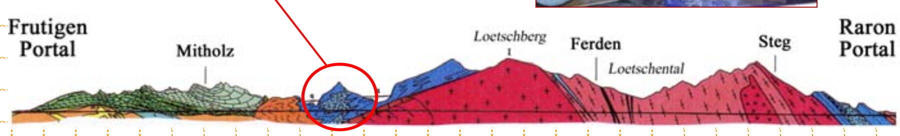


Loew *et al.* (2000)

Geological Challenges: Lötschberg Base Tunnel

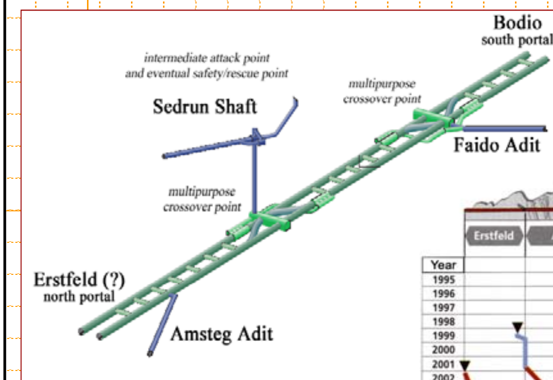
Karst:

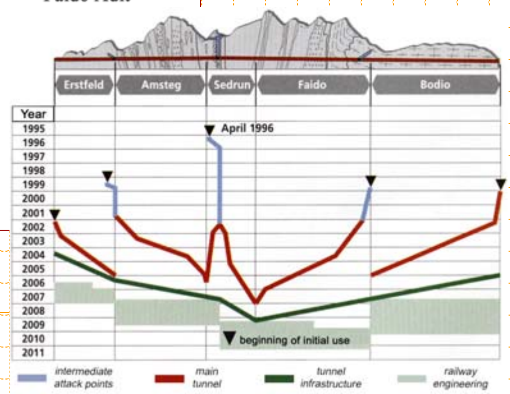
Given the porous nature of karst, large volumes of water and a high risk of water ingress was expected over a section about 3 km long. It was constantly necessary to carry out preliminary boring in order to discover whether any large, water-filled karst sink-holes might endanger the tunnel driving operations.



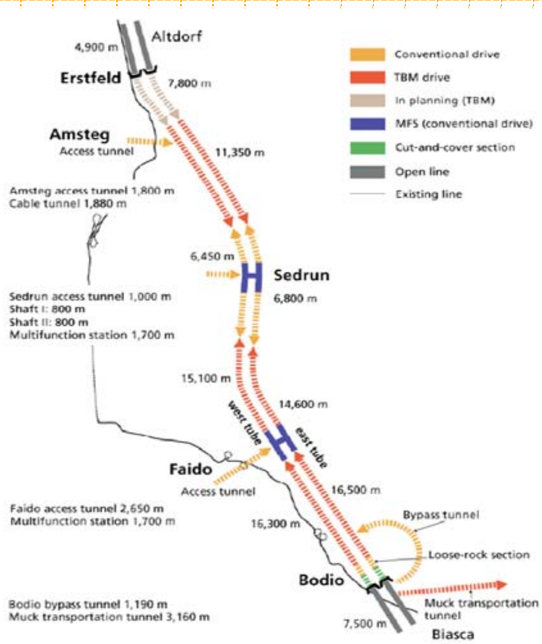
Gotthard Base Tunnel

Length = 57 km
Sedrun shaft = 800 m
Pillar = 40 m width
Excavated material = 24 M tonnes

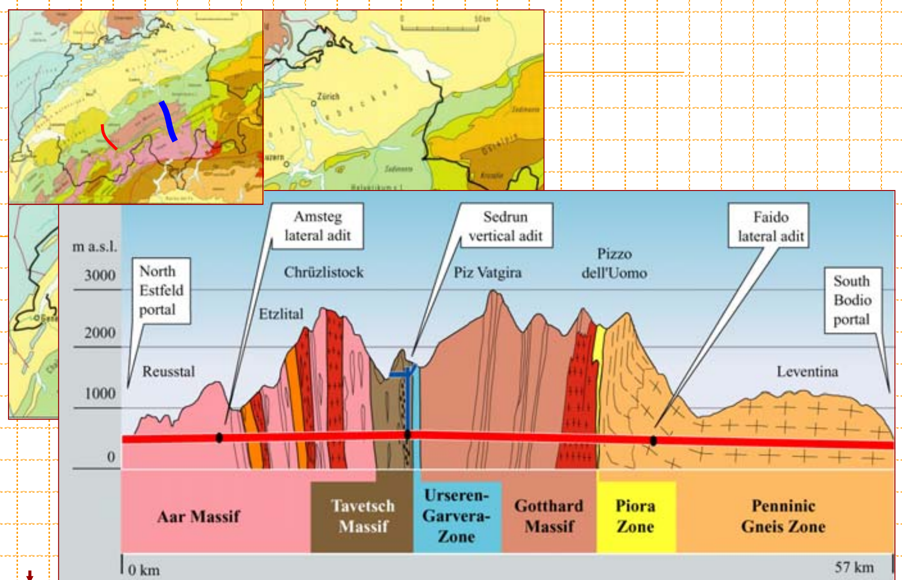




Gotthard Base Tunnel



Gotthard Base Tunnel: Geological Prognosis



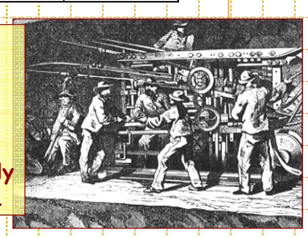
Loew et al. (2000)

Geological Challenges: Gotthard Base Tunnel

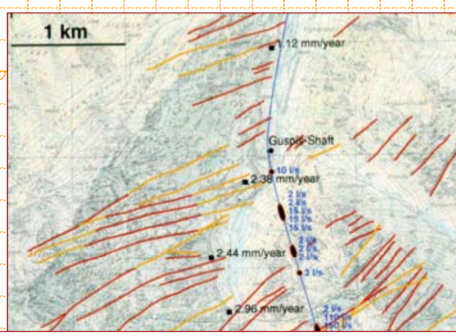
Geologic Unit	Potential Key Hazard	Tectonic Unit	Max. Length
Cataclastic Faults	High pressure water inflow.	Crystalline Massifs, Penninic Gneisses	~100 @ 5m
Weak Rocks (Phillites, Schists, Cataclasites)	Strongly squeezing ground.	Crystalline Massifs	1.3 km
Granites	Rockburst.	Crystalline Massifs	>14 km
Sugar Grained Dolomites	Water saturated debris inflow, cohesionless rock.	(Par)autochthonous Triassic Sediments	~200 m

Loew et al. (2000)

The first Gotthard rail tunnel was constructed between 1872-1882, and cut the travel time from Zurich to Milan from 27 to 5.5 hours. However, 310 men died and 877 were incapacitated during construction of the 14.9 km tunnel. Numerable challenges and harsh conditions were encountered, many of which were augmented by the equally harsh contract signed by the tunnel designer Louis Favre .

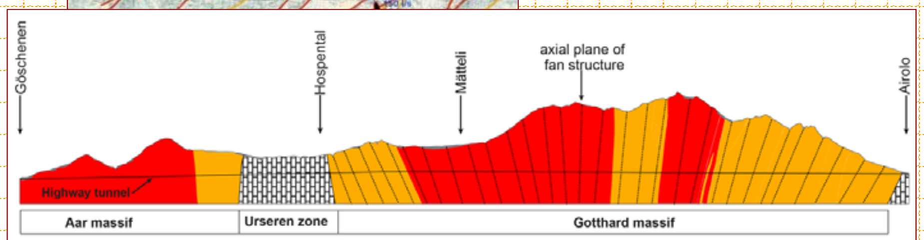


Geotechnical Challenges: Known Knowns

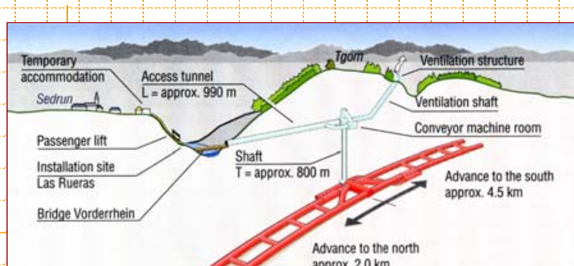


Brittle Fault Zones

Zangerl et al. (2006)

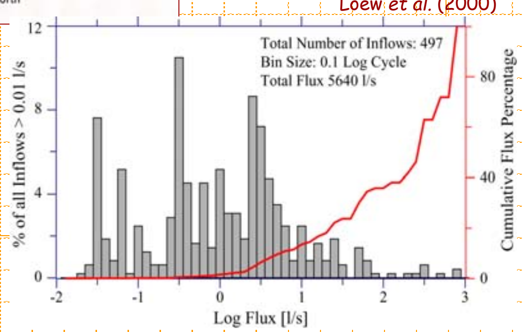


Brittle Fault Zones - Water Inflows

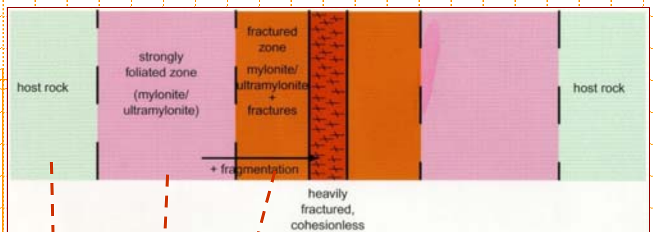


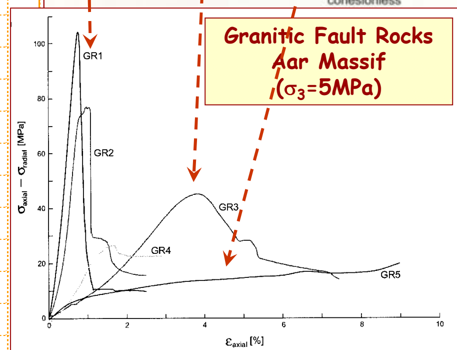
Loew et al. (2000)

Fault zones may form highly permeable conduits for groundwater, leading to tunnel inflows. Encountering large quantities of water may lead to flooding of the excavation, especially if there is no outlet for the water to drain to.



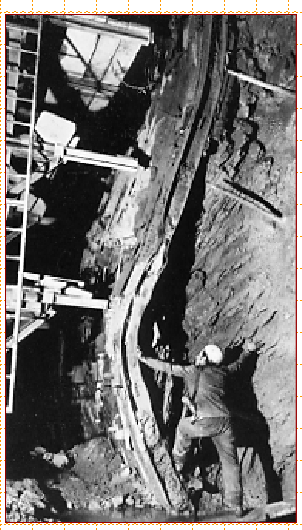
Brittle Fault Zones – Weak Ground

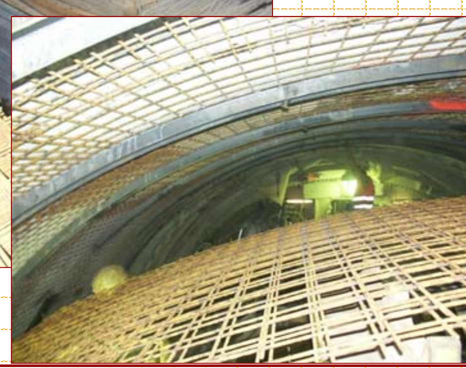




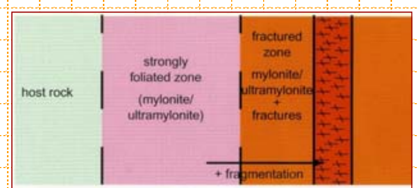
Laws *et al.* (2003)

Brittle Fault Zones – Ground Support

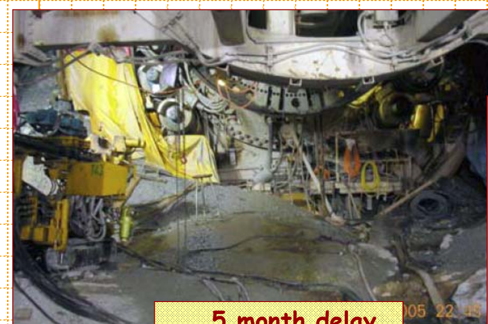




Amsteg (June 2005) – West TBM

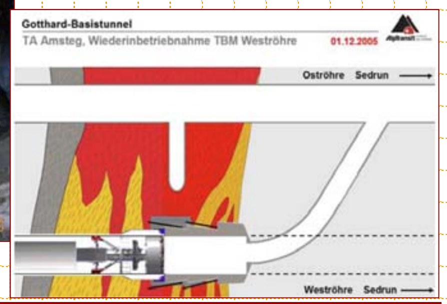


... West TBM crosses hydrothermally altered rock adjacent to fault zone, enounters flows of 2-3 l/s that flushes loose material into the cutter head.

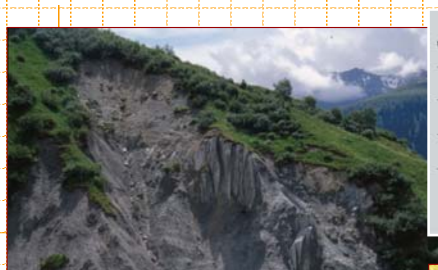


... 5 month delay, $10 million cost.

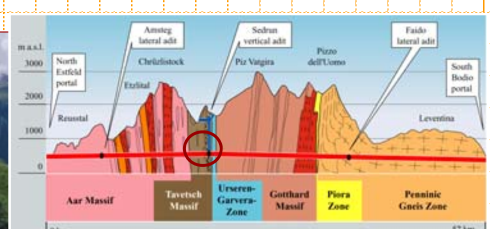
Ehrbar (2008)



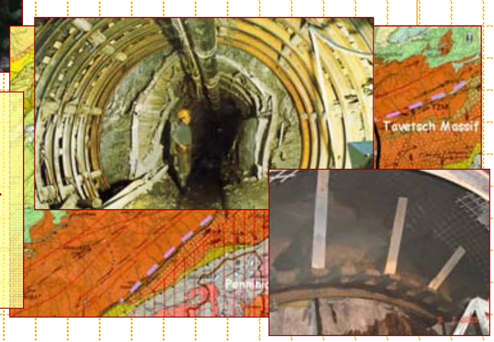
Geotechnical Challenges: Known Knowns



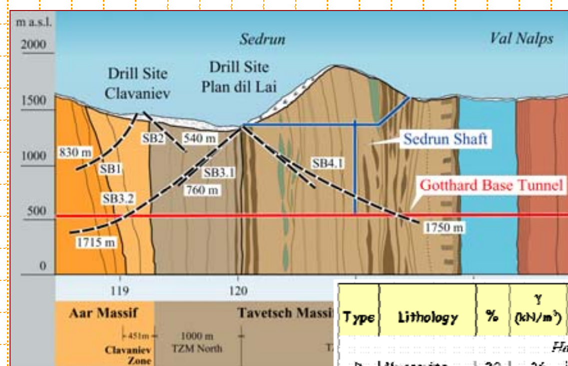
Squeezing Ground – Tavetsch Massif



Squeezing ground refers to weak, plastic rock material which displaces into the tunnel excavation under the action of gravity and induced stresses. This squeezing action may result in damage/failure to the ground support system, or require the costly re-excavation of the tunnel section.



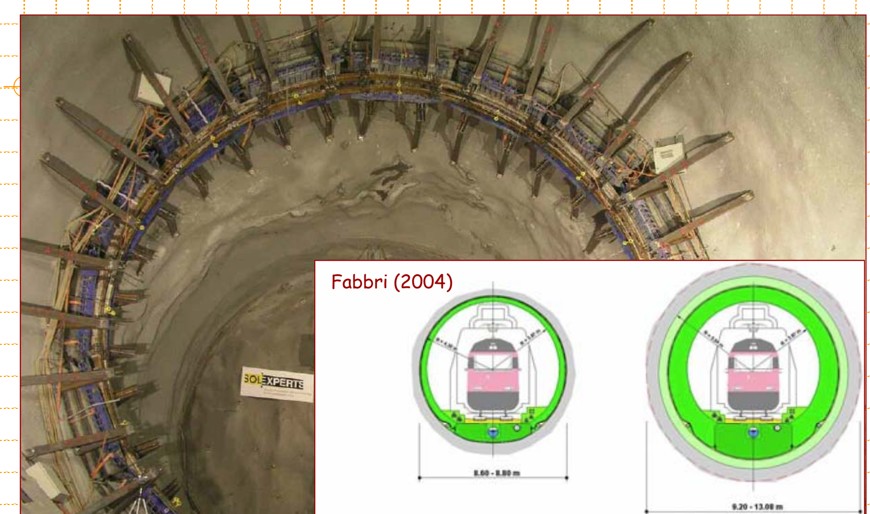
Geotechnical Challenges: Squeezing Ground



Ehrbar & Pfenninger (1999)

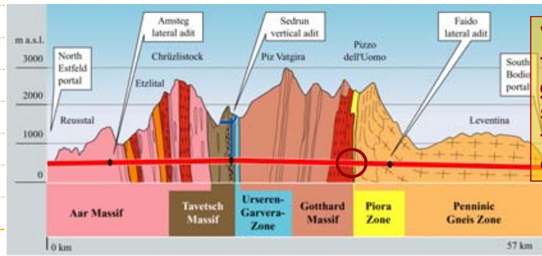
Type	Lithology	%	γ (kN/m³)	E GPa	ν [-]	ϕ Peak [°]	ϕ Res. [°]	c Peak [kPa]	c Res. [kPa]
	Hard and brittle rocks								
D	Muscovite Gneiss	29	26	25	0.20	36	34	2000	500
	Soft and ductile rocks								
F	Schist	8	26	15	0.20	30	30	150	150
G	Phyllite	1	26	10	0.25	28	28	100	100
	Ductile Cataclastic Rocks								
D	Cataclastic Gneiss	24	24 - 26	20	0.25	34	34	400	400
F	Cataclastic Schist	14	24 - 26	12	0.20	30	30	120	120
G	Cataclastic Phyllite	1	24 - 26	8	0.25	28	28	75	75
H, J	Cohesionless Cataclasite	23	24 - 26	2-7.5	0.30	24	26	75	250

Squeezing Ground Support

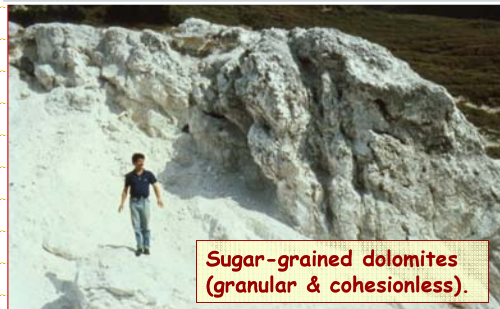


Deformation	0 cm	70 cm
Rock support	5 cm	50 cm
Inner lining	min. 30 cm	60 - 120 cm

Geotechnical Challenges: Known Unknowns

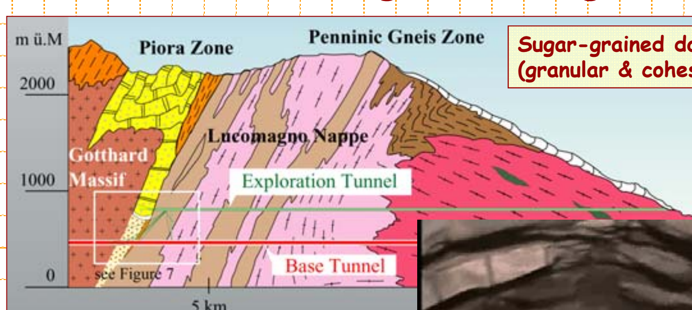


Where ground possesses the ability to flow freely (i.e. "running ground"), for example with water saturated cohesionless materials, then special support and control difficulties can arise.



Sugar-grained dolomites (granular & cohesionless).

Geotechnical Challenges: Running Ground

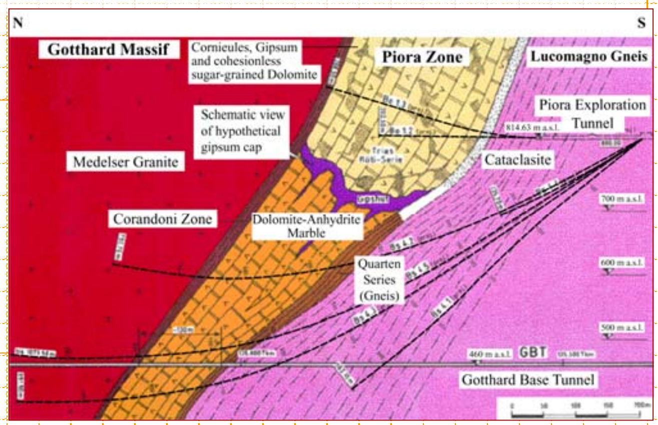


Sugar-grained dolomites (granular & cohesionless).

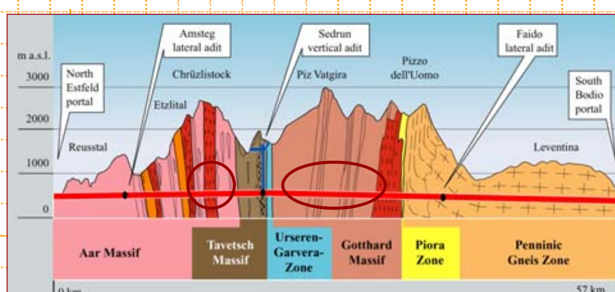
Geotechnical Challenges: Running Ground

The tunnel will cross the Triassic Piora Zone, a highly weathered and fractured aquifer under high hydraulic pressure. Based on exploratory drilling, it was found that the tunnel will pass ~250 meters below the base of the aquifer through unweathered and unfractured dolomite/ anhydrite-sequences.

Considered the greatest geological risk to the feasibility and success of the tunnel project, in Nov. 2008 the TBM passed safely through the Piora.

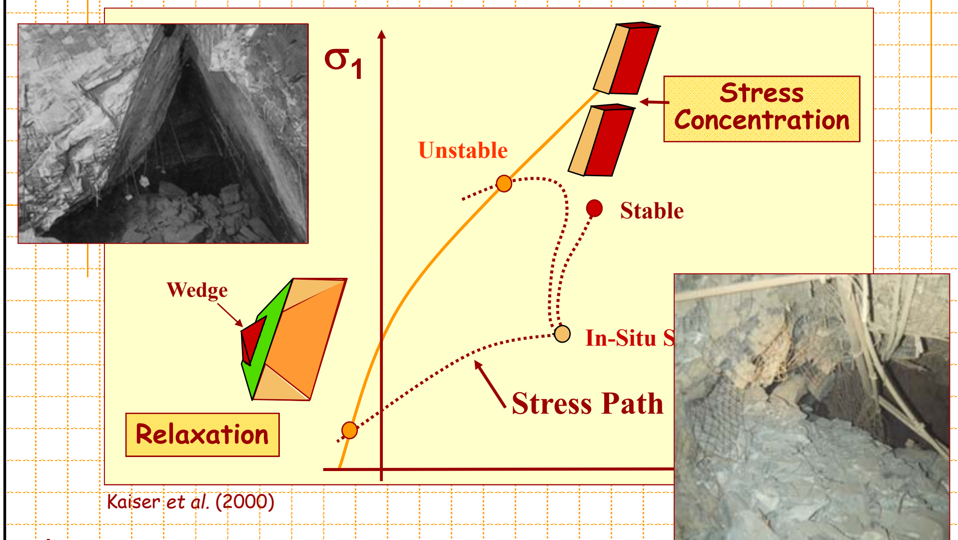


Geotechnical Challenges: Known Unknowns



Rockbursts involve sudden releases of stored strain energy through the failure of strong rock. They manifest themselves through the sudden ejection of rock into the excavation. Rockbursting potential is of special concern in cases of deep tunnelling where high stress concentrations form due to overburden loads or tectonic activity.

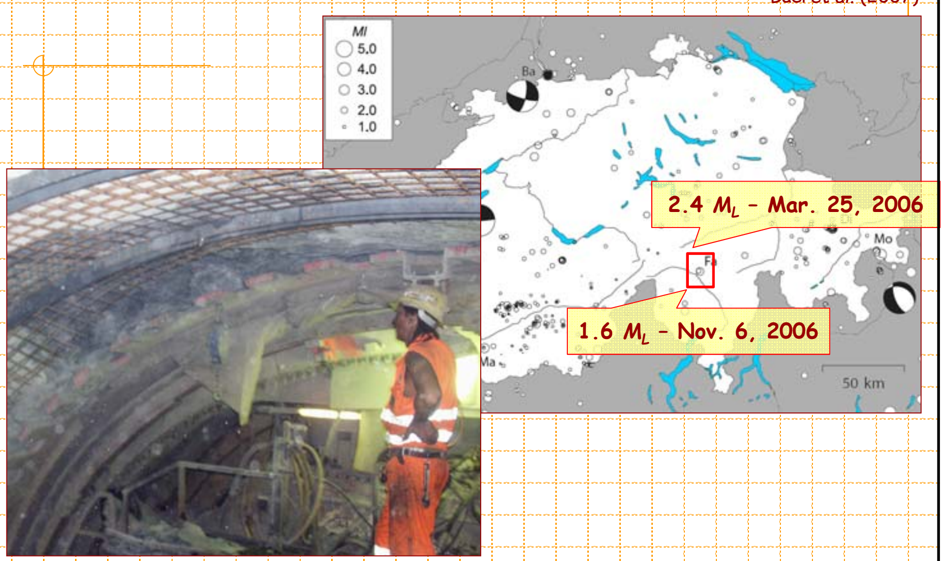
Stress-Controlled Failure & Stress Path



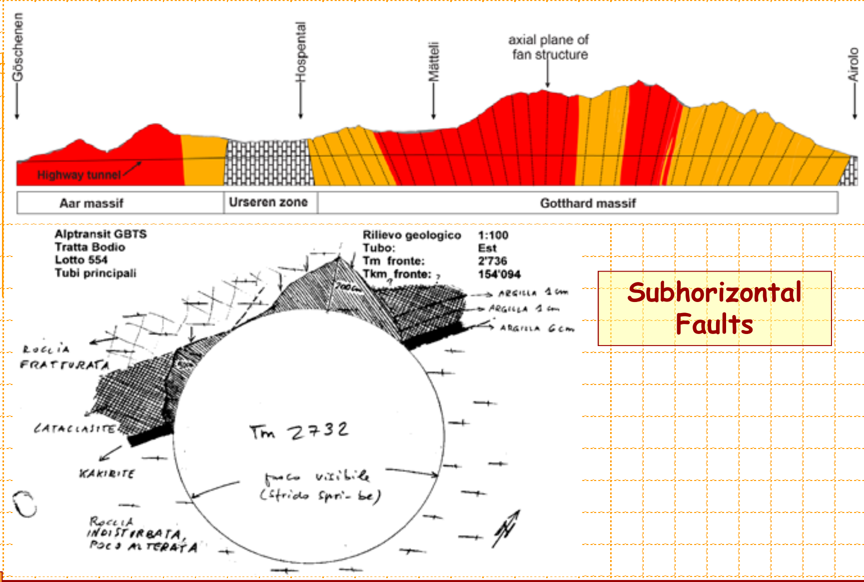
Kaiser *et al.* (2000)

High Overburden – Spalling & Rock Bursting

Baer *et al.* (2007)

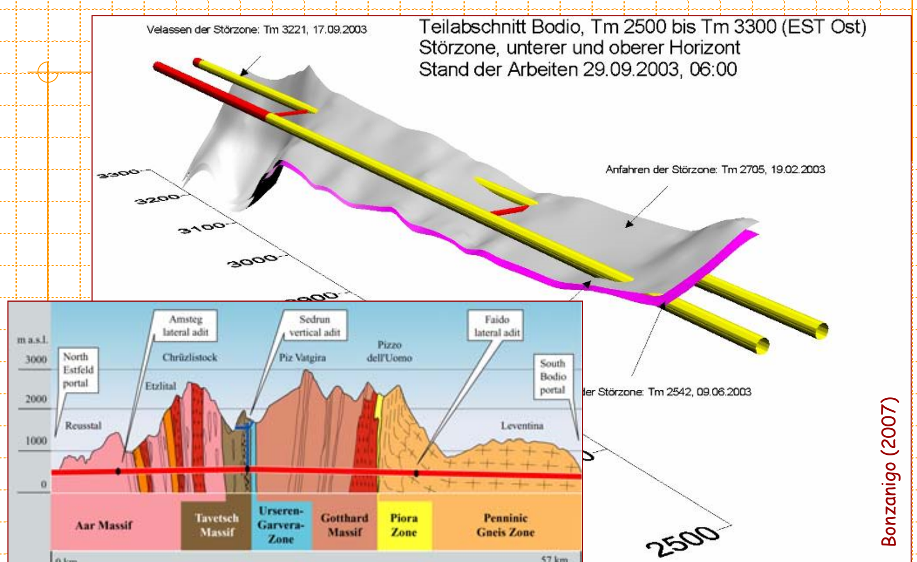


Geotechnical Challenges – Unknown Unknowns



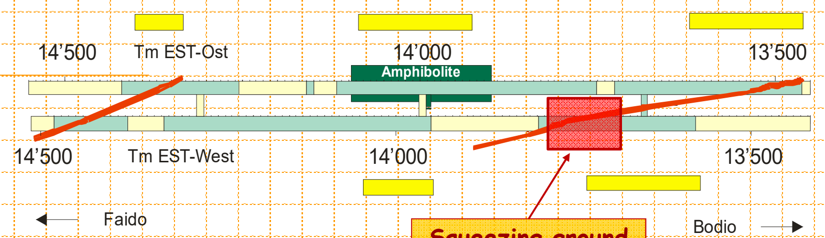
Subhorizontal Faults

Faido-Bodio: "Unexpected" Faults



Bonzanigo (2007)

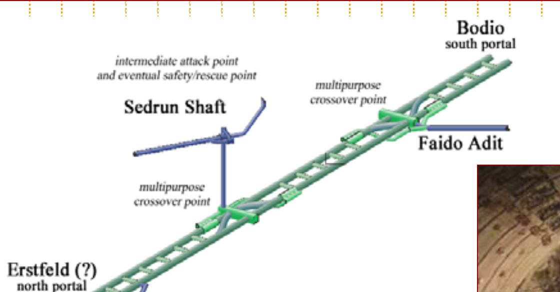
Faido-Bodio: "Unexpected" Faults



Squeezing ground blocks TBM

The total delay for passing through these faults along this section: ... one year.

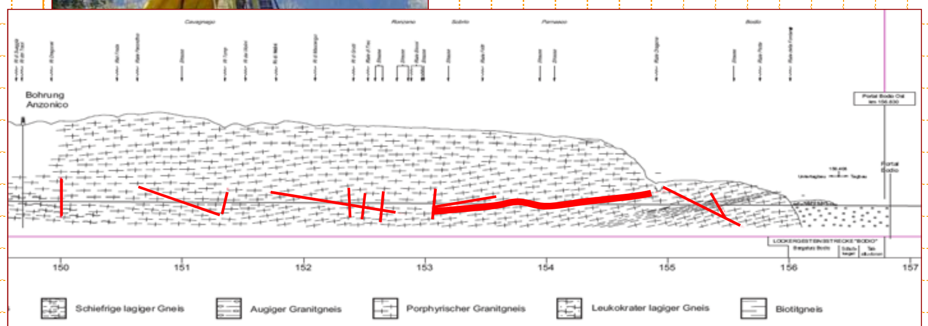
Fault Zones & the Faido Cross-Over



Ehrbar (2008)

Similar ground conditions (i.e. unexpected faults) at the Faido multipurpose cross-over station were responsible for a further 2-year delay and was over budget by more than 200%.

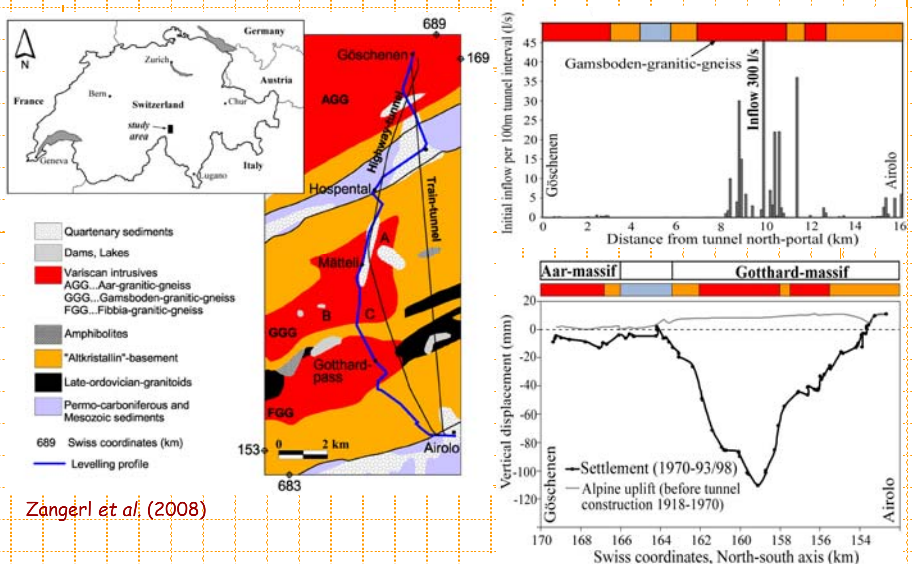
Faido-Bodio: "Unexpected" Faults



"Unexpected" Subsidence in Crystalline Rock

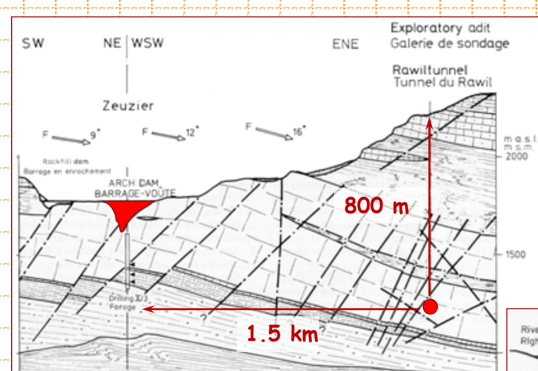
Sure…
when cows
fly!

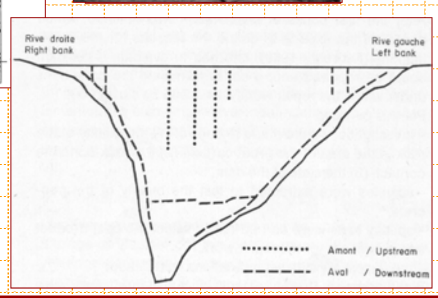
"Unexpected" Subsidence in Crystalline Rock



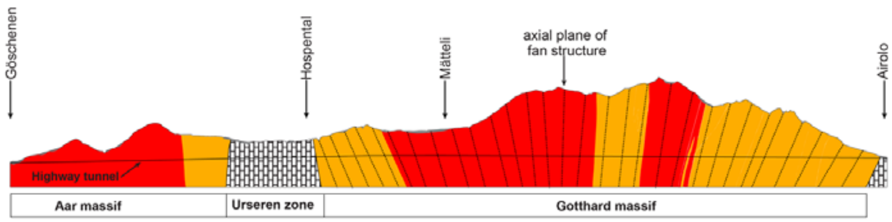
Zangerl *et al.* (2008)

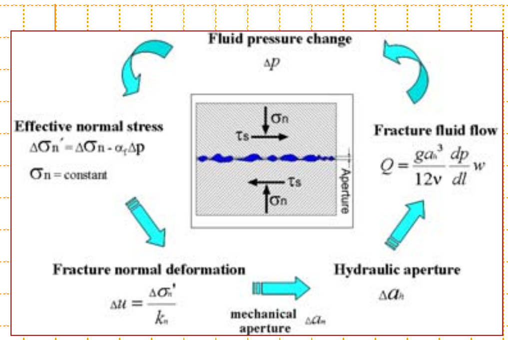
"Unexpected" Subsidence in Crystalline Rock

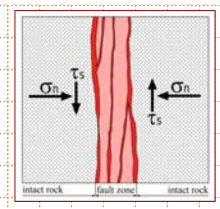




"Unexpected" Subsidence in Crystalline Rock





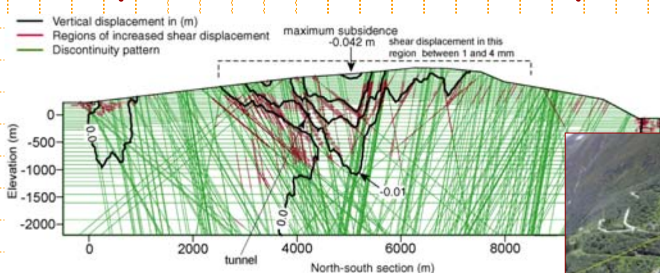


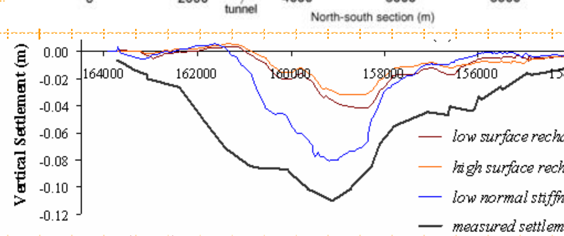
$\Delta\sigma_n{}' = \Delta\sigma_n - \alpha_f \Delta p$ ⇨ normal deformation (i.e. closure)

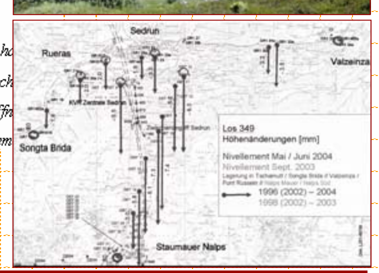
⇨ dilation due to shear

$\sigma_n \neq$ constant ⇨ "Poison ratio" effect

"Unexpected" Subsidence in Crystalline Rock

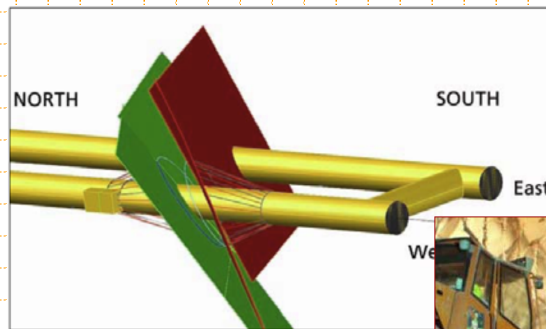






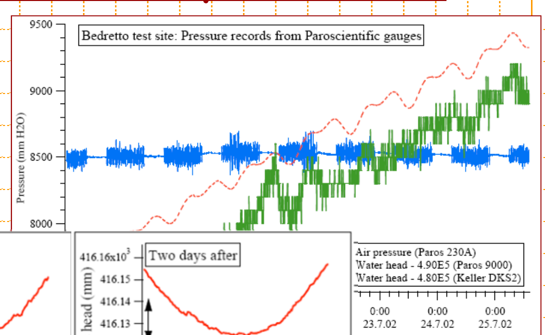
Zangerl et al. (2008)

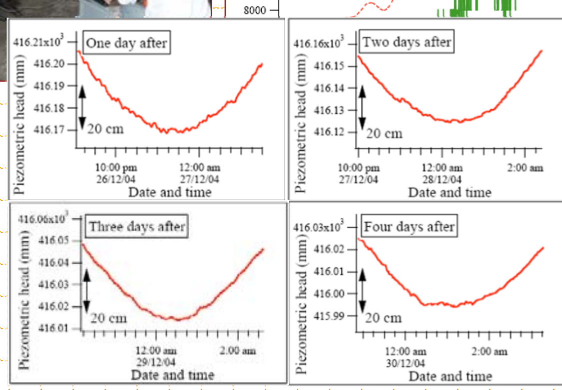
"Unexpected" Subsidence in Crystalline Rock



Grouting of fault zone with 13 l/s inflow, near Nalps Dam.

"Unexpected" Subsidence in Crystalline Rock



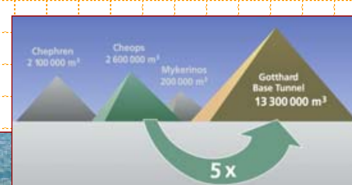


GBT: Other Geological Challenges

Bodio

GBT: Other Geological Challenges

Given that tunnel overburden will exceed 2000m, temperatures as high as 45°C are projected. In addition, silicosis, an incurable disease of the lungs, caused by the unprotected respiration of quartz dust presents a potential hazard to workers. Ventilation designs must account for both factors to ensure worker safety.



More than 13 million m^3 of waste rock will be generated, leading to environmental issues as to where to put it. At the same time, the extraction of gravel resources for concrete in the Swiss midlands is becoming more difficult. The solution, therefore, was to specially break, sort & wash the waste rock so that it could be used for concrete aggregate.

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