Lessons learned from tunnelling in sulphate-bearing rocks

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A quote

«The opposite of theory is not the practice but the observation, the experimental research. And the opposite of practice is not the theory, but the science which consists of theoretical and experimental research.»

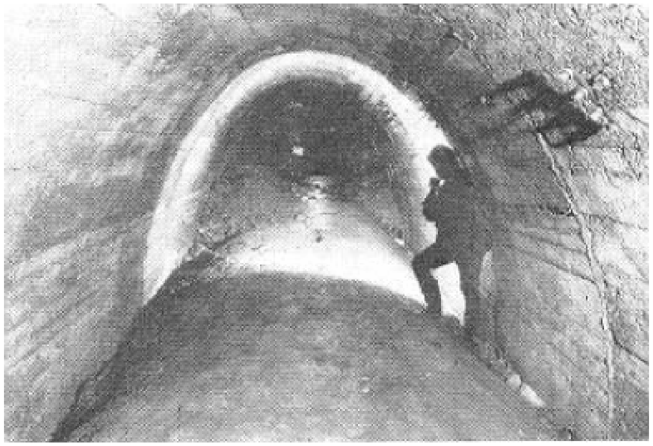
Paul Fillunger (1935)

Causes of Rock Swelling

- Occurrence of expansive clayey minerals (Smectite, Chlorite, etc)
  - Suction in interstitial water: suction reduction and hydration of expansive clayey minerals in the presence of free water
  - Debonding: degradation due to loading-unloading & wetting-drying in cemented under load rocks (*strain energy locked*)
- Crystal growth
  - Oxidation/reduction processes: transformation of minerals in aggressive environments (e.g. pyrite oxidation)
  - *Via solventis*: occurrence of mineralized solutions capable of precipitate crystals on discontinuities

Damage in Tunnels due to Swelling in SBR

Tunnels in the Gipskeuper (Germany and Switzerland)



Wagenburg PG (1974)
Baden-Württemberg (Spaun, 1974)

Belchen (1967)
Jura Mountains (Amstad & Kovári, 2001)

Tunnels in the Lower Ebro Basin (Spain)

Camp Magre (2002)

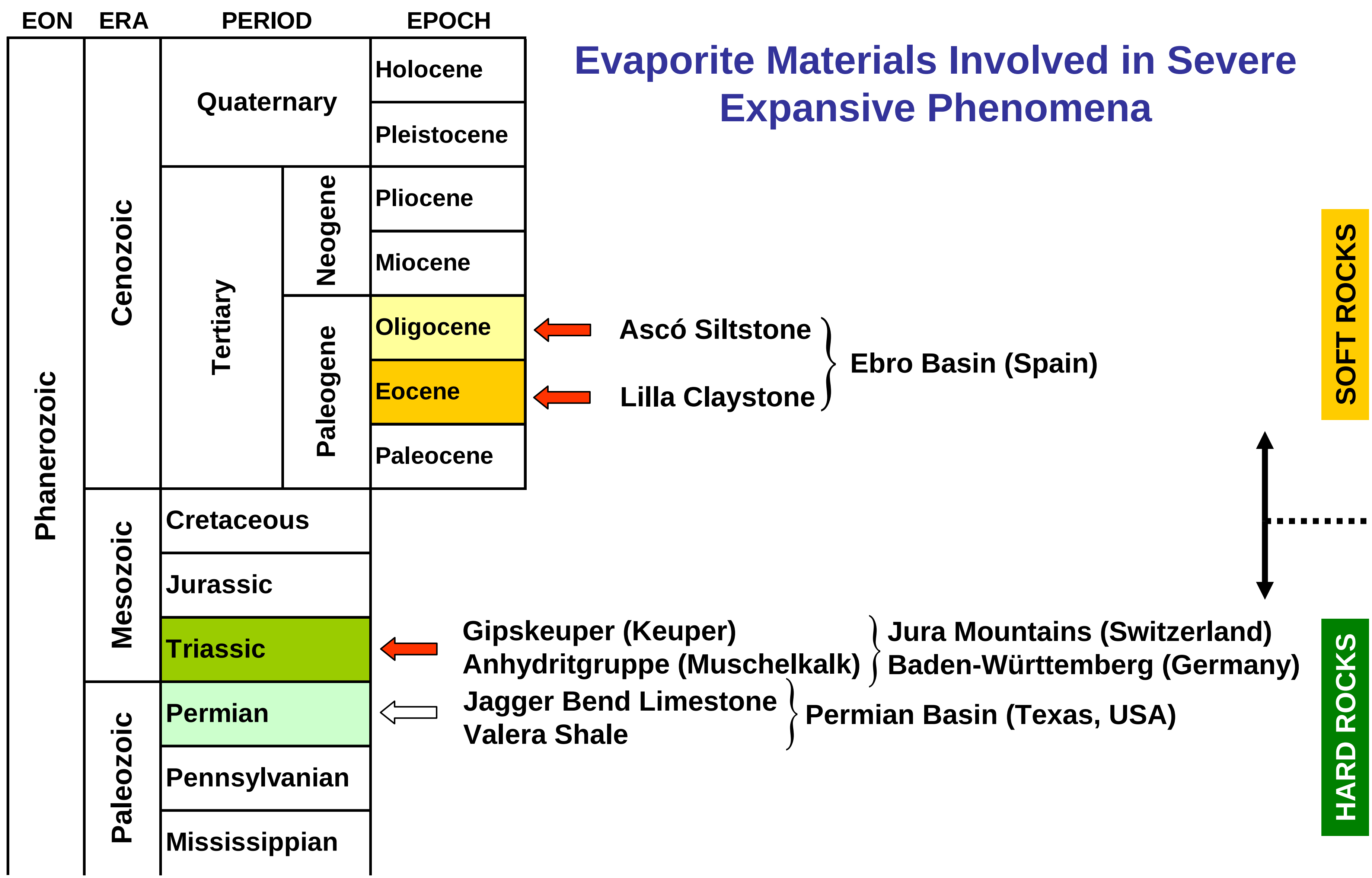
Lilla (2003)

Outline of the lecture

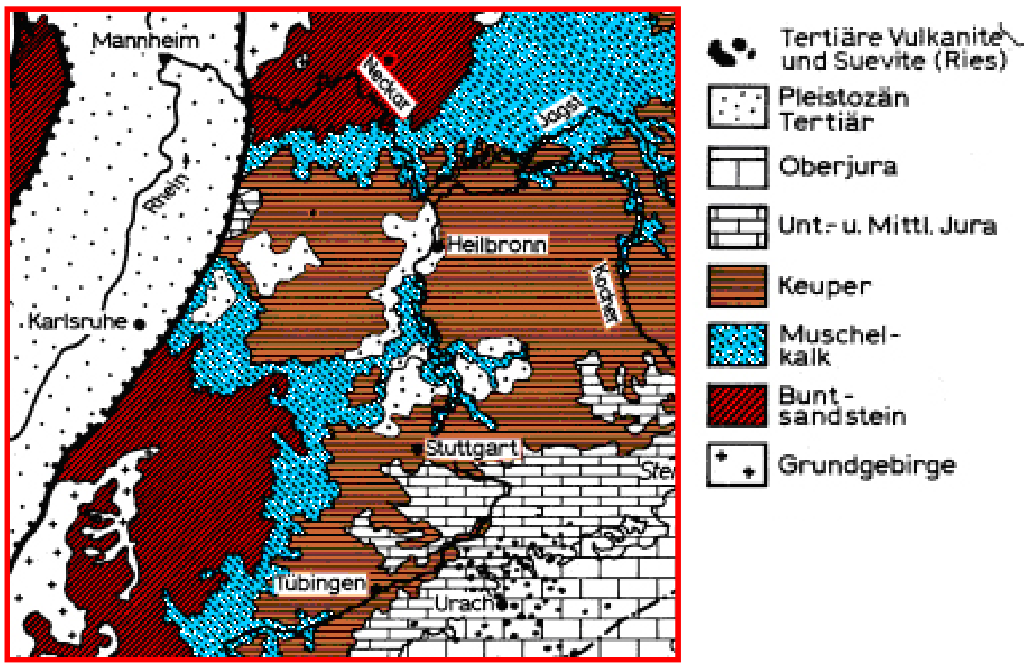
1. Sulphate-bearing rocks (SBR) and sulphate-rich waters (SRW)
2. Phenomenology of swelling in SBR
3. Alternative support designs in Lilla Tunnel
4. Swelling mechanisms in SBR

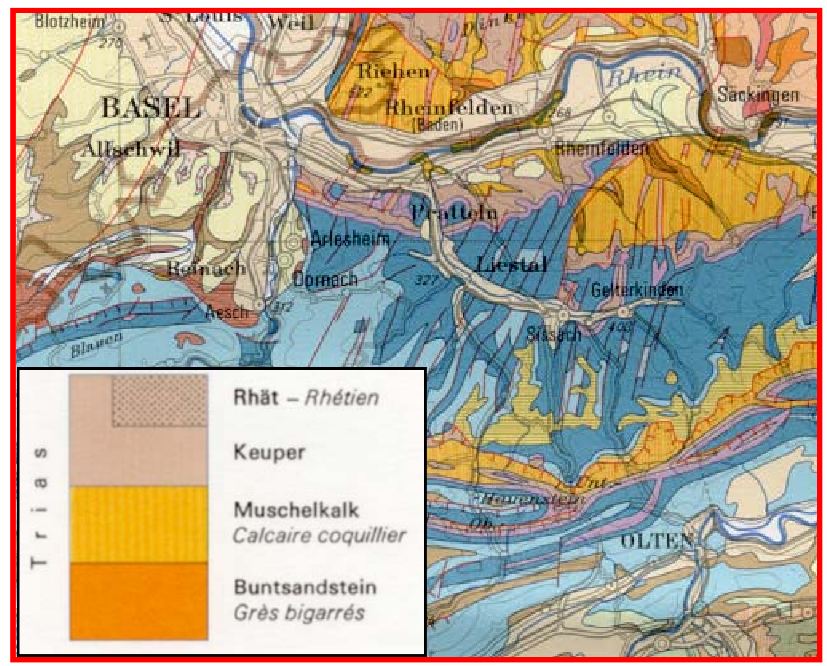
1. Sulphate-bearing rocks and sulphate-rich waters

Sulphate-Bearing Rocks



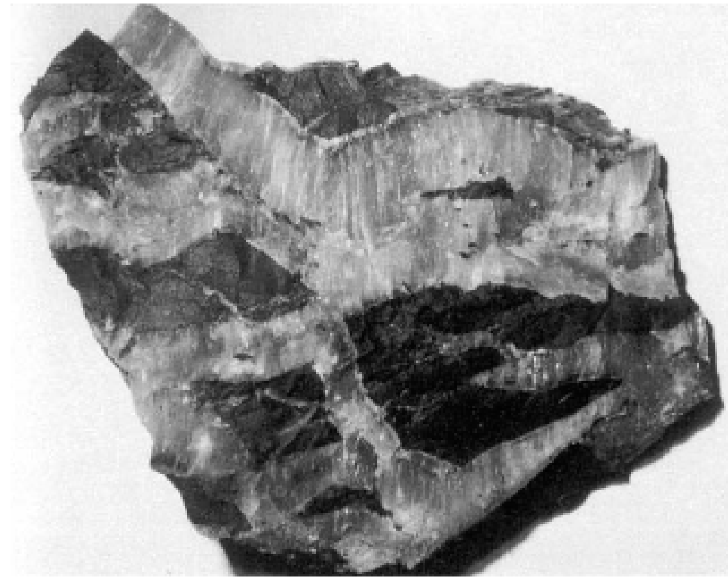
Triassic SBR from Baden-Württemberg and Jura Mountains





Triassic SBR from Baden-Württemberg and Jura Mountains

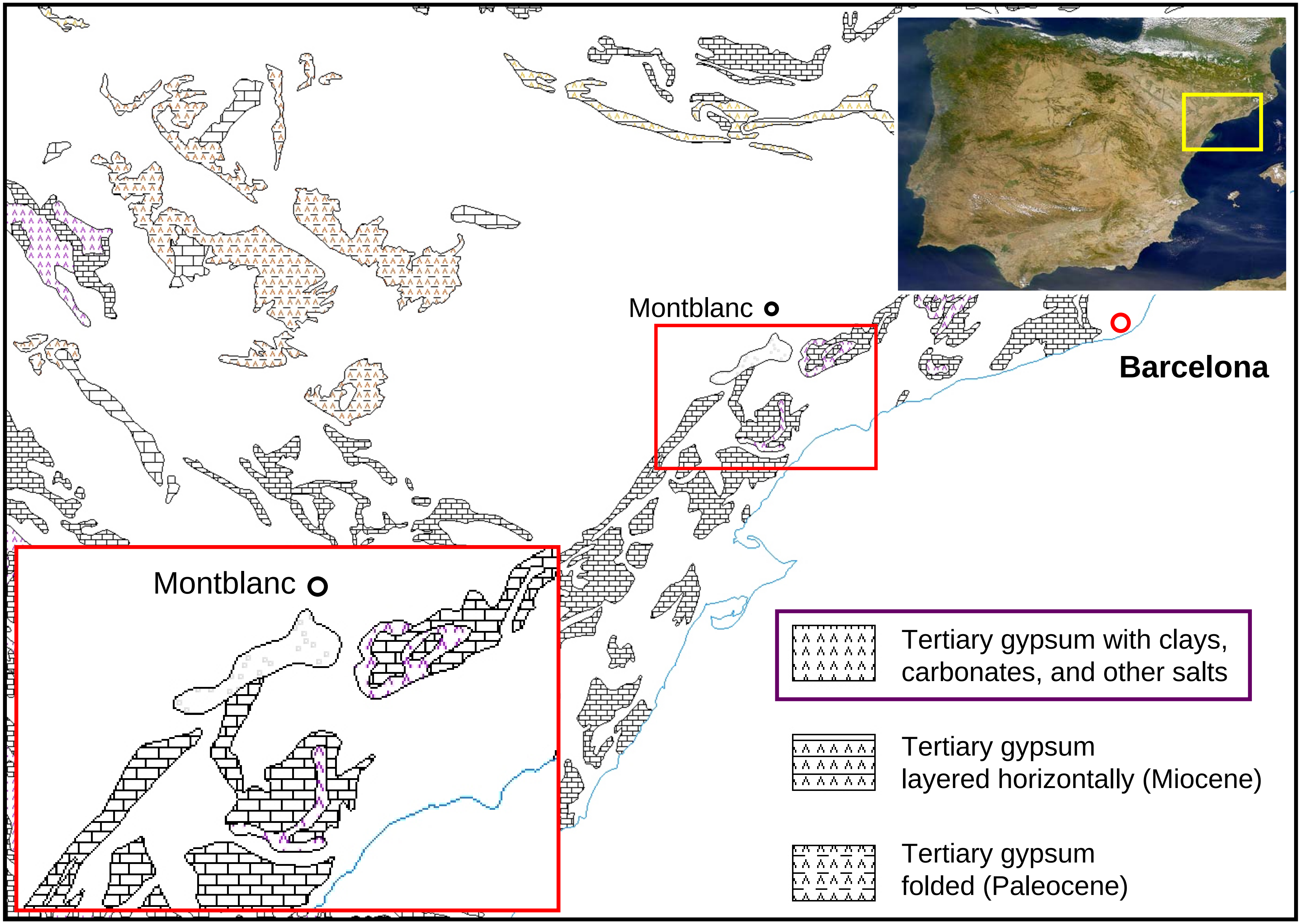
Anhydritgruppe (Muschelkalk)



Gipskeuper (Keuper)

	Mineralogical composition (%)								
Material	Anh	Gyp	Clay	Carb	Qtz	Feld	Gs	w (%)	ρt (Mg/m^3)
Anhydritgruppe	45	1	2	1	1	1	2.66	1.0	2.0
	90	4	50	25	15	5	2.86	3.0	2.4
Gipskeuper	30	1	5	0	5	1	2.60	0.5	2.2
	75	20	20	20	20	5	2.84	4.5	2.4

Tertiary SBR from the Lower Ebro Basin



Tertiary SBR from the Lower Ebro Basin

Ascó Siltstone		Lilla Claystone	
Mineralogy relative content (%)			
Quartz	8.1	Quartz	2 – 7
Dolomite	18.2	Dolomite	11 – 13
Calcite	34.3	Calcite	–
Anhydrite	11.1	Anhydrite	13 – 28
Gypsum	9.1	Gypsum	0 – 7
Clay (Illite, Paligorskite & Smectite)	16.2	Clay (Illite & Paligorskite)	51 – 67
Other	3.0	Other	–
Physical and Mechanical Properties			
Gs	2.71	Gs	2.82 – 2.90
Water content (%)	2.4 – 4.3	Water content (%)	0.5 – 4.5
Total density (Mg/m^3)	2.56	Total density (Mg/m^3)	2.40 – 2.86
qu (MPa)	19 – 50	qu (MPa)	17 – 170

Sulphate-Rich Waters

Gipskeuper & Anhydritgruppe (Triassic)

Project	SO_4 concentration (ppm)	Reference
Weinsberg tunnel	up to 1500	Gremminger & Spang (1978)
Kappelesberg tunnel	1957 – 2755	Krause (1975)
Adler tunnel	2990	Chiaverio & Hürzele (1996)
Belchen tunnel	up to 6000	Grob (1972)
Belchen tunnel	1290	Werder (1989)
Freudenstein tunnel	up to 5600	Berner (1991)
Engelberg Base tunnel	> 8600	Kuhnhenn (1979)

Lower Ebro Basin (Tertiary)

Macroconstituent	Ascó II NPS	Lilla tunnel
	Concentration (ppm)	
Sulphates	2800	1783
Bicarbonates	215	302
Chlorides	25700	39
Carbonates	40	10
Nitrates	-	6
Calcium	202	500
Magnesium	568	141
Sodium	13486	29
Potassium	-	3

Sulphate-Bearing Rocks & Sulphate Rich Waters

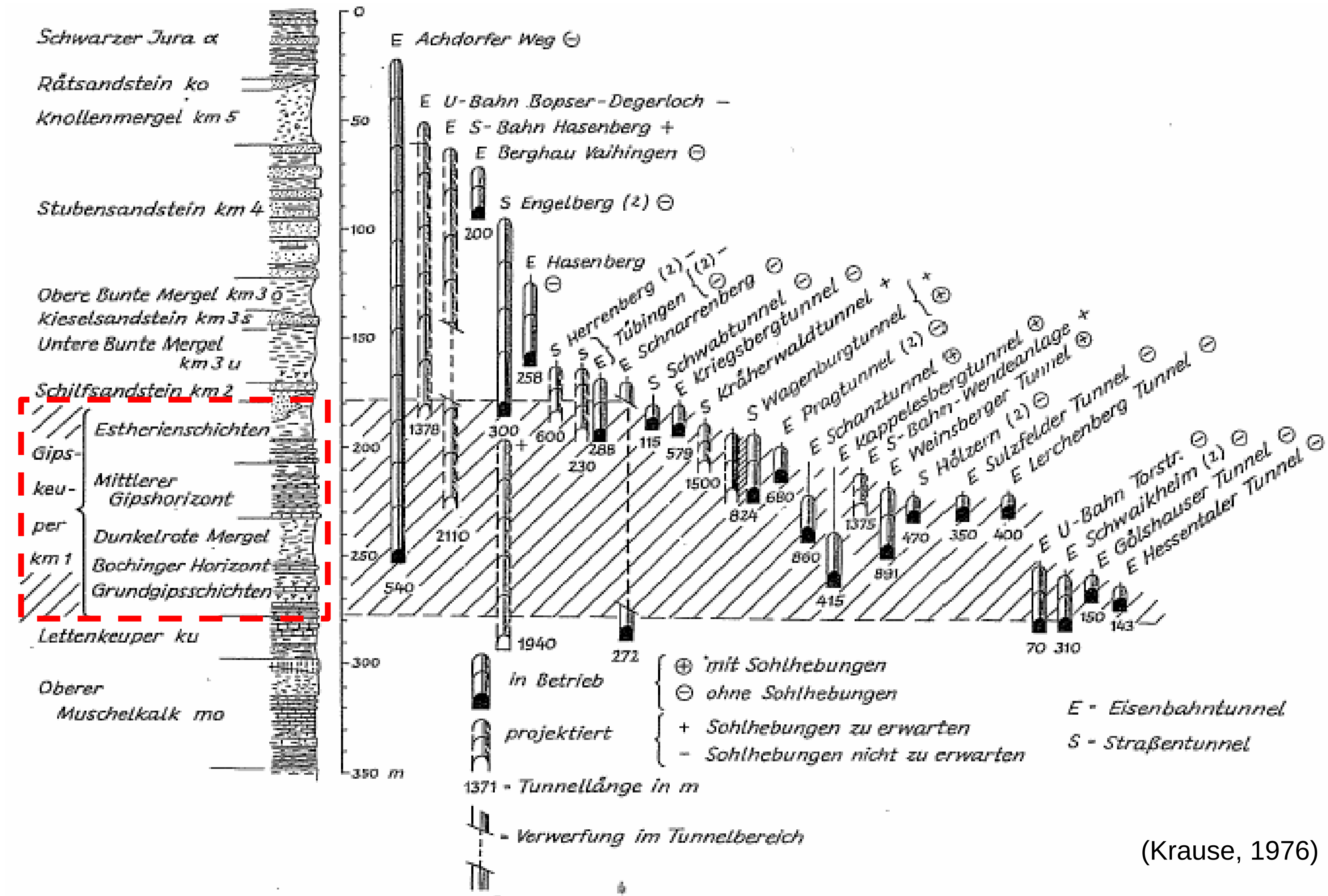
Some Key Features

Gipskeuper & Anhydritgruppe (Triassic)	**Ebro Basin Siltstones & Claystones (Tertiary)**
• **Hard rocks** • **Massive anhydrite is present** • **Matrix with active clays (Corrensite)**	• **Soft rocks** • **Massive anhydrite is not present** • **Matrix without active clays (Illite, Paligorskite)**

¡High sulphated water occur in both cases!

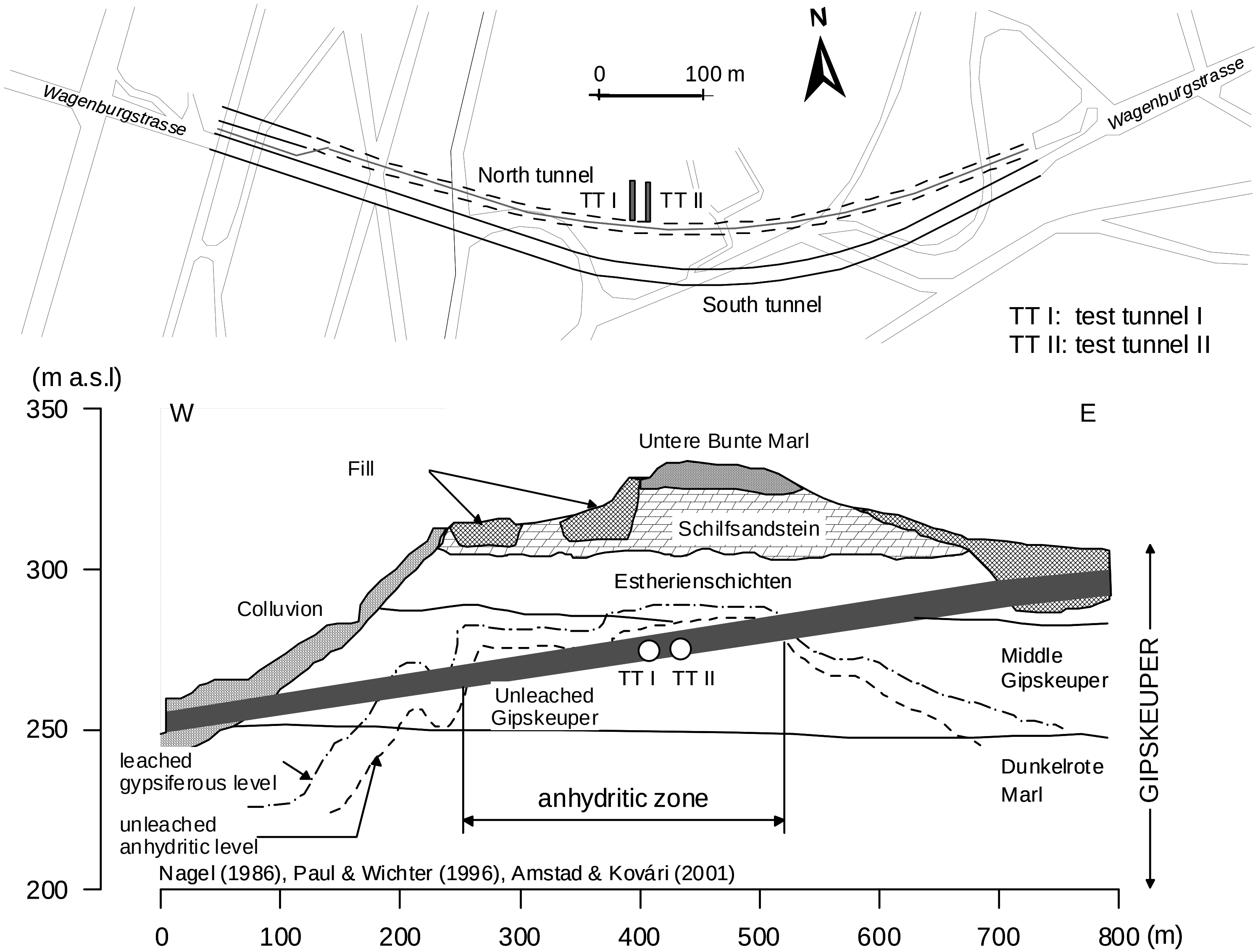
2. Phenomenology of swelling in sulphate-bearing rocks

Tunnels in SBR from Baden-Württemberg



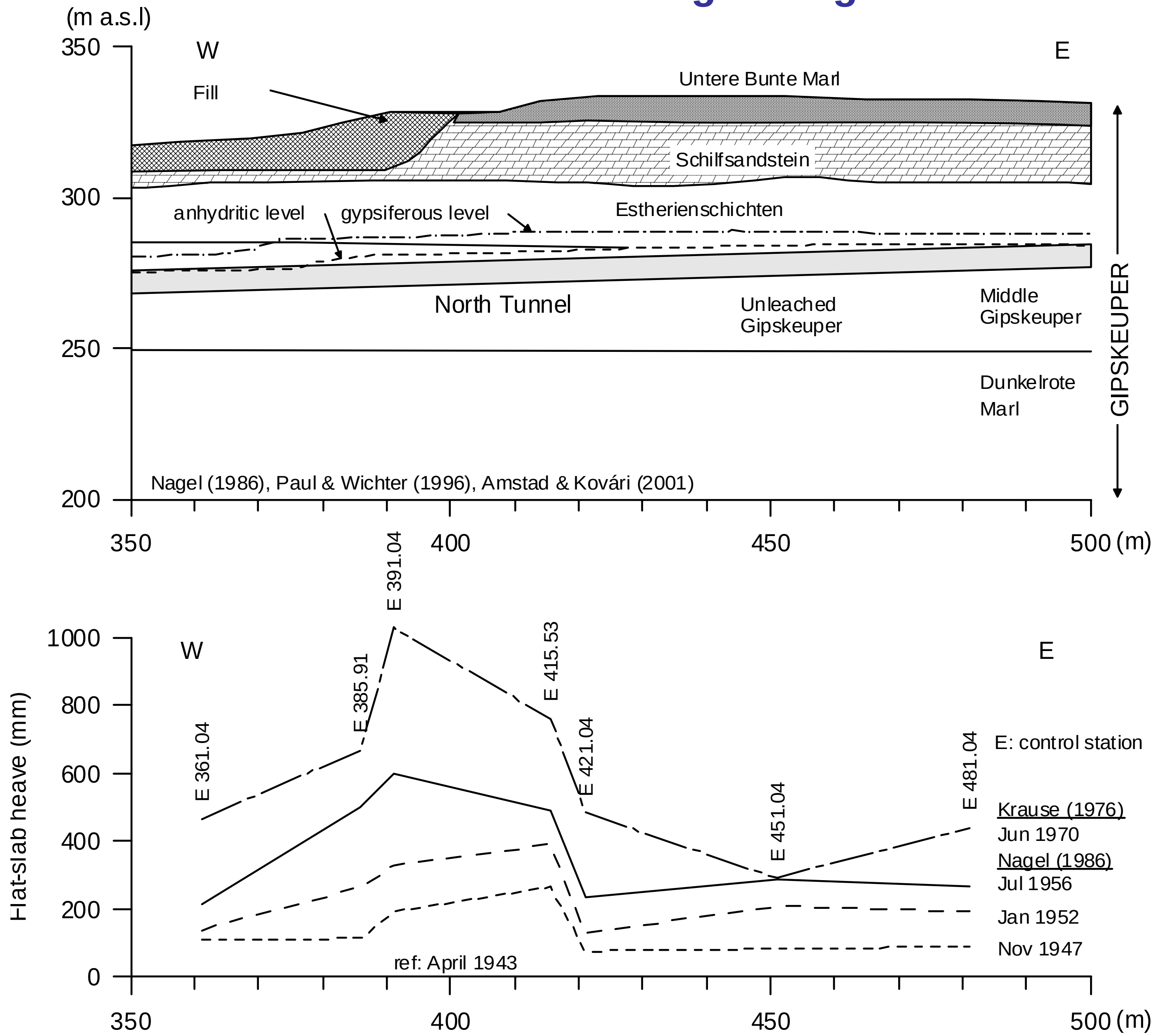
(Krause, 1976)

Tunnels in SBR from Baden-Württemberg

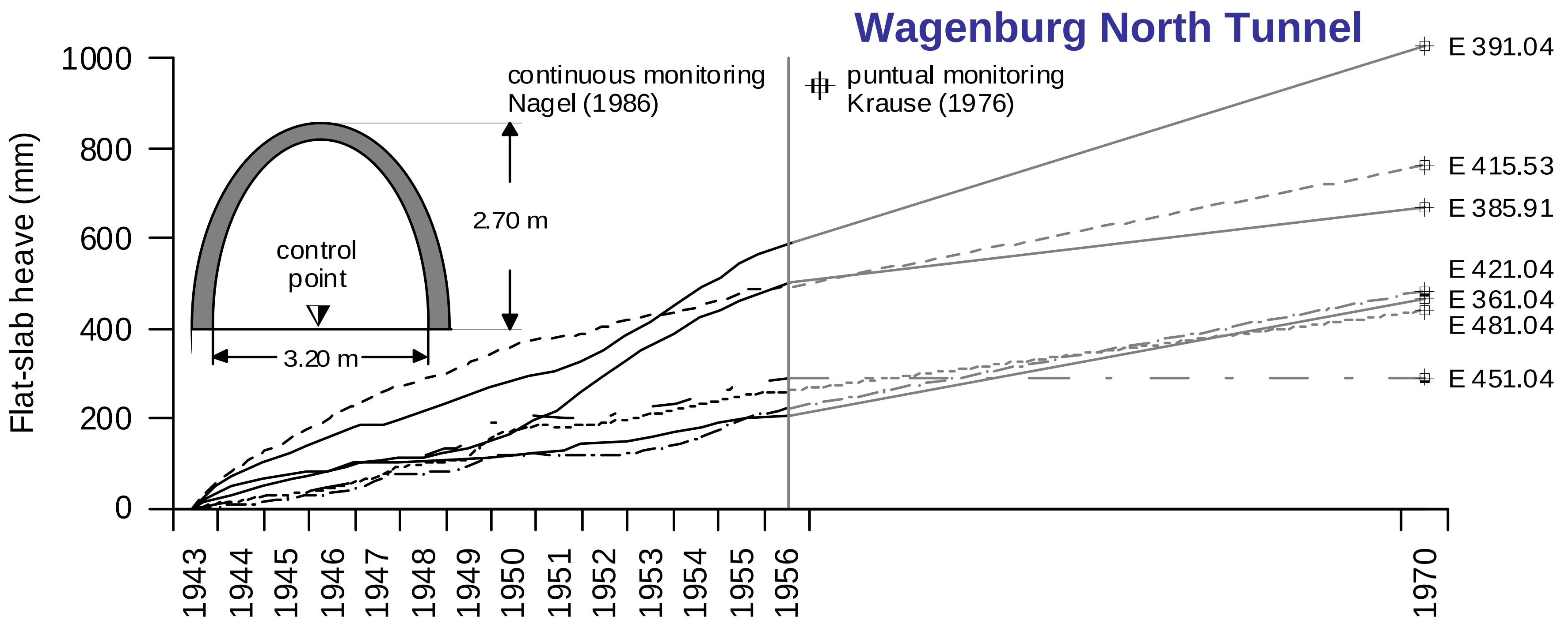


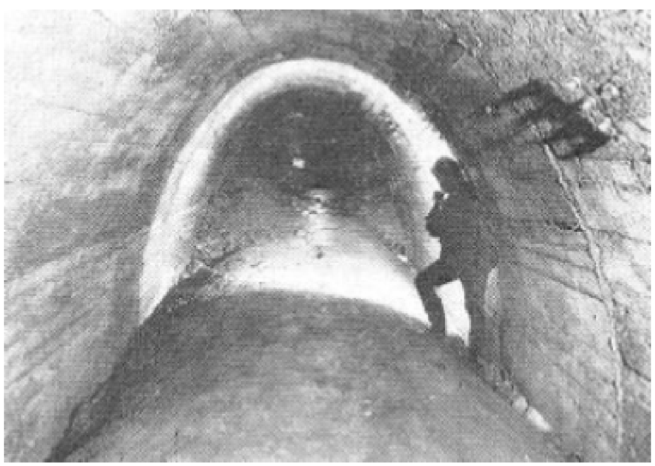
Tunnels in SBR from Baden-Württemberg

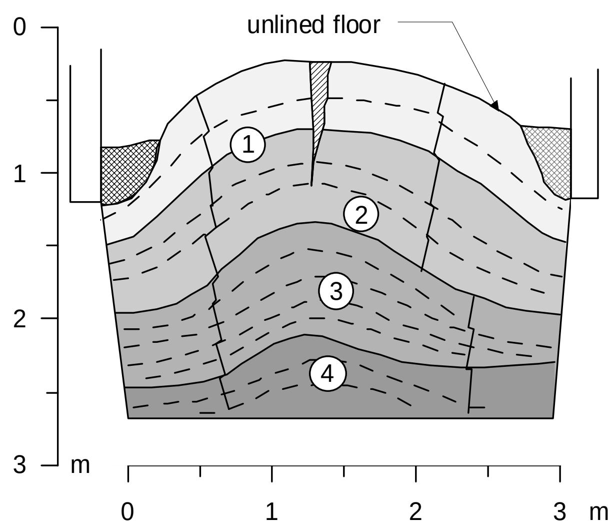
Wagenburg North Tunnel



Tunnels in SBR from Baden-Württemberg





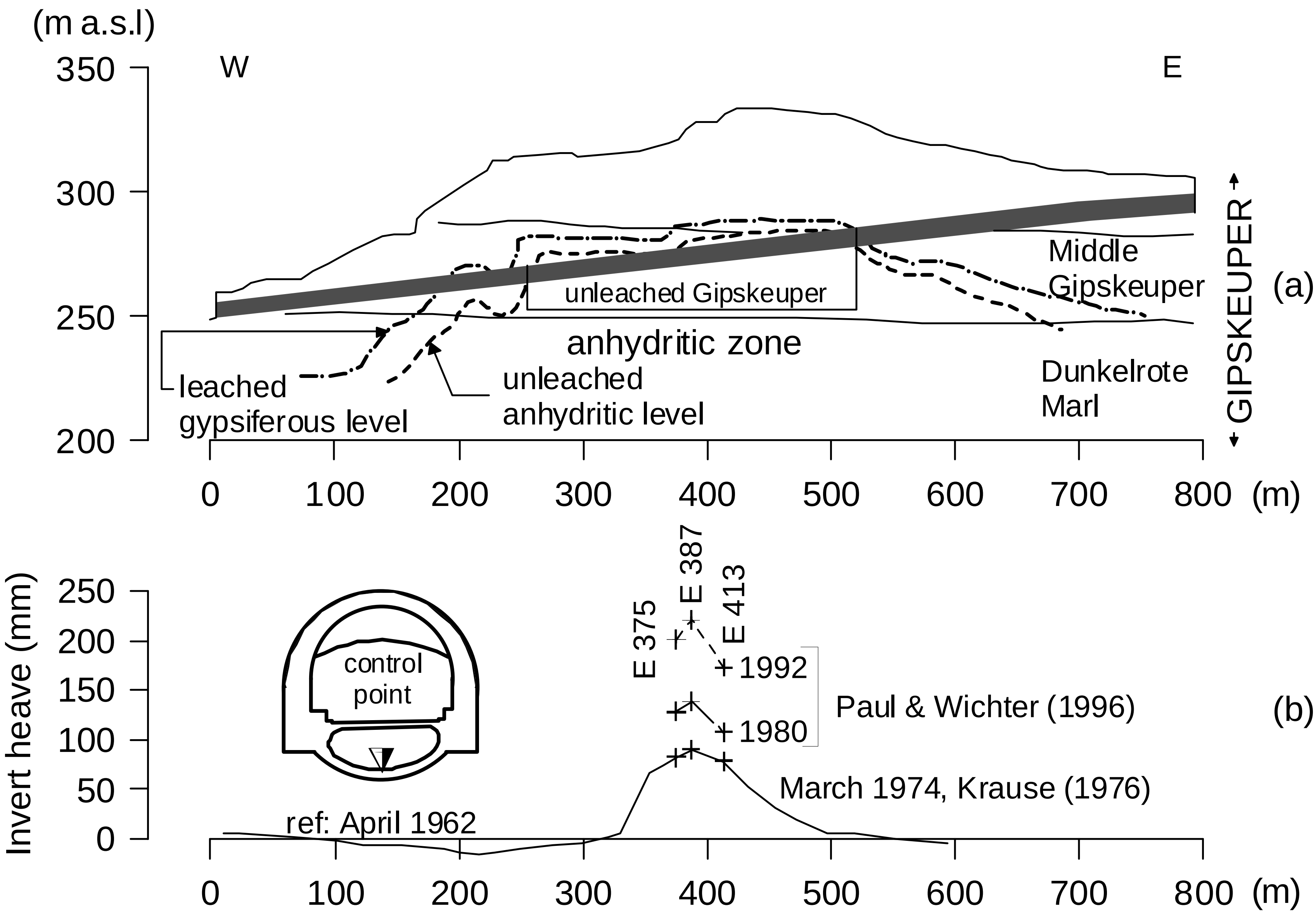


(1) segregate-impure gypsum crystals and macrocrystals
(2) segregate-pure gypsum crystals in fine sheets
(3) gypsum macrocrystals and fibrous gypsum
(4) transition between (1) and (2)

Krause (1977) & Nagel (1986)

Tunnels in SBR from Baden-Württemberg

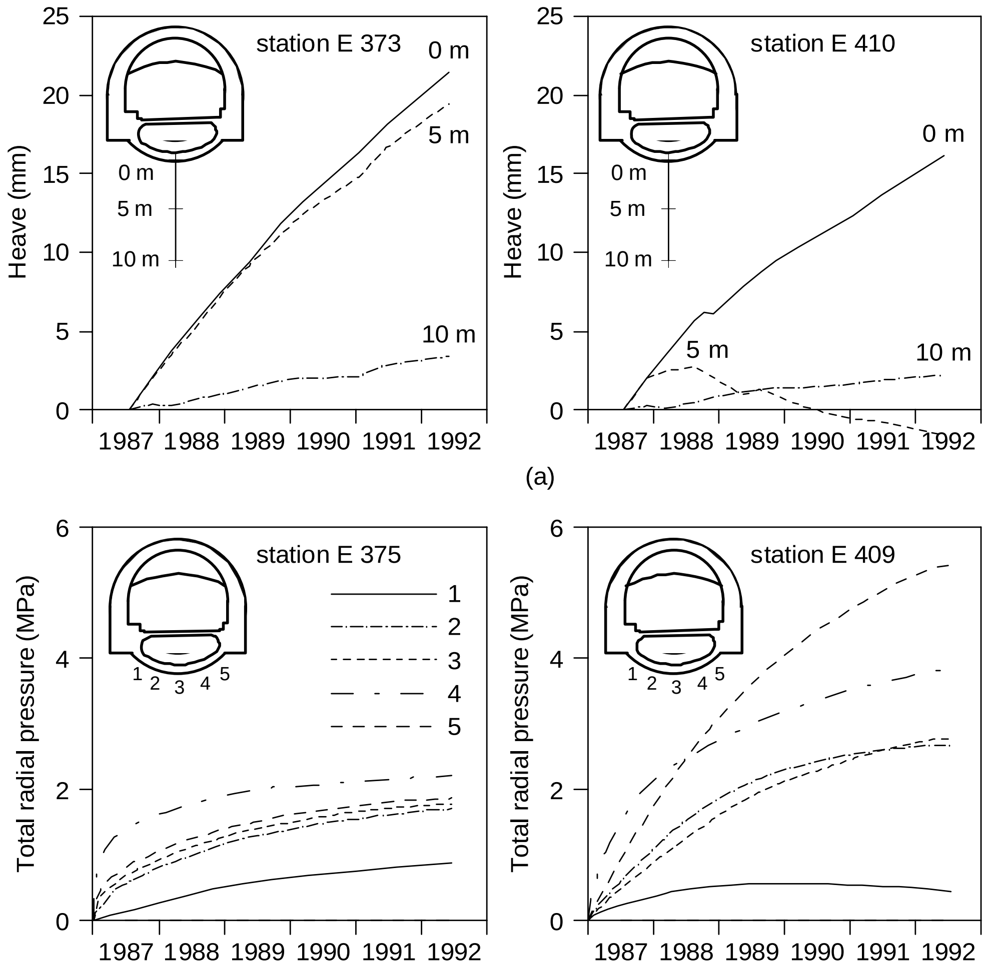
Wagenburg South Tunnel

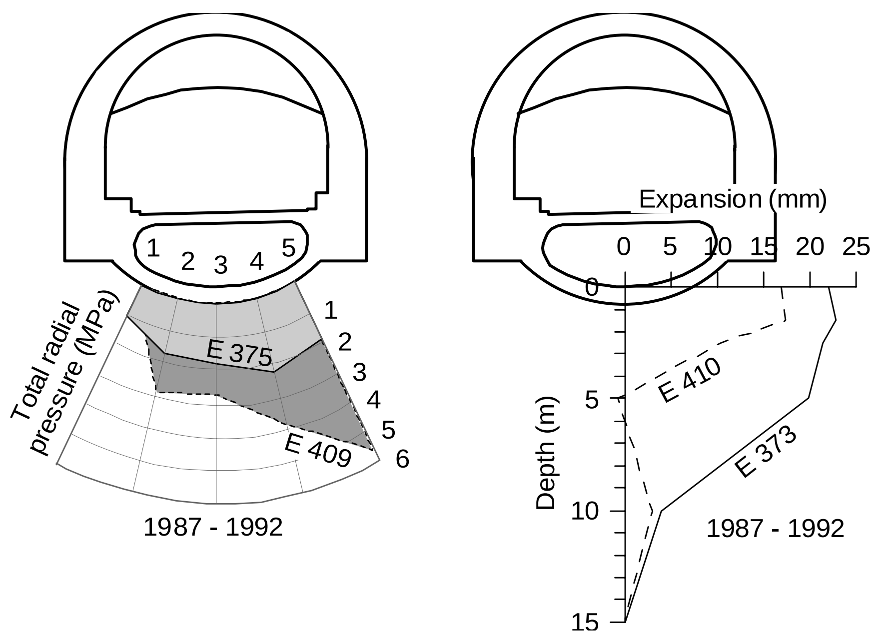


Tunnels in SBR from Baden-Württemberg

Wagenburg South Tunnel

Heave, swelling pressure and active zone in sections reconstructed in 1986 (Paul & Wichter, 1996; Paul & Walter, 2004)



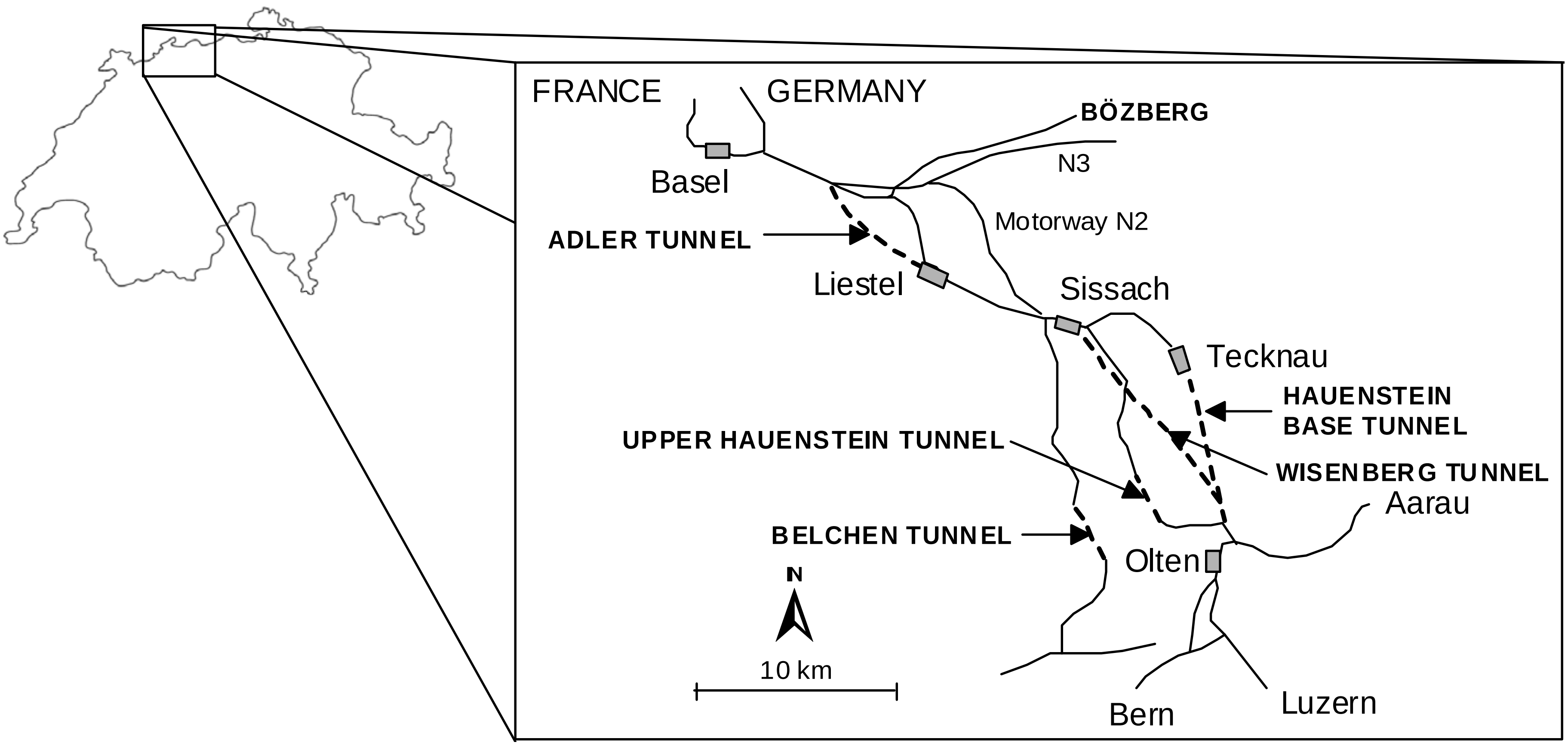


Tunnels in SBR: a quote

«…..inspections of foundation materials in Wagenburg during the early 70's -and also in Kappelesberg tunnel-have showed that the original anhydrite was converted almost completely to gypsum in the heaving floors without showing any visible increase in volume. Except for strongly leached sections, the sulphate rocks have remained essentially compact».

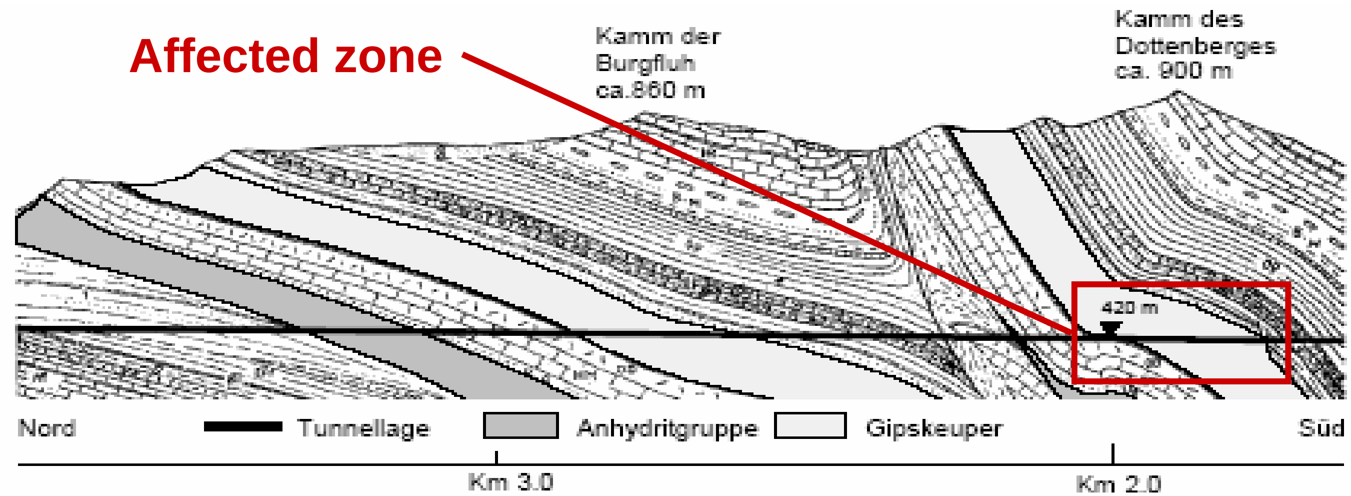
Krause, (1976)

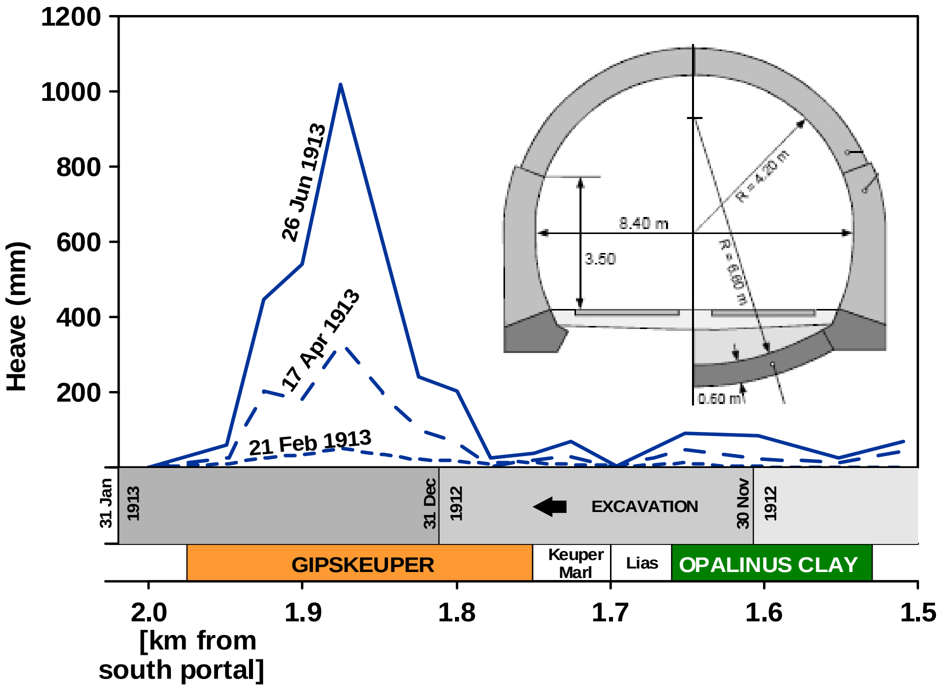
Tunnels in SBR from Jura Mountains

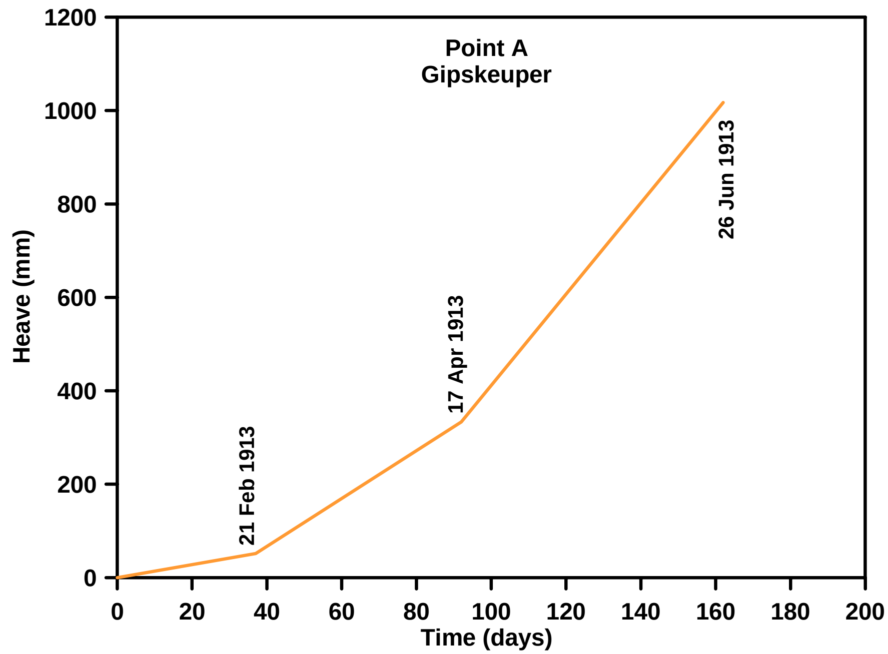


Tunnels in SBR from Jura Mountains

Hauenstein Tunnel

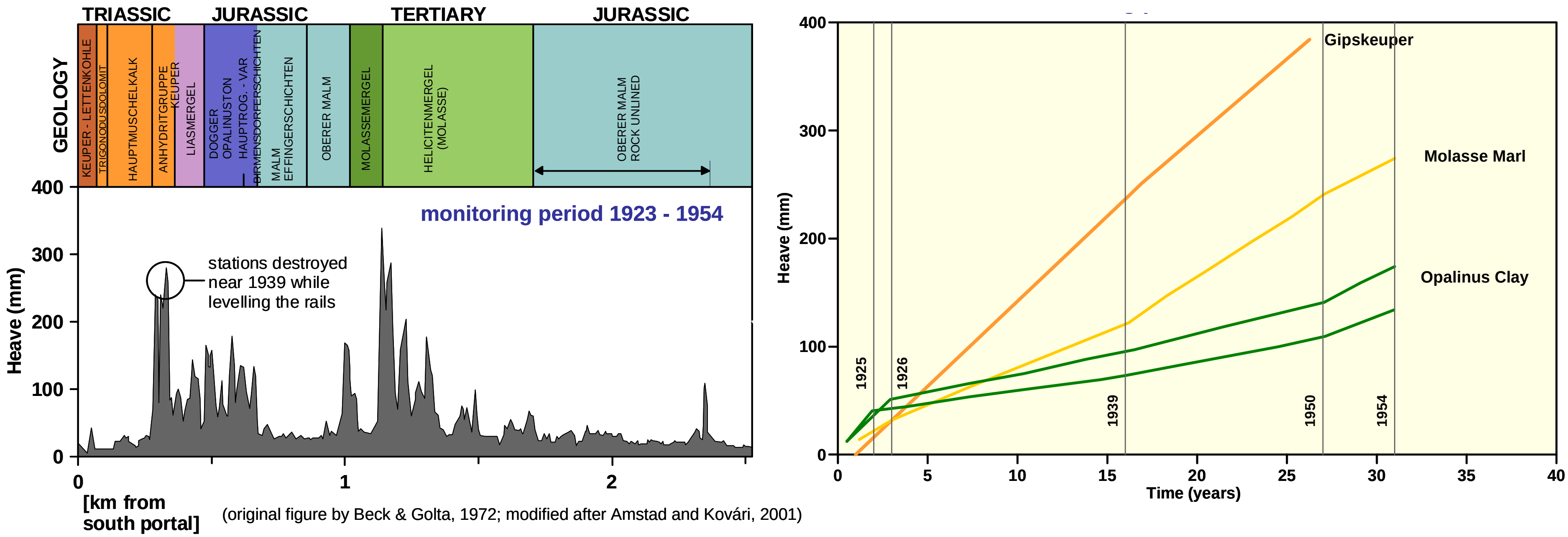






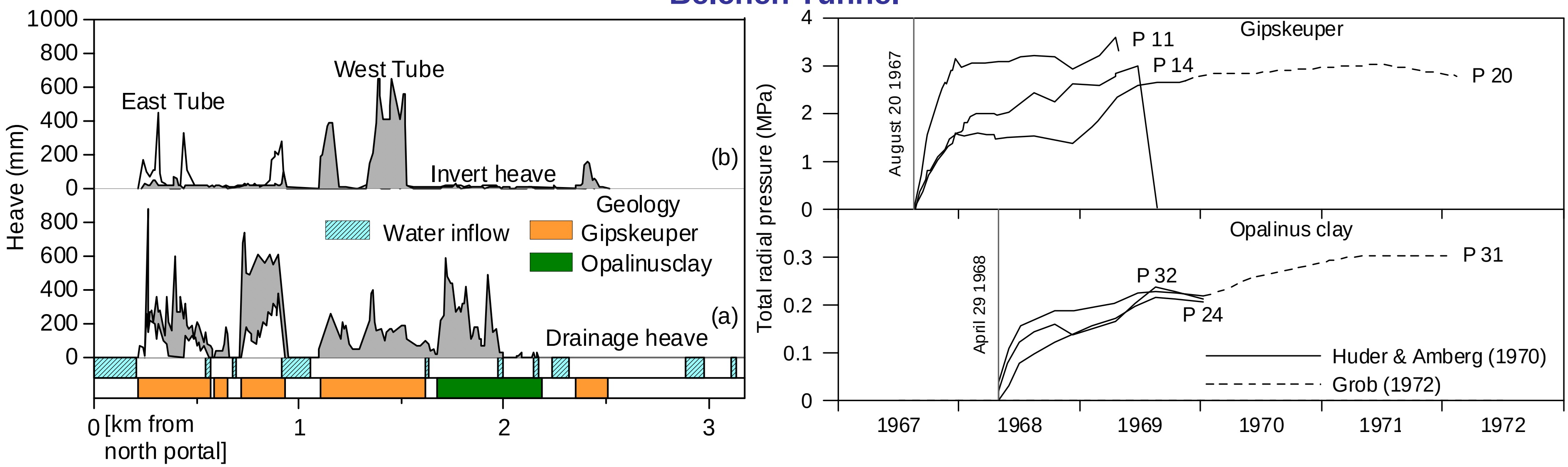
Tunnels in SBR from Jura Mountains

Bözberg Tunnel



(original figure by Beck & Golta, 1972; modified after Amstad and Kovári, 2001)

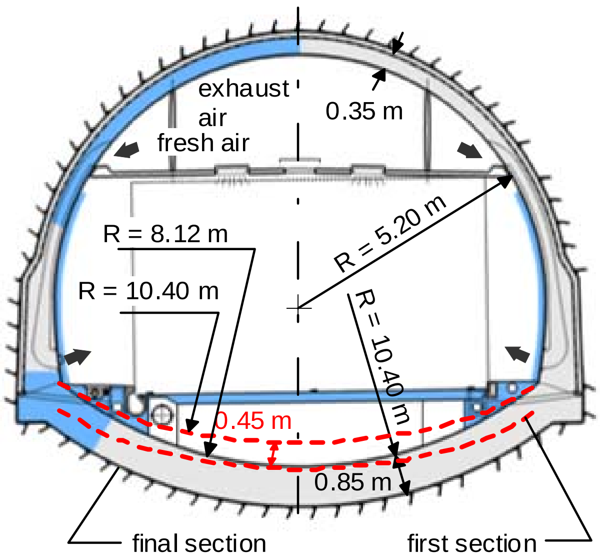
Belchen Tunnel

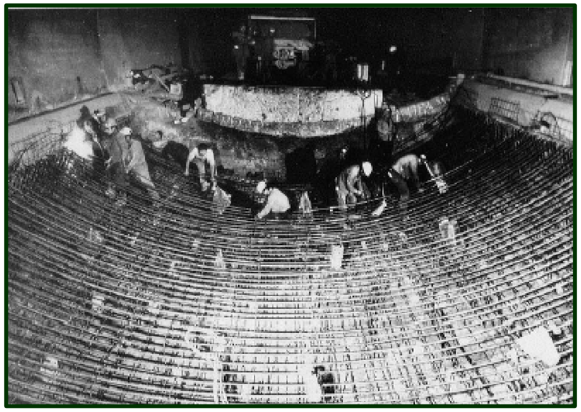


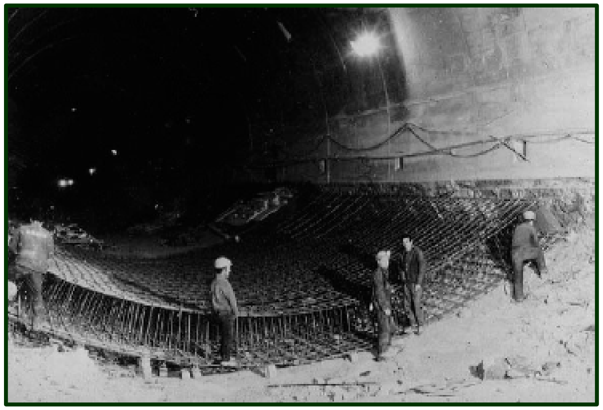
Tunnels in SBR from Jura Mountains

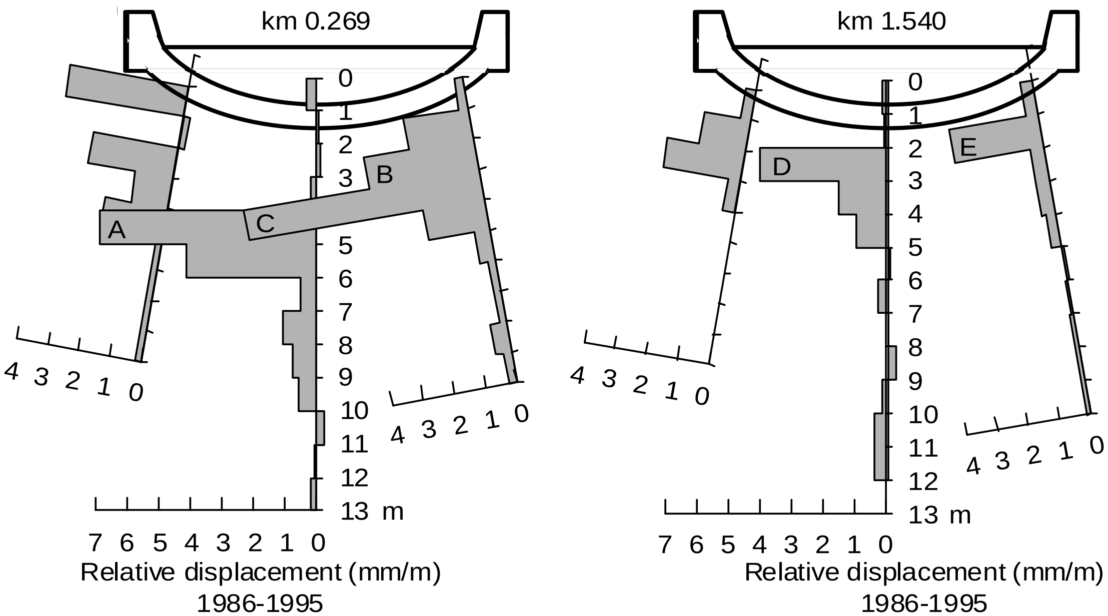
Belchen Tunnel

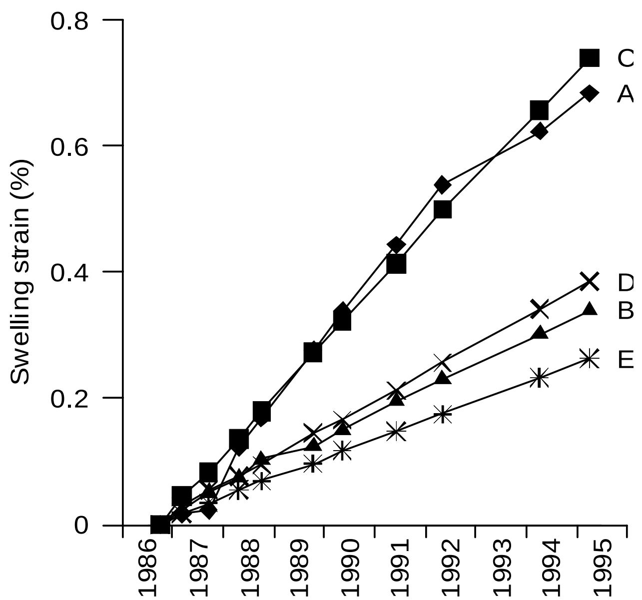
Reconstruction: 1967-1970





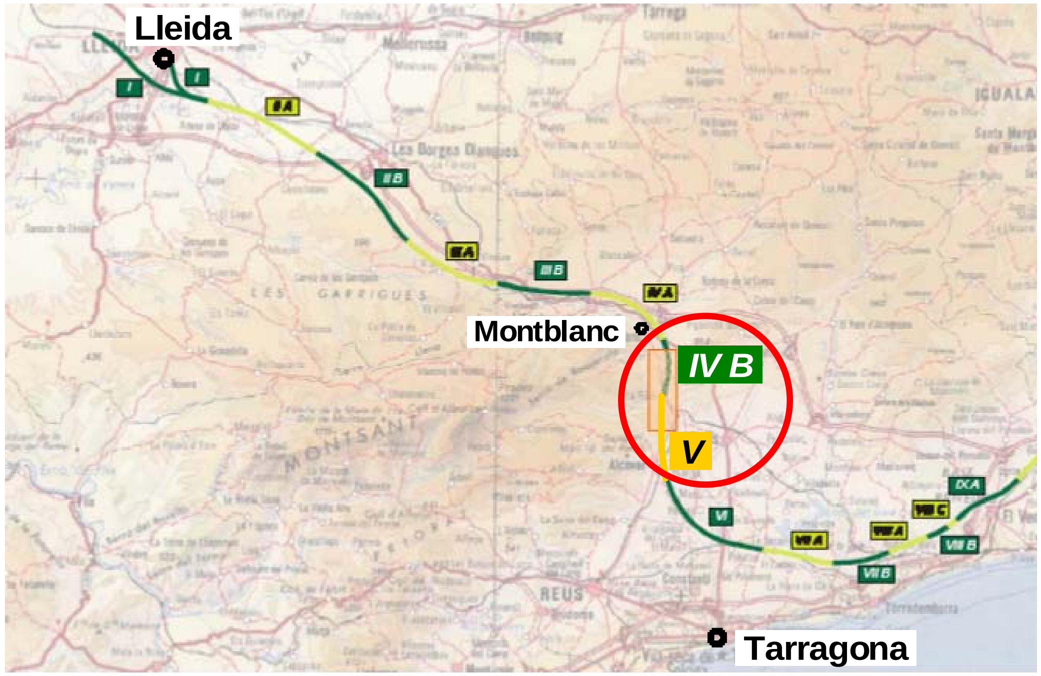






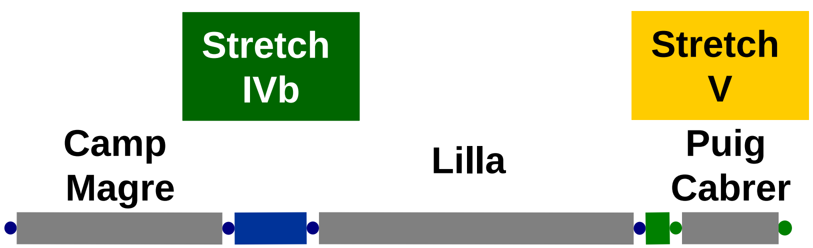
3. Alternative support designs in Lilla Tunnel

Tunnels in SBR from the Lower Ebro Basin



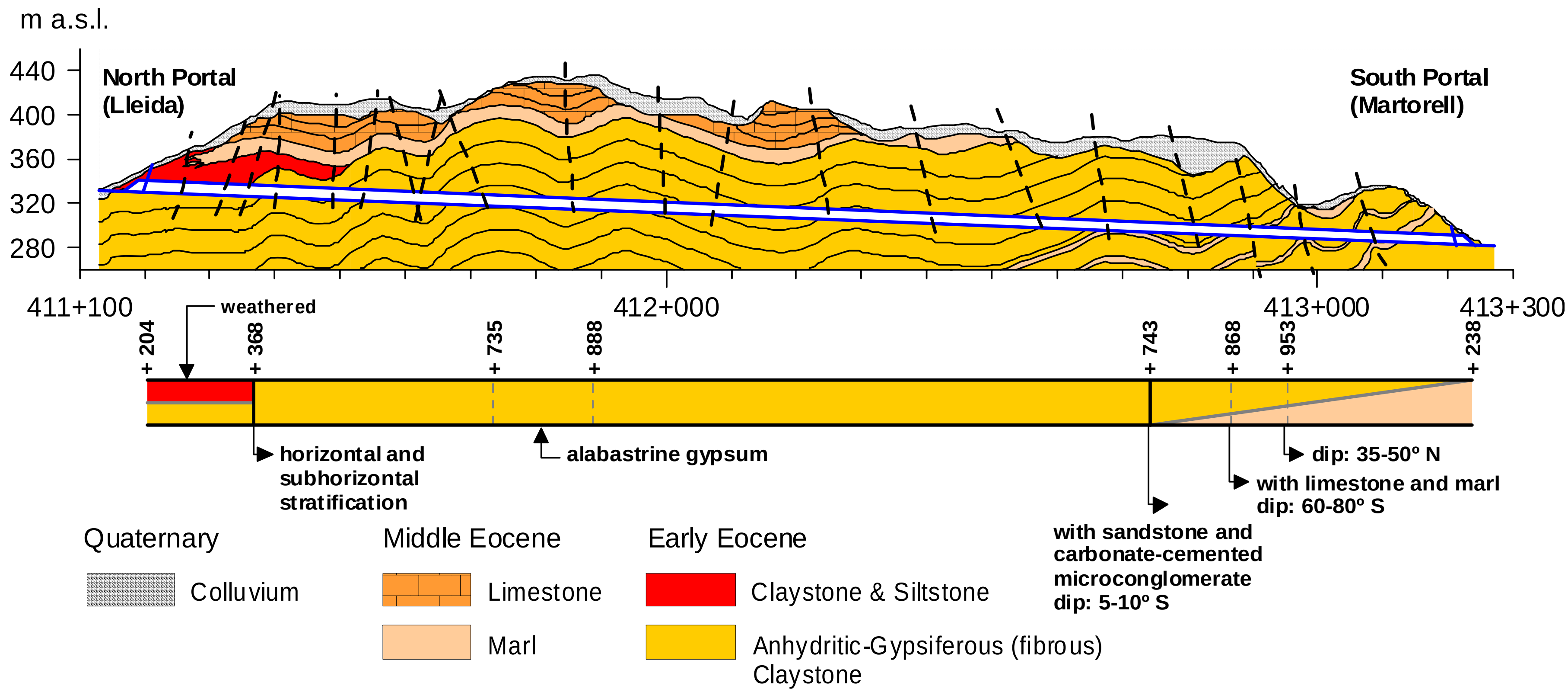
Railway Authority

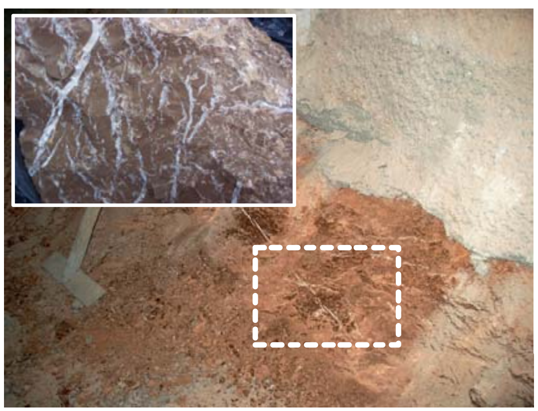
Tunnels in Section Lleida-Martorell



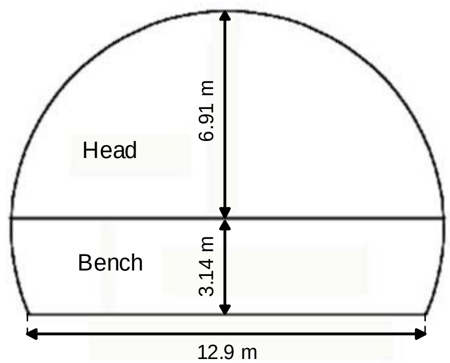
Tunnel	Length (m)	Maximum Cover (m)	Excavated Cross-Section (m^2)
Camp Magre	954	52	140
Lilla	2034	110	117
Puig Cabrer	607	191	137

Lilla Tunnel



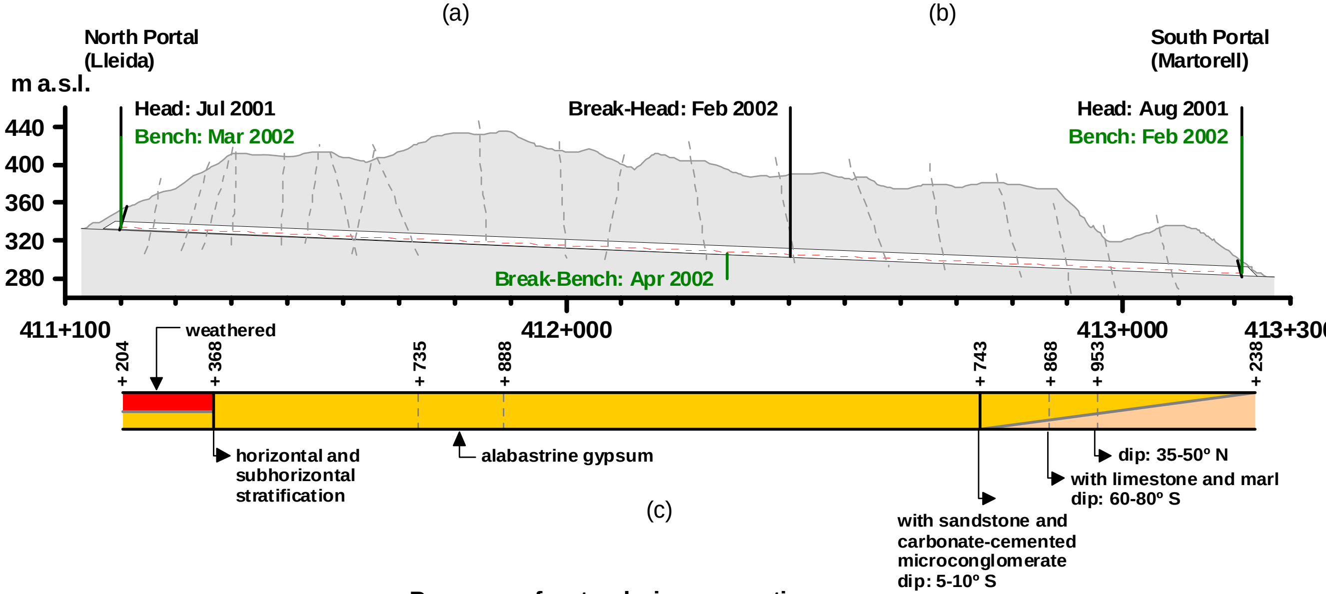


Lilla Tunnel – Conditions During Excavation

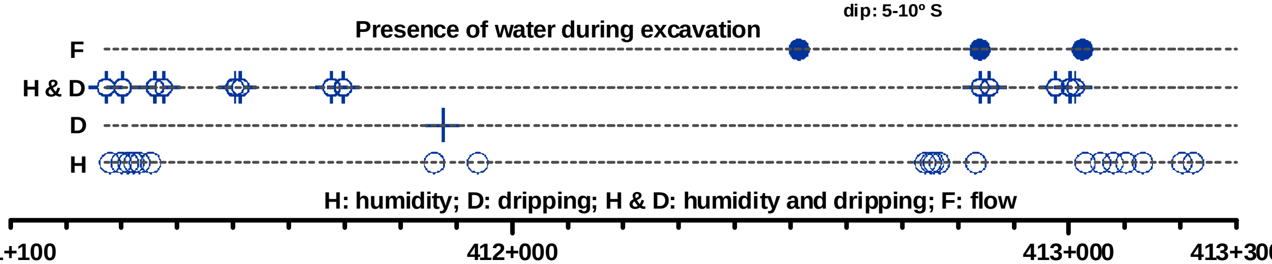


(a)

(b)

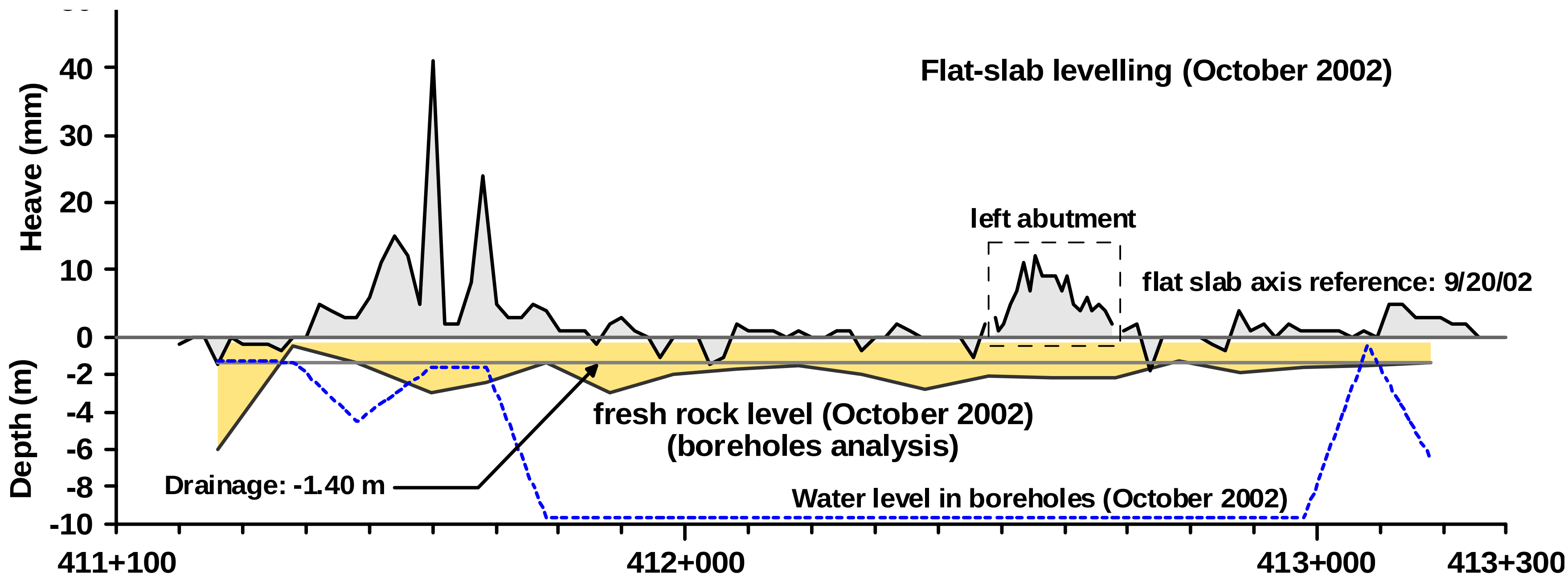


(c)

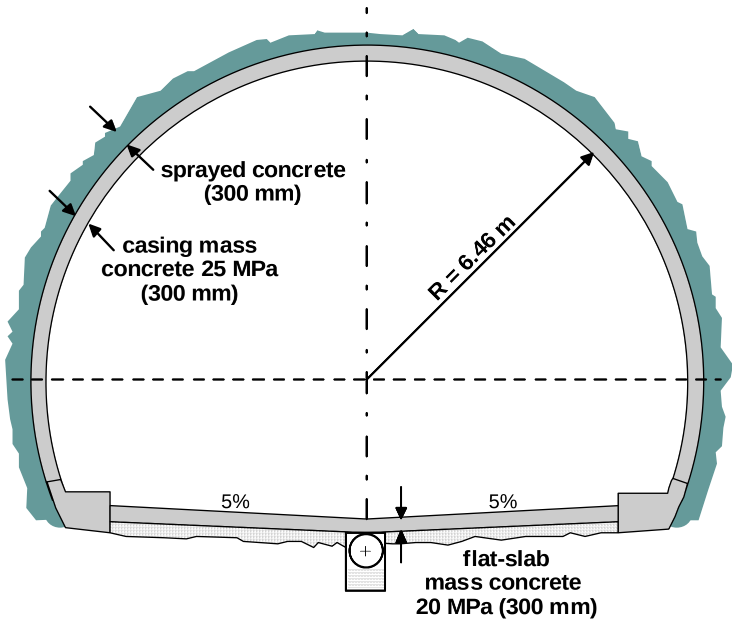


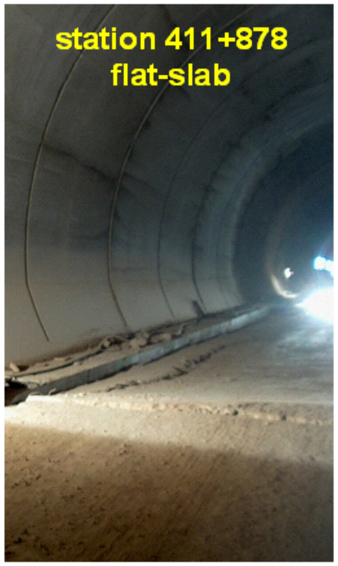
(d)

Lilla Tunnel – Expansive Phenomena Just After Excavation

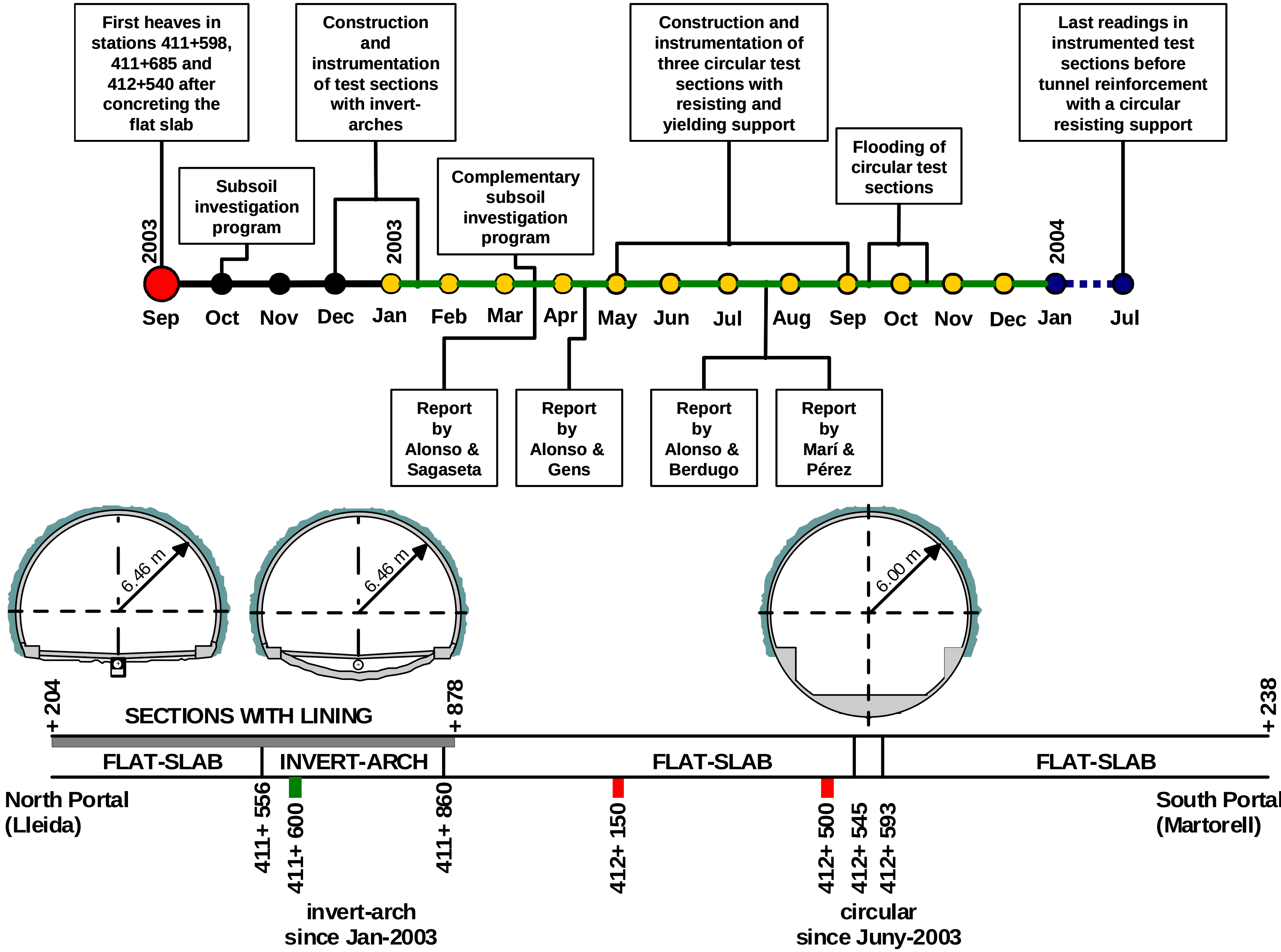


(d)

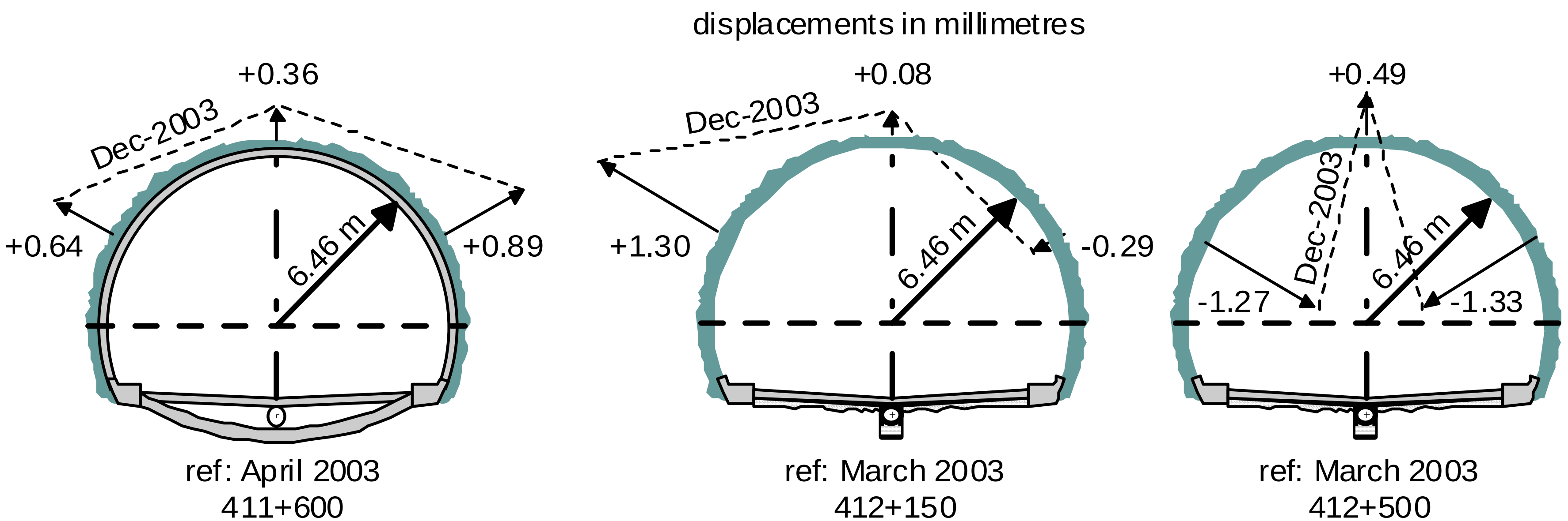


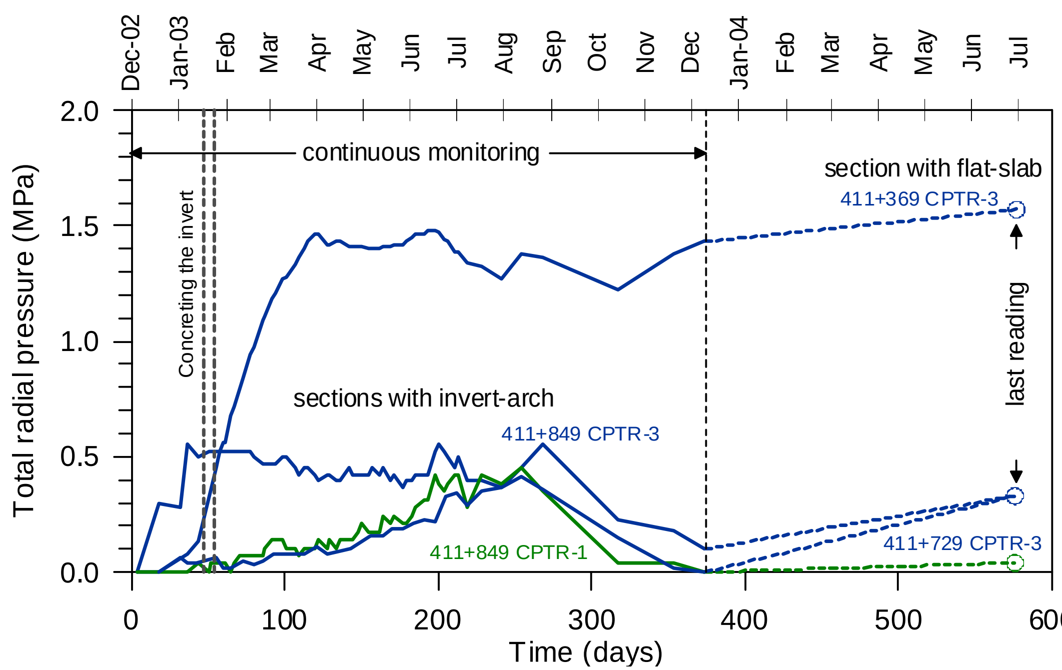


Lilla Tunnel – Alternative Support Designs

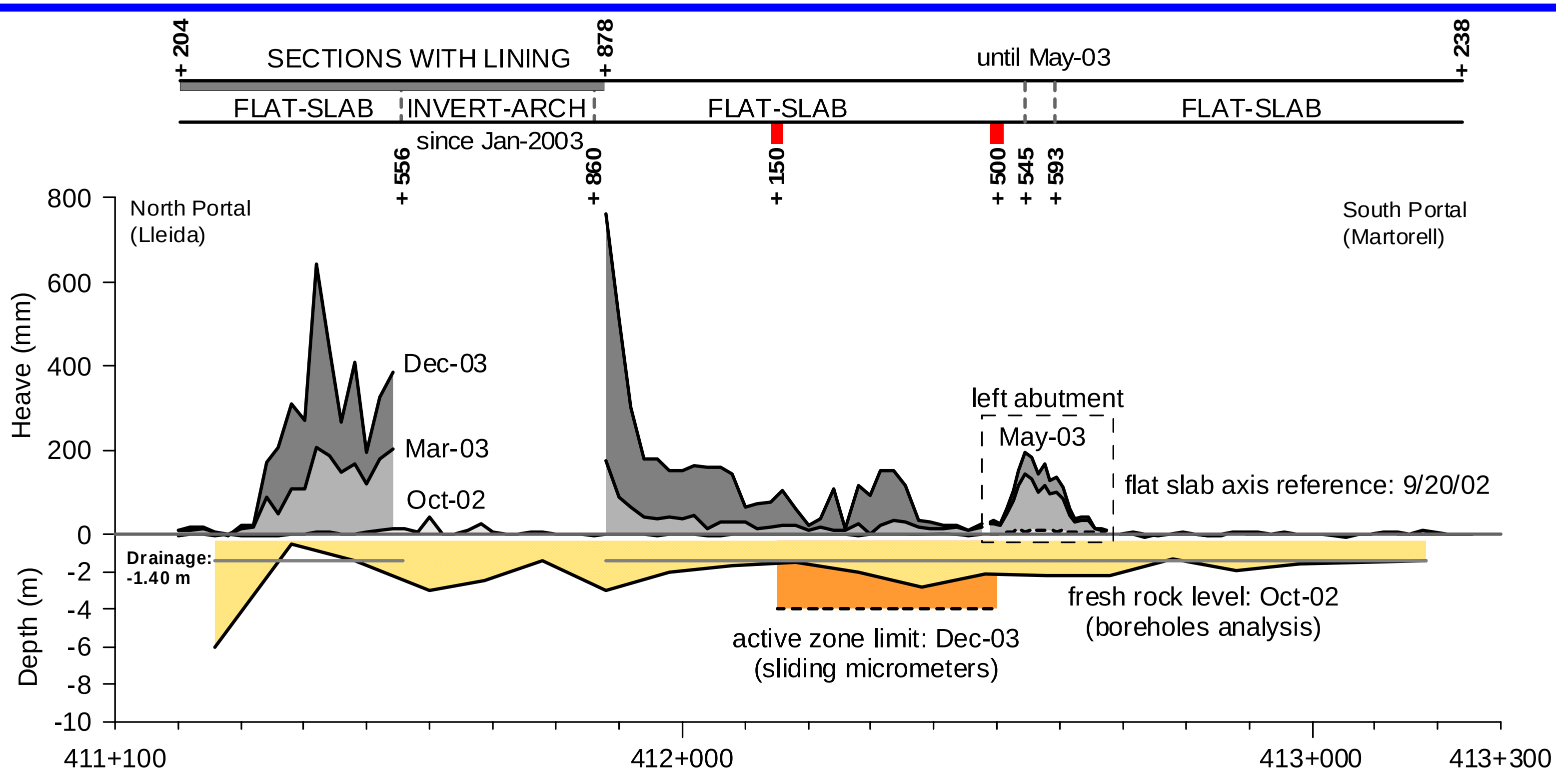


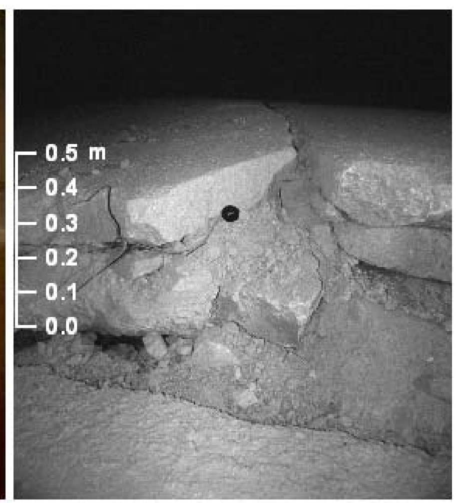
Lilla Tunnel – Performance of the Vault



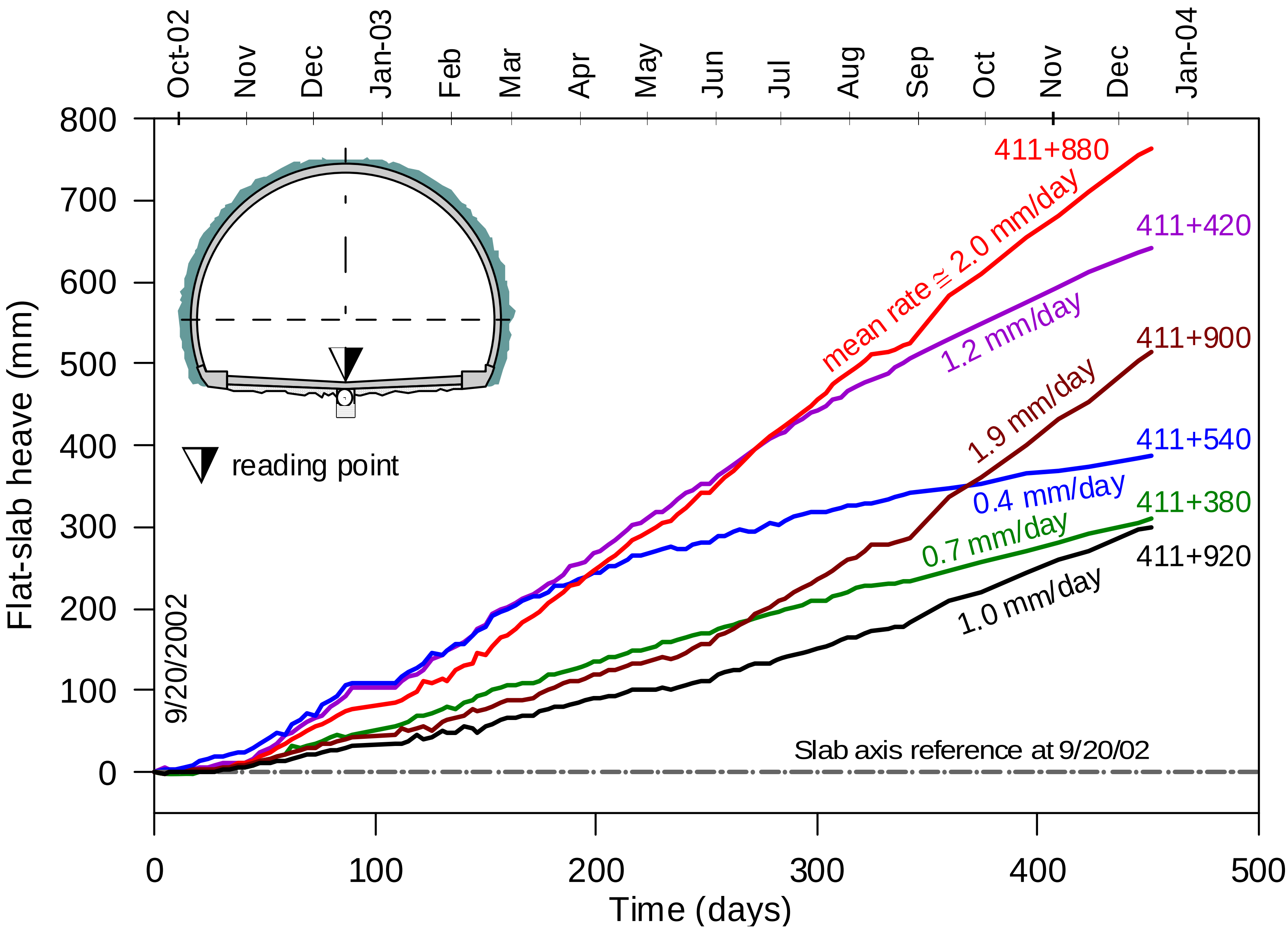


Lilla Tunnel – Heave and Damage of the Flat-Slab

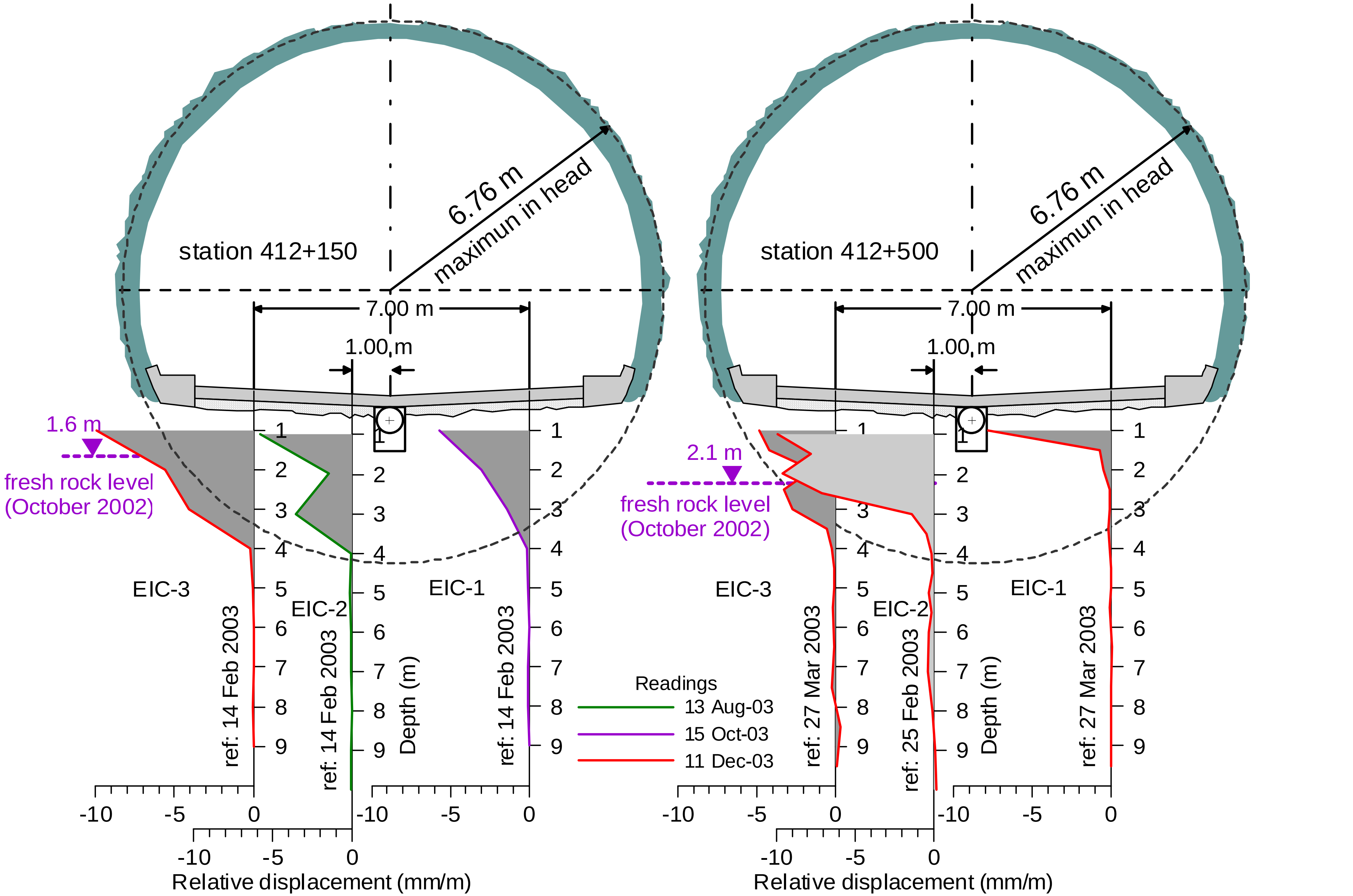




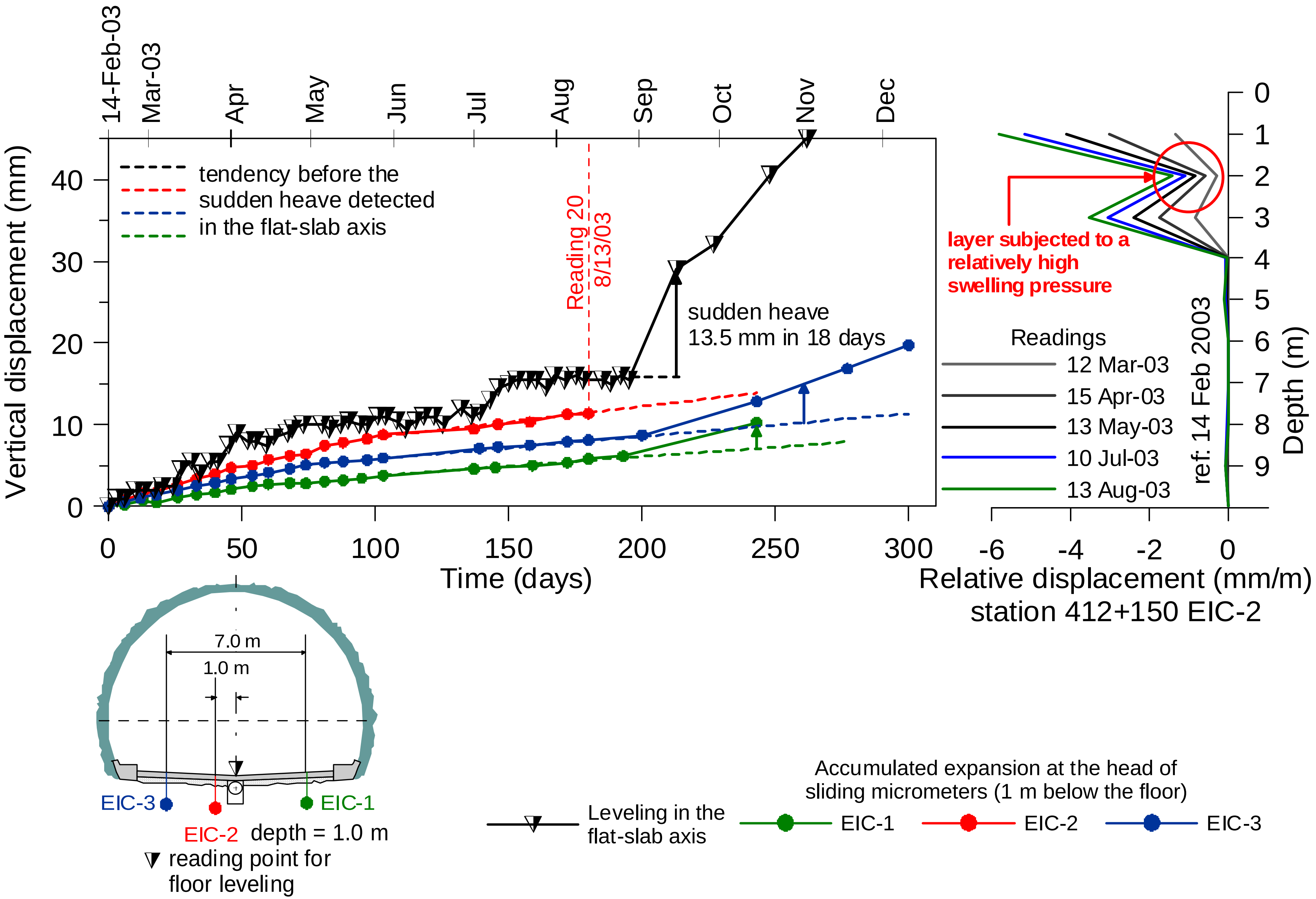
Lilla Tunnel – Heave of the Flat-Slab



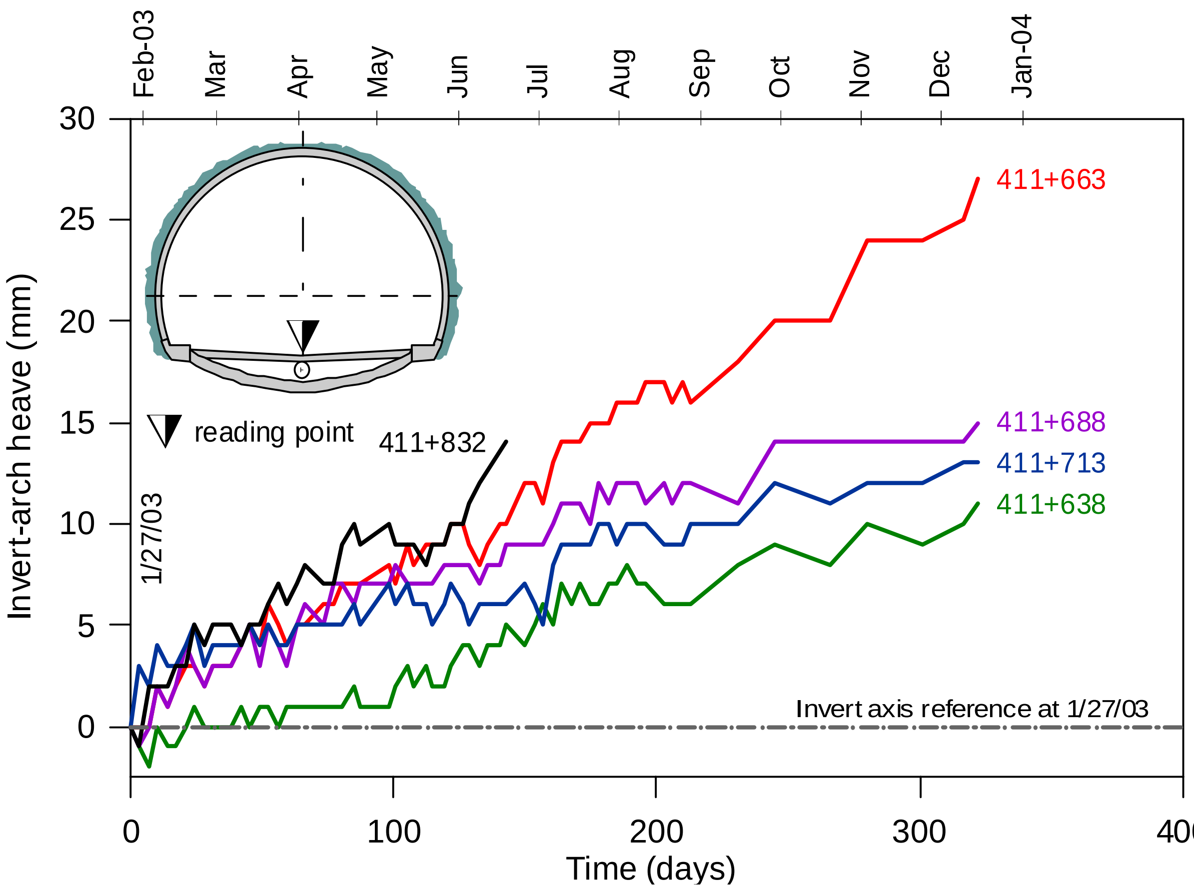
Lilla Tunnel – Active Zone Below the Flat-Slab

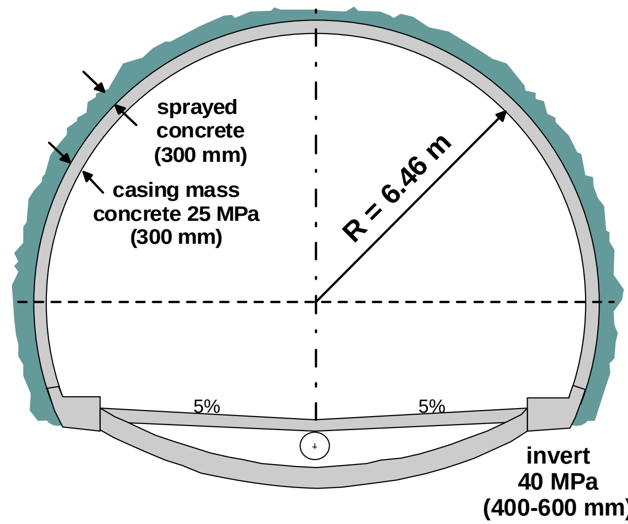


Lilla Tunnel – Heave of the Flat-Slab: Station 412+150

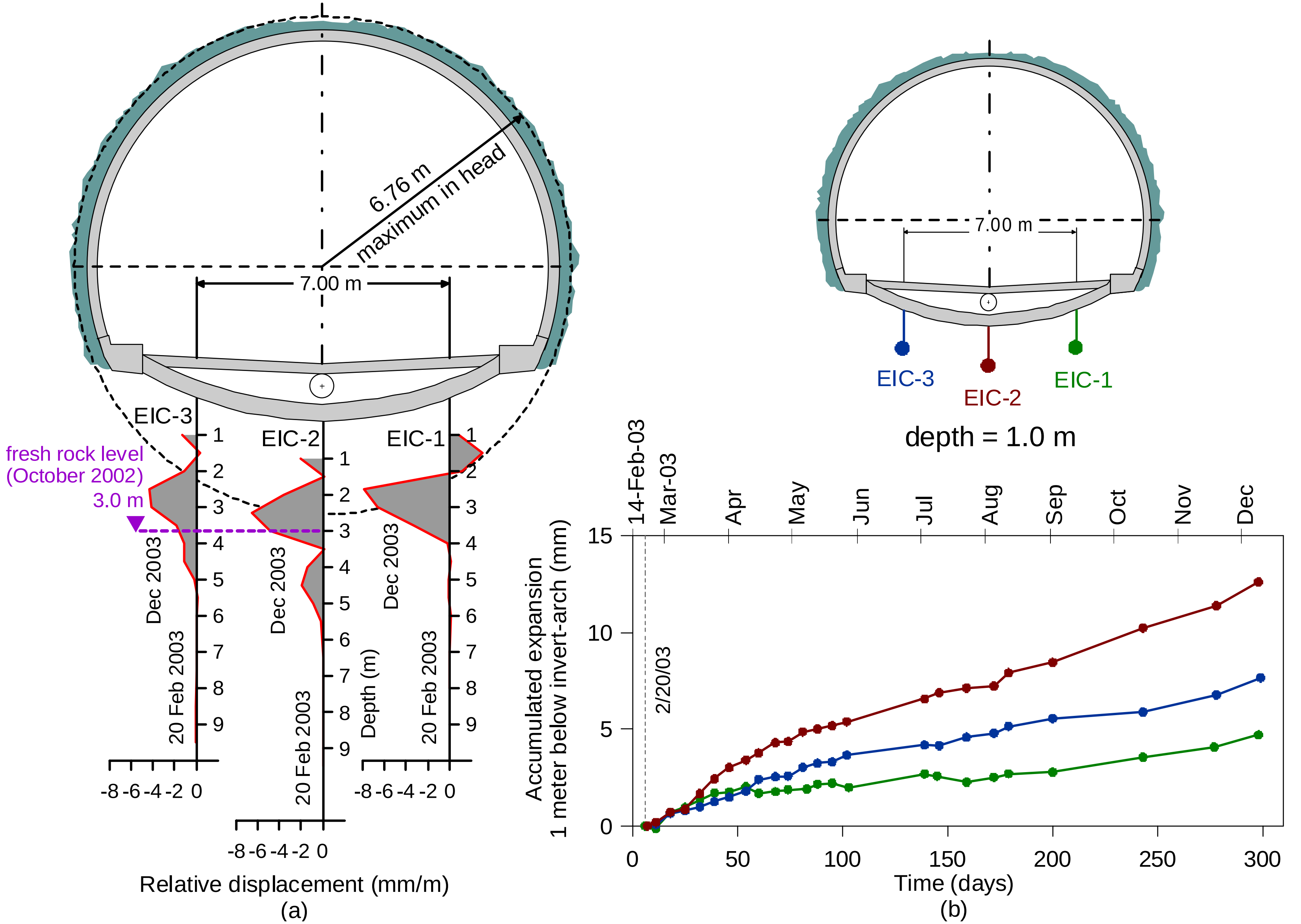


Lilla Tunnel – Heave of the Invert-Arch

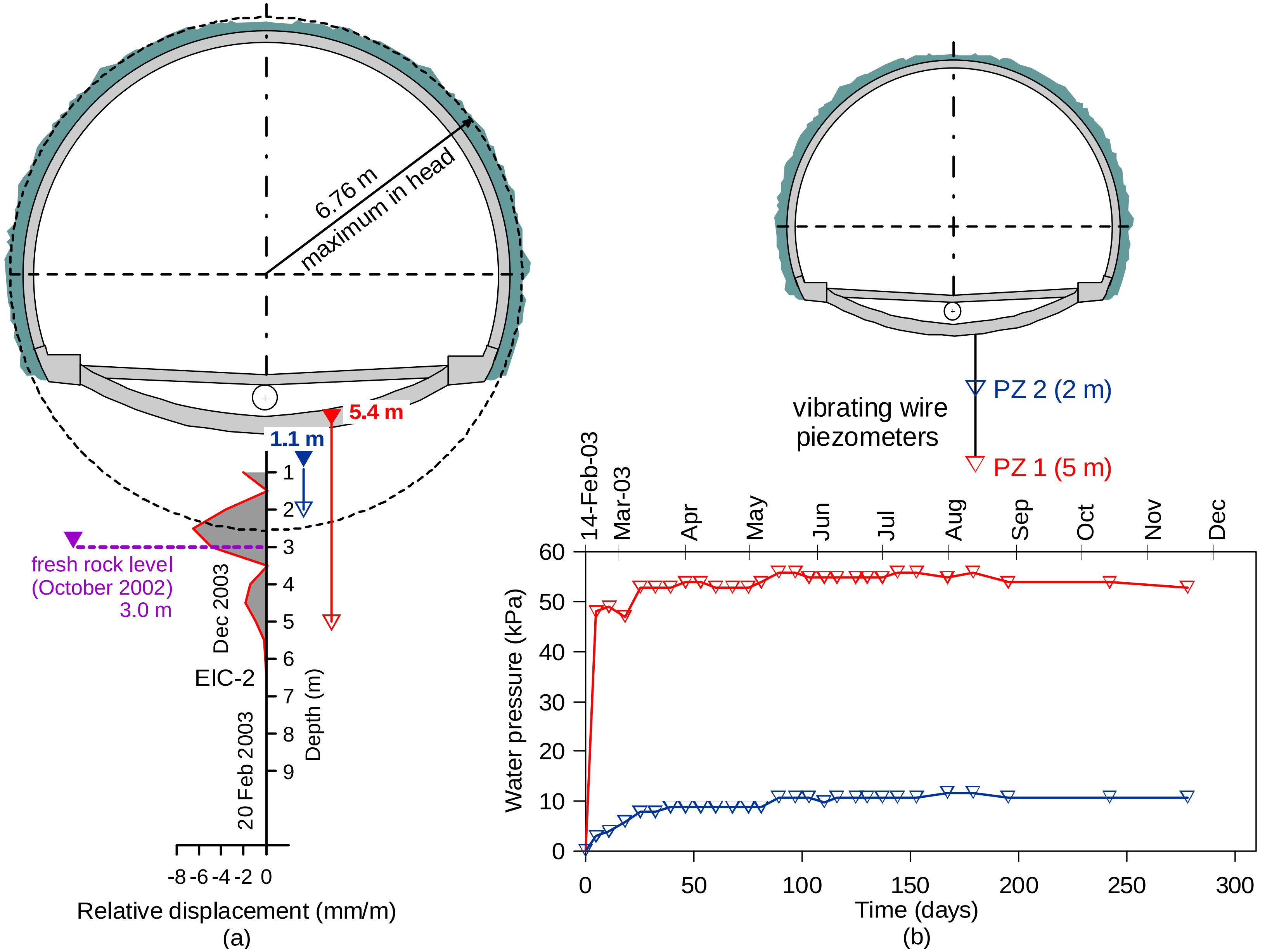




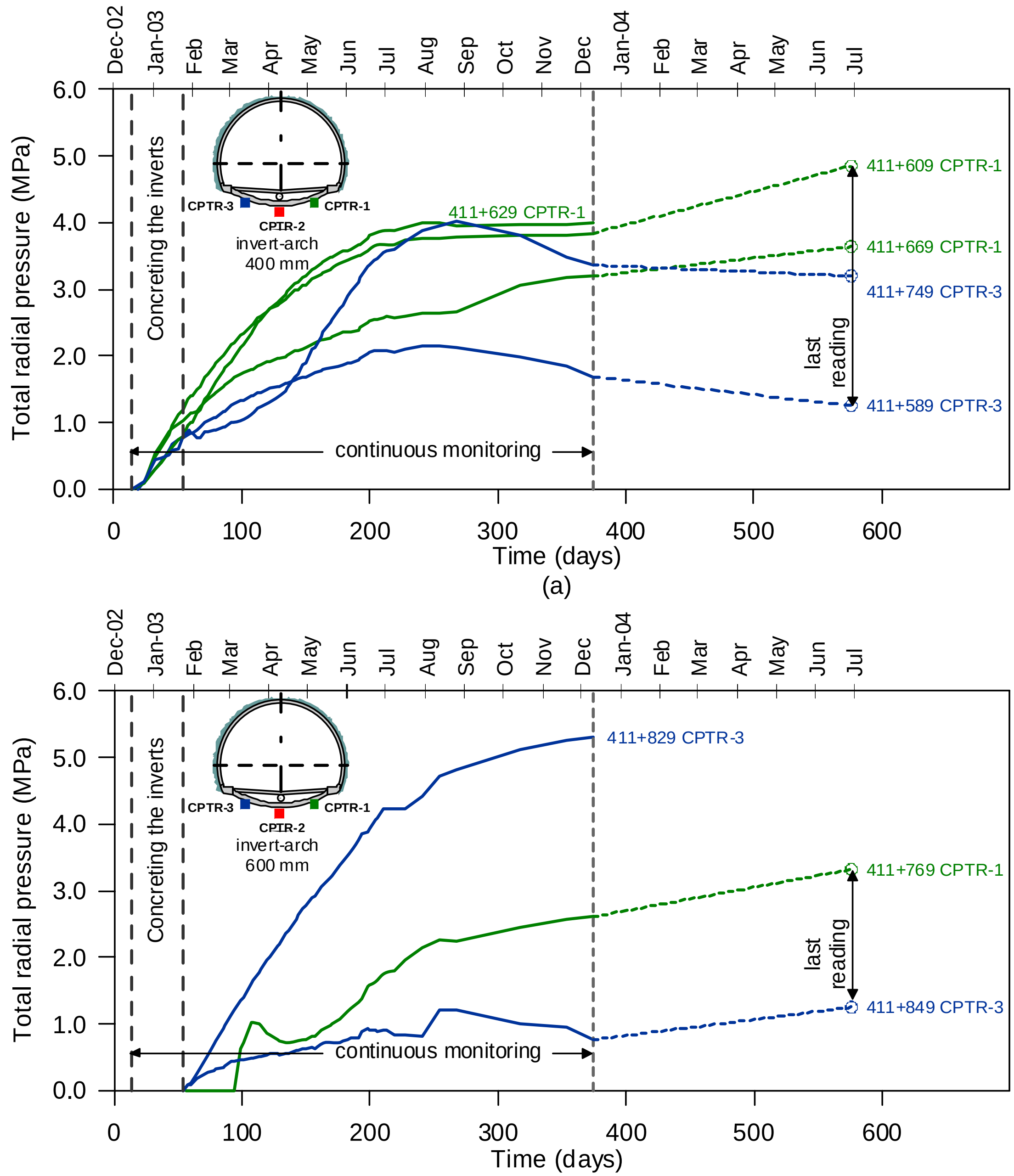
Lilla Tunnel – Active Zone Below the Invert-Arch



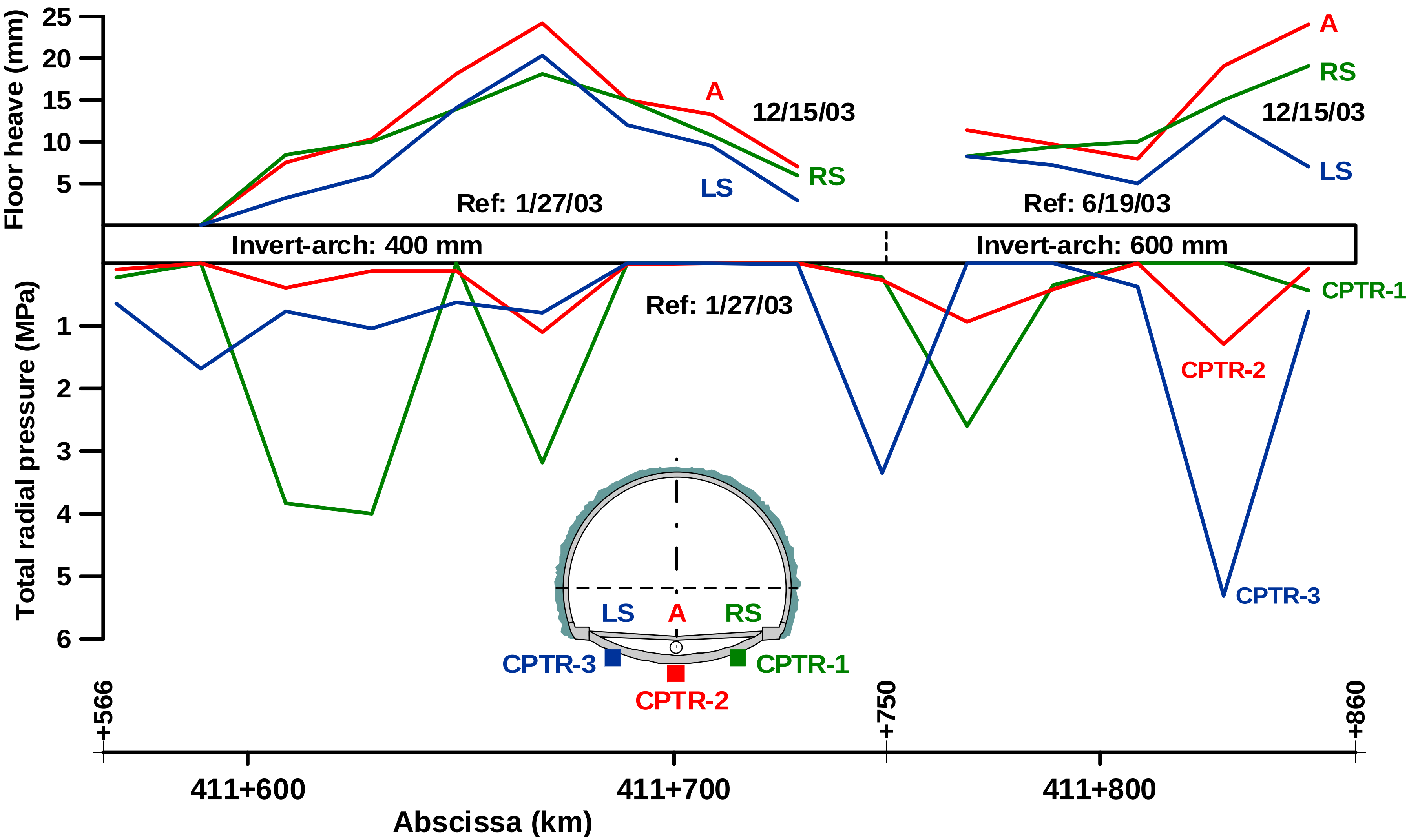
Lilla Tunnel – Piezometric Readings Below the Invert-Arch



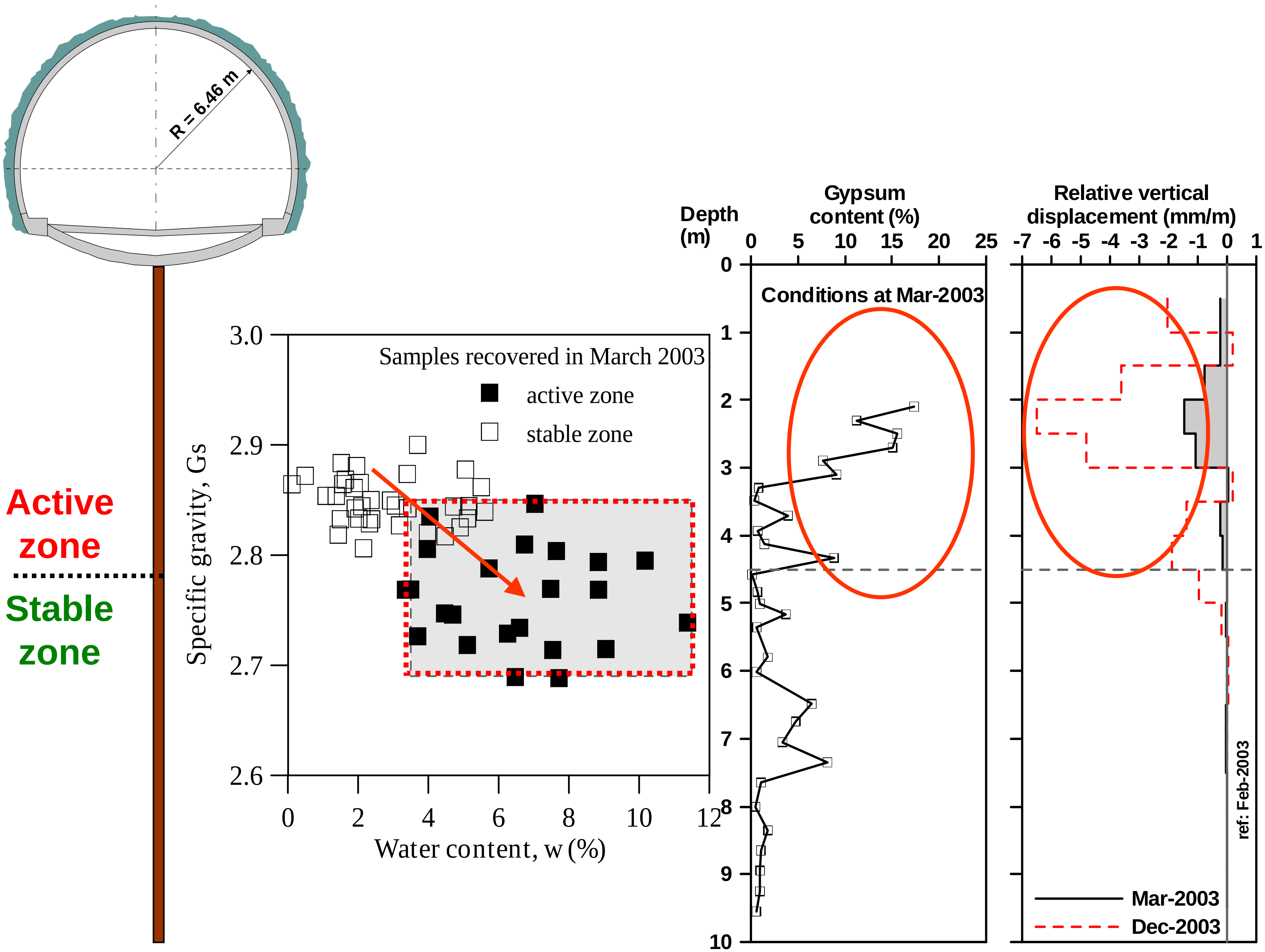
Lilla Tunnel – Swelling Pressure in the Invert-Arch



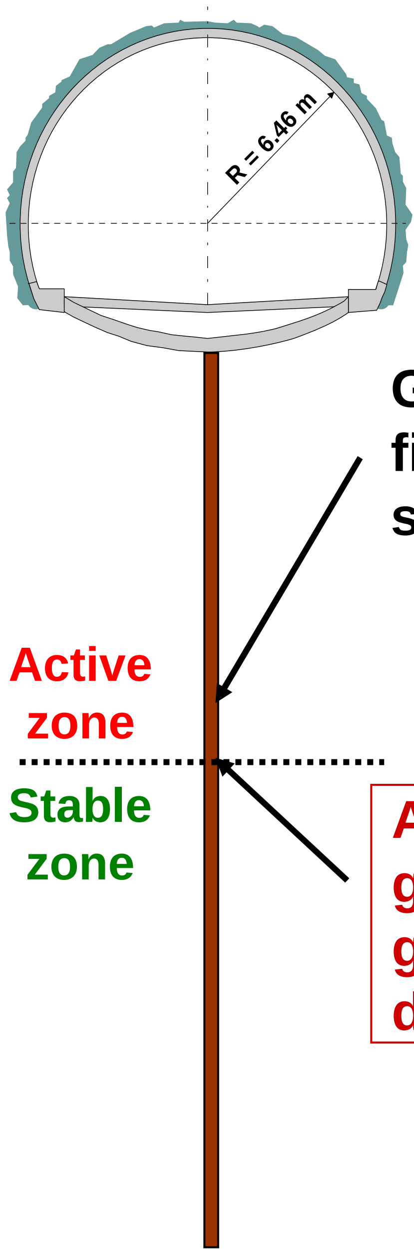
Lilla Tunnel – Swelling Pressure in the Invert-Arch



Lilla Tunnel – Degradation and Swelling of the Rock



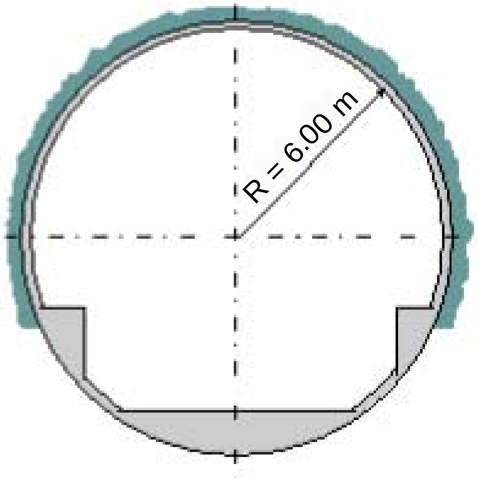
Lilla Tunnel – Degradation and Swelling of the Rock



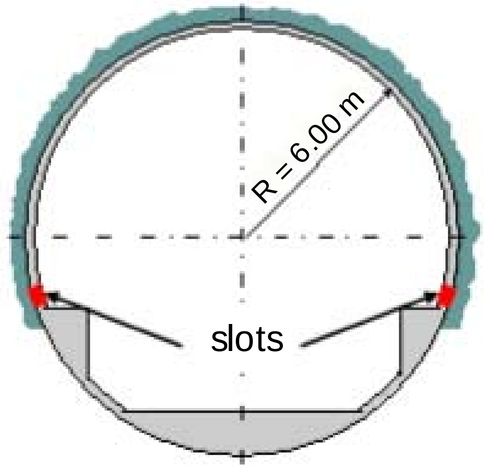
Gypsum needles filling slikenside surfaces

Aggregations of gypsum crystals growing on a discontinuity

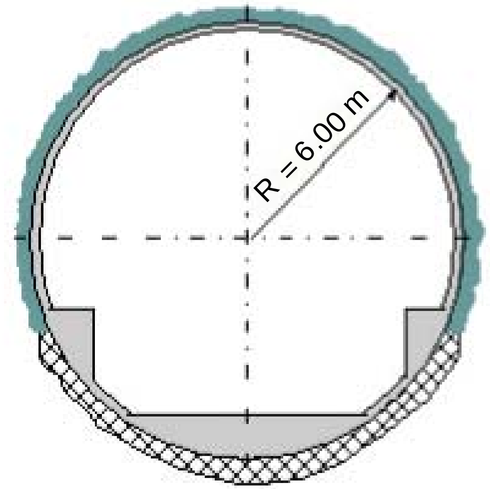
Lilla Tunnel – Circular Test Sections



Rigid section
412+545 - 412+565

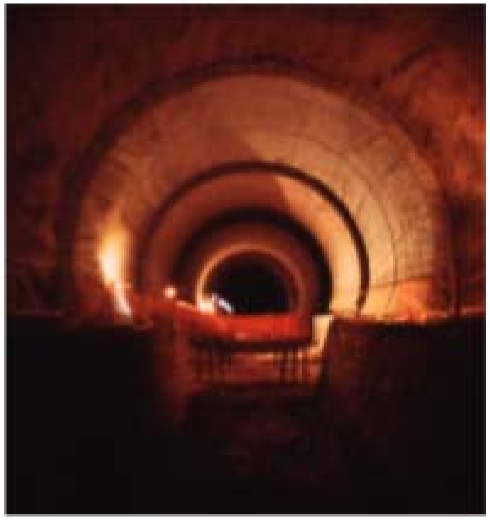


Section with slots
412+571 - 412+581

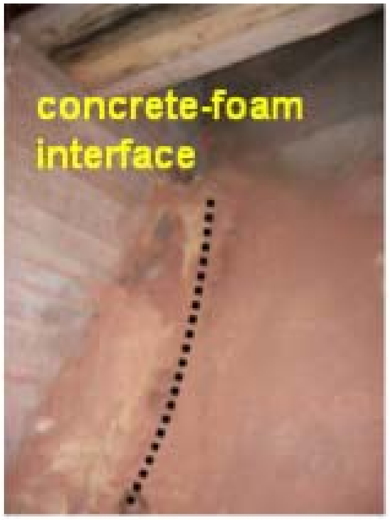


Section with foam
412+583 - 412+593

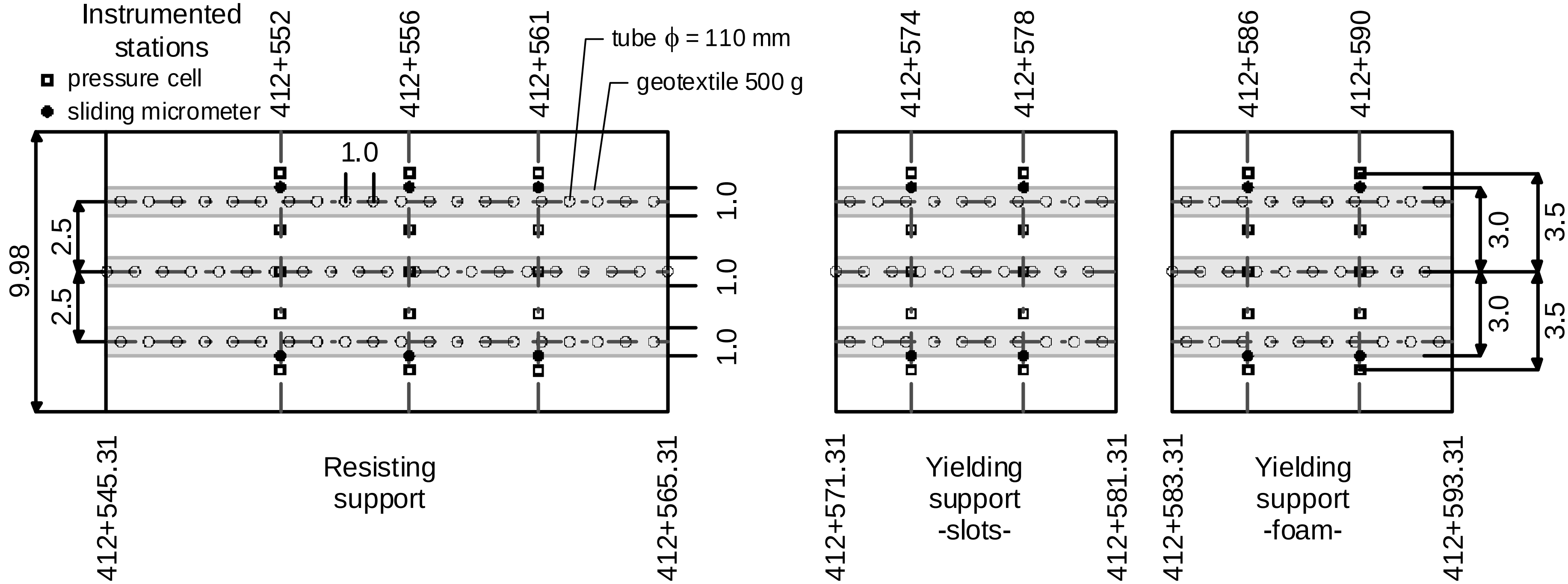
Resisting support

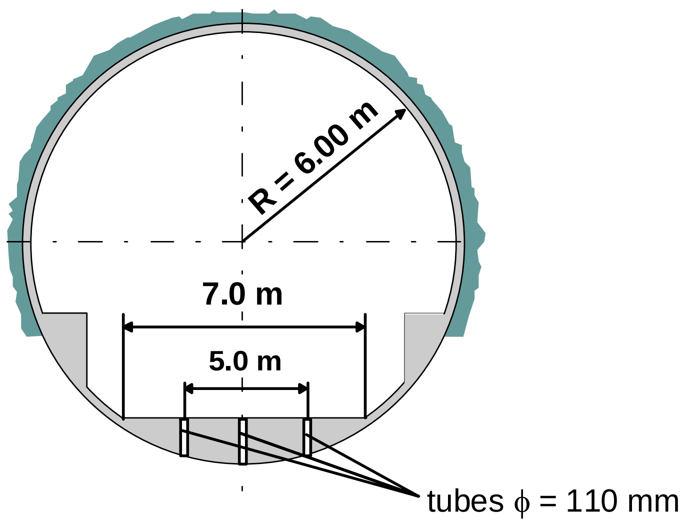


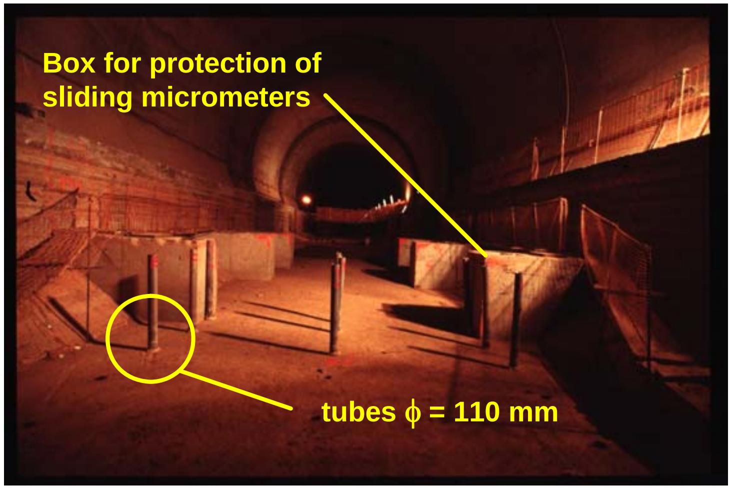
Yielding supports

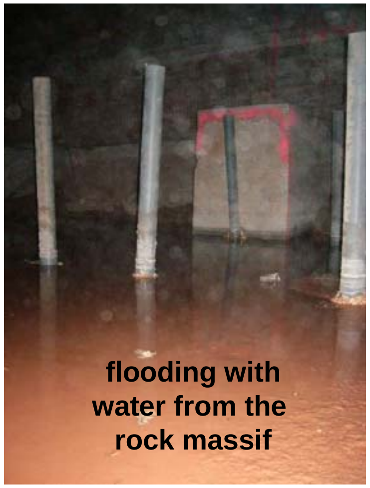


Lilla Tunnel – Circular Test Sections: Flooding Tests

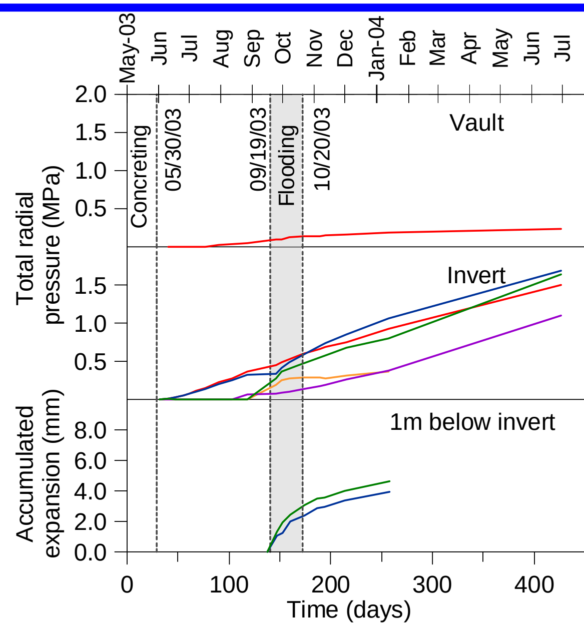




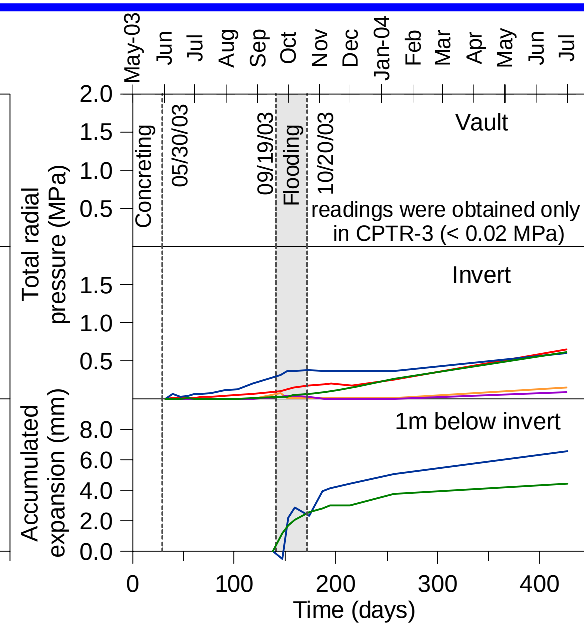




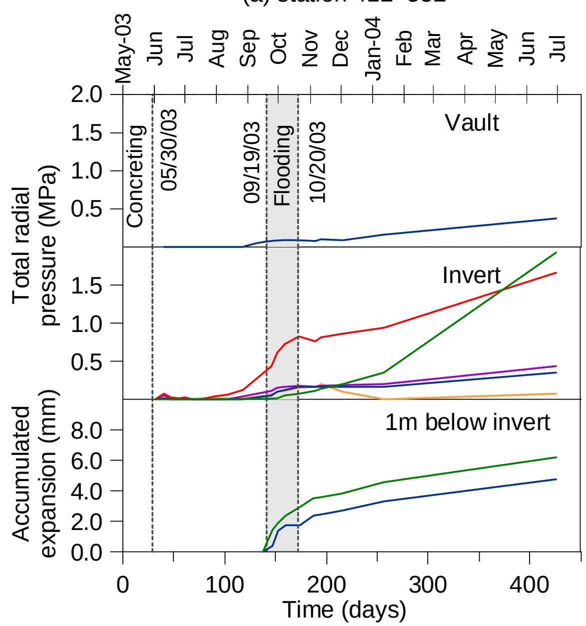
Lilla Tunnel – Circular Test Section with Resisting Support



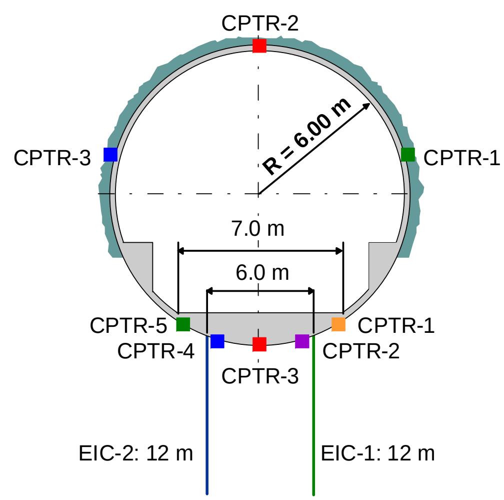
(a) station 412+552



(b) station 412+556

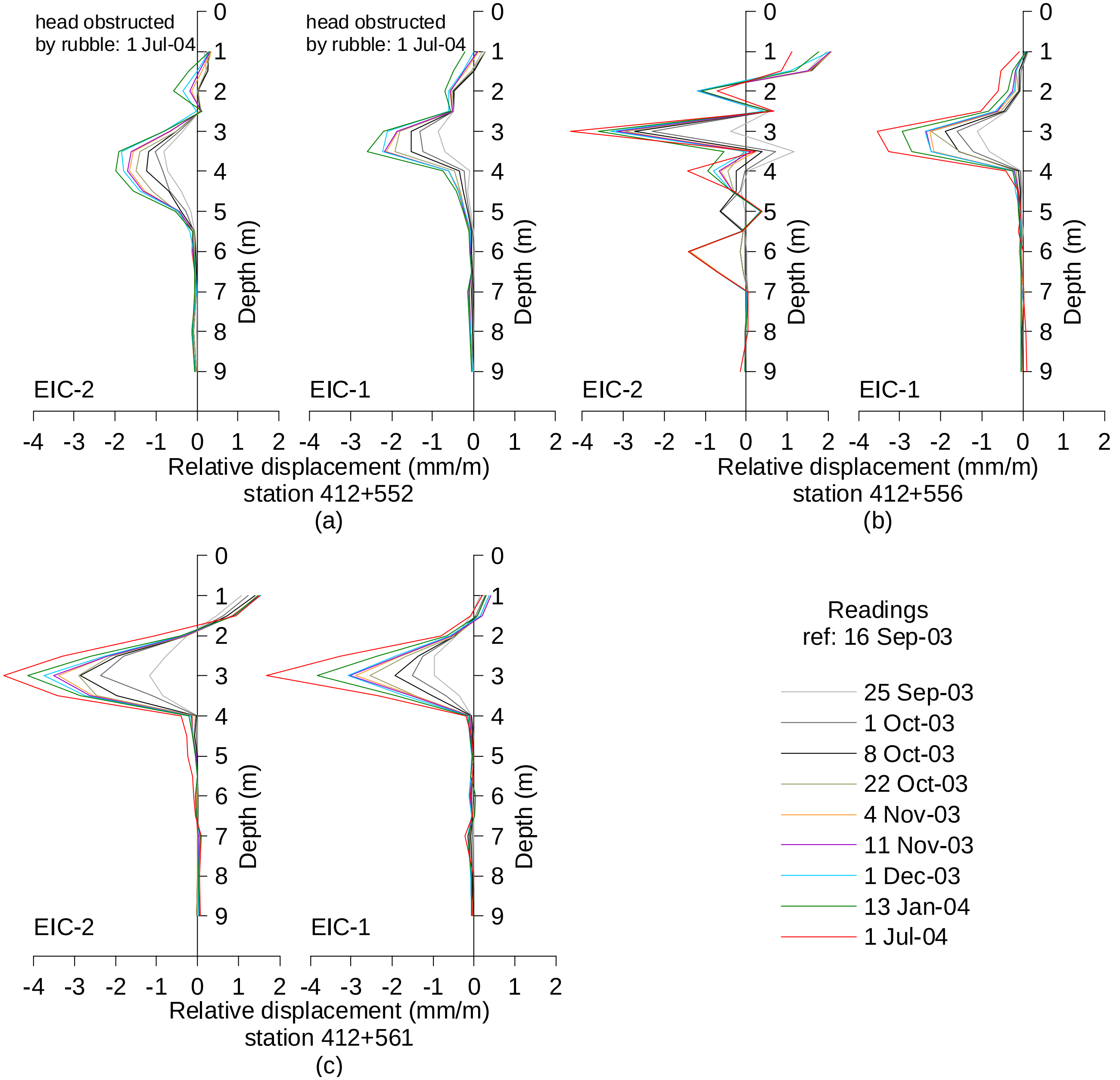


(c) station 412+561

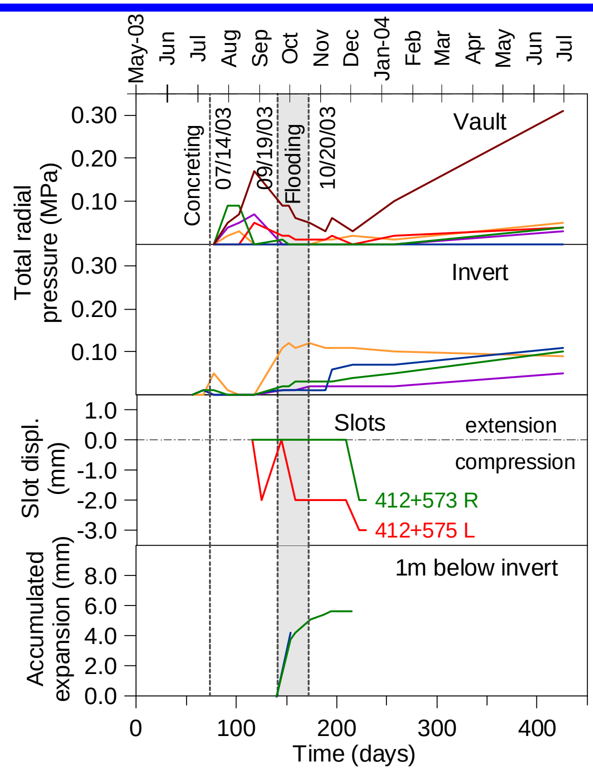


(d) typical cross-section with resisting support

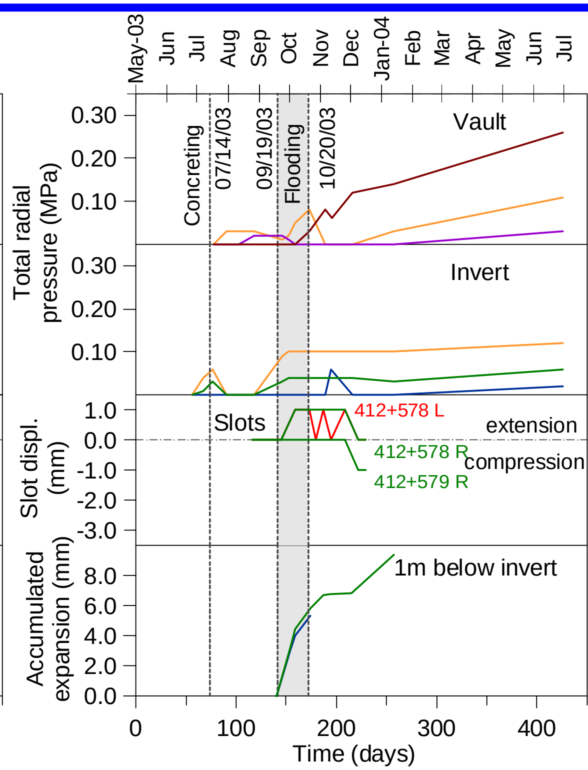
Lilla Tunnel – Circular Test Section with Resisting Support



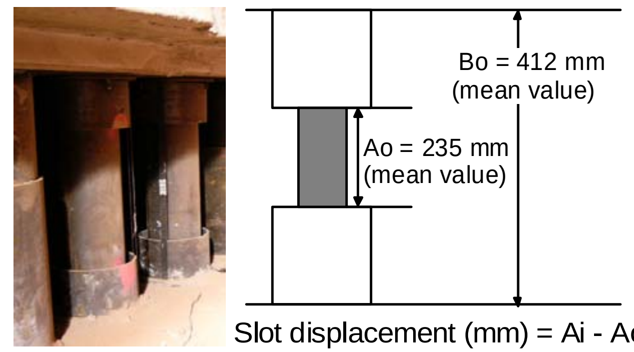
Lilla Tunnel – Circular Test Section with Slots

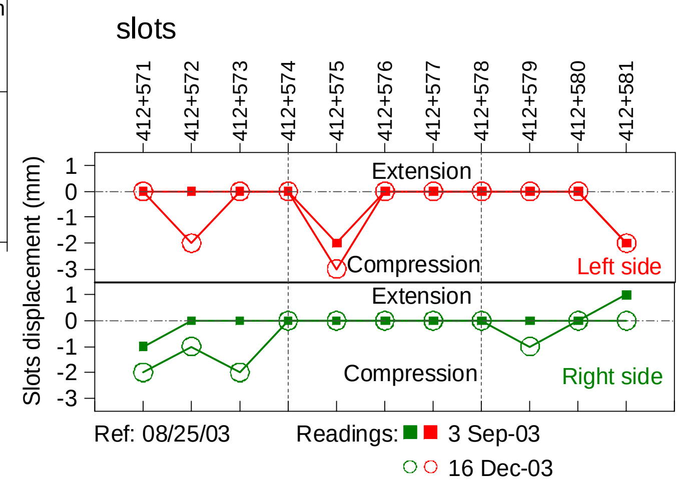


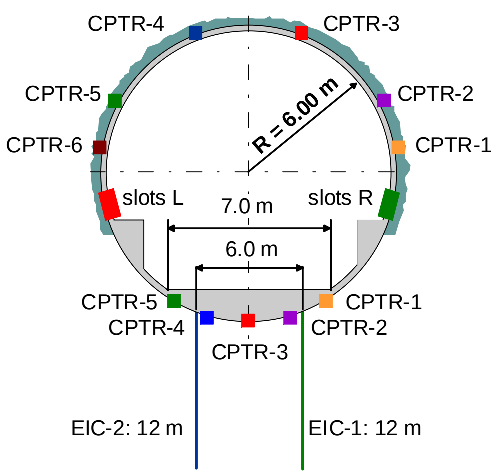
(a) station 412+574



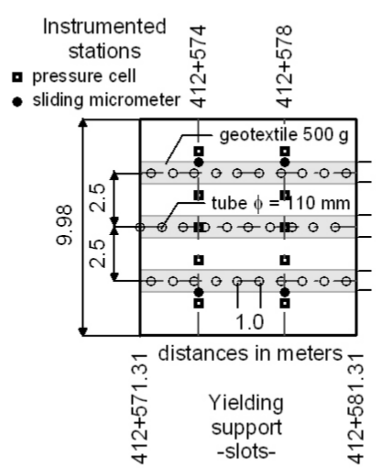
(b) station 412+578





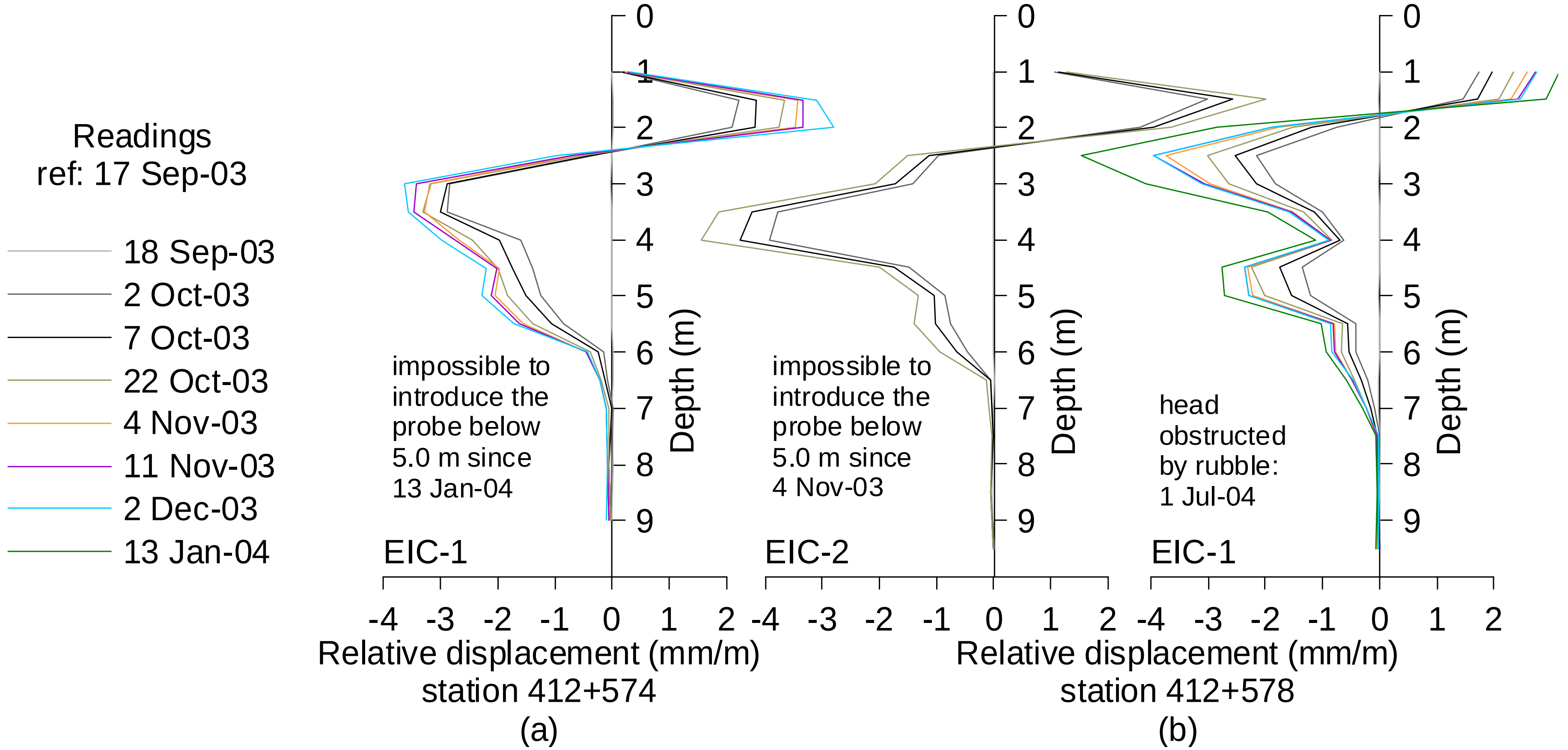


(c) typical cross-section with yielding support-slots

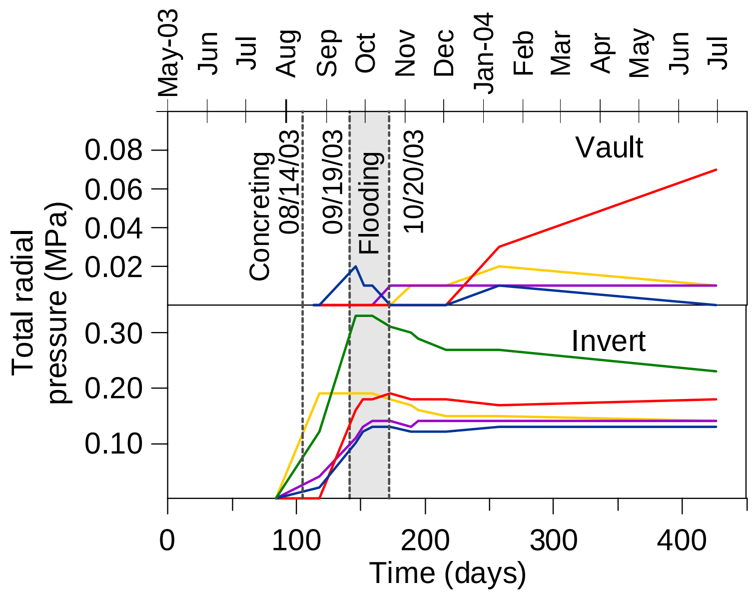


(d) plant view of the test section

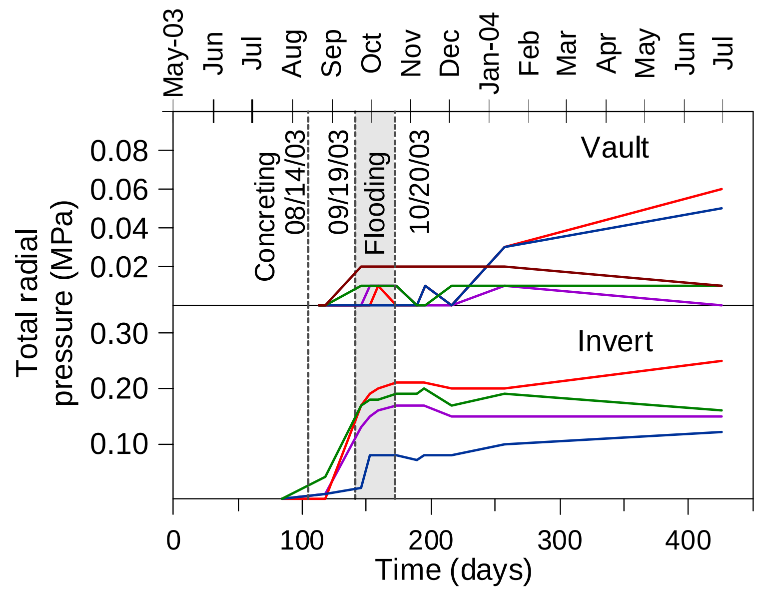
Lilla Tunnel – Circular Test Section with Slots



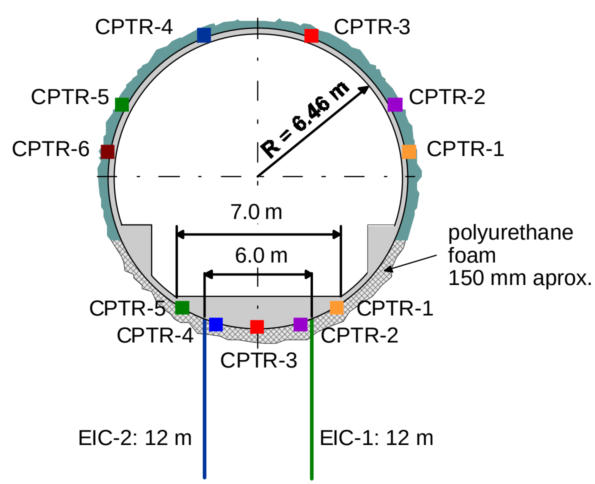
Lilla Tunnel – Circular Test Section with Foam



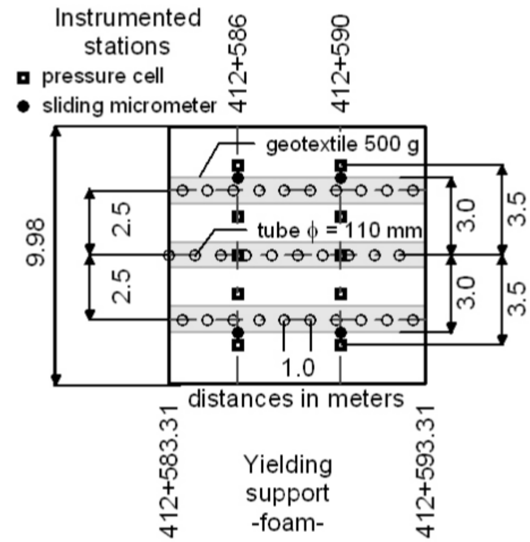
(a) station 412+586



(b) station 412+590

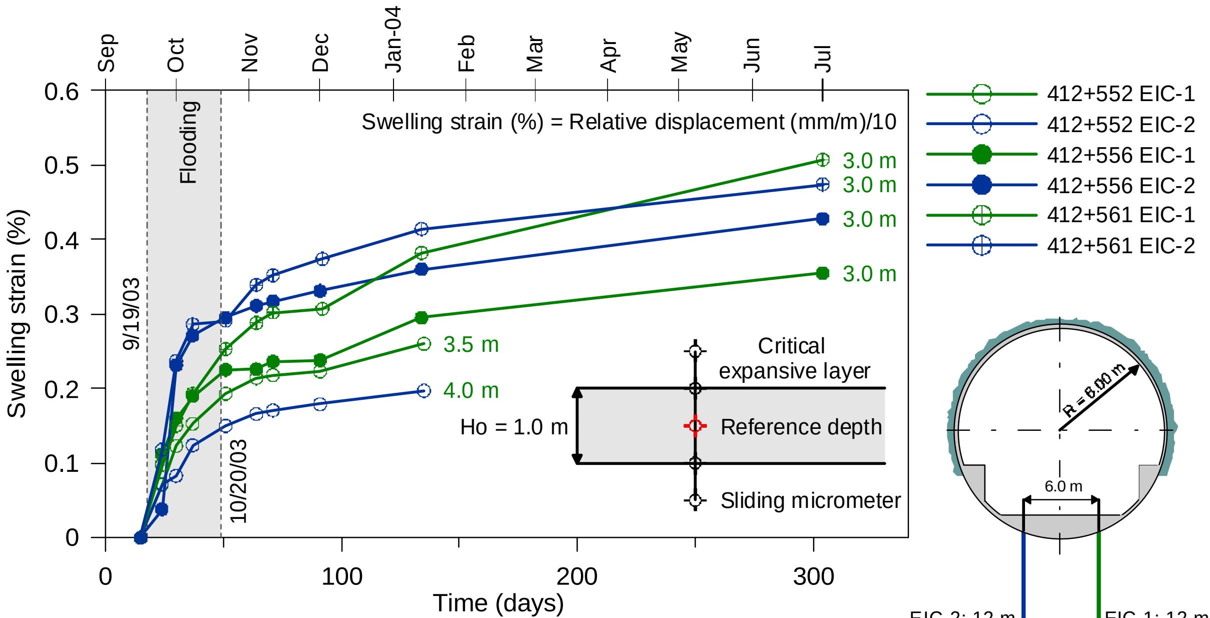


(c) typical cross-section with yielding support-foam

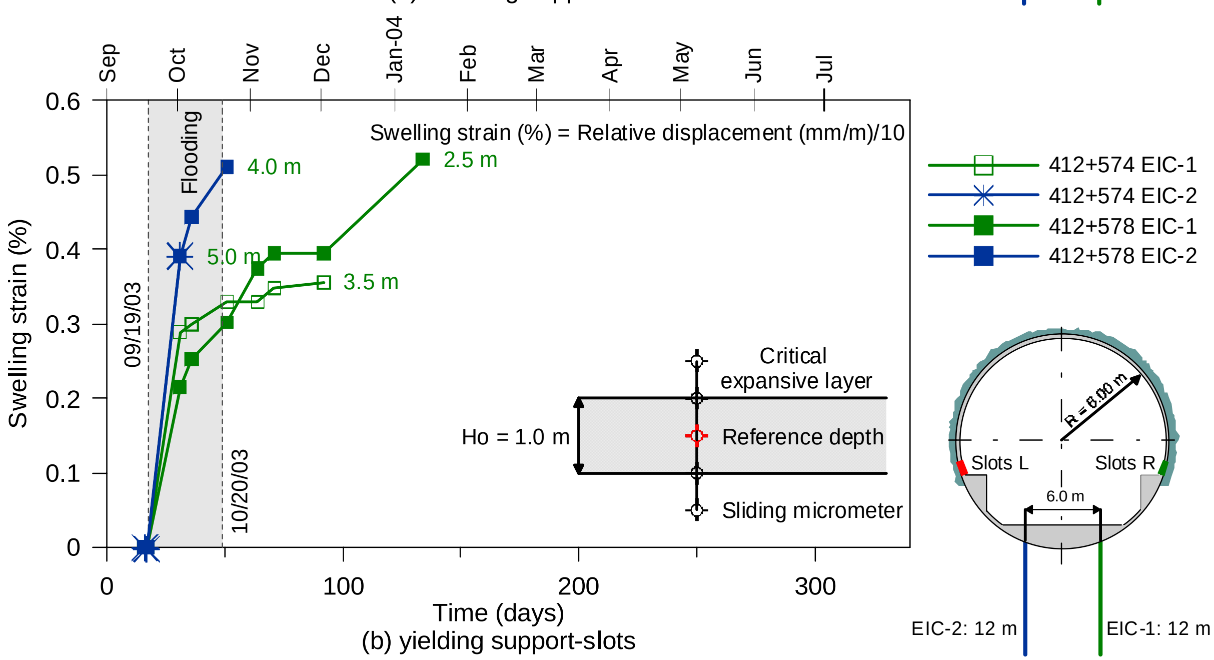


(d) plant view of the test section

Lilla Tunnel – Rock Expansions in Circular Test Sections

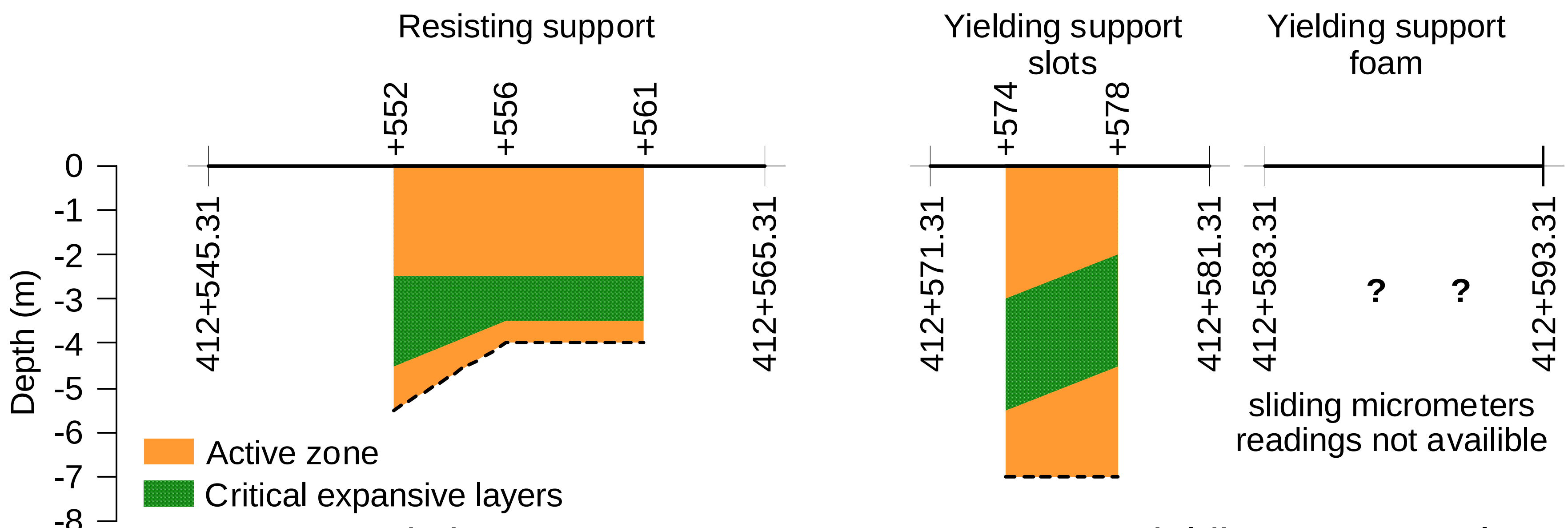


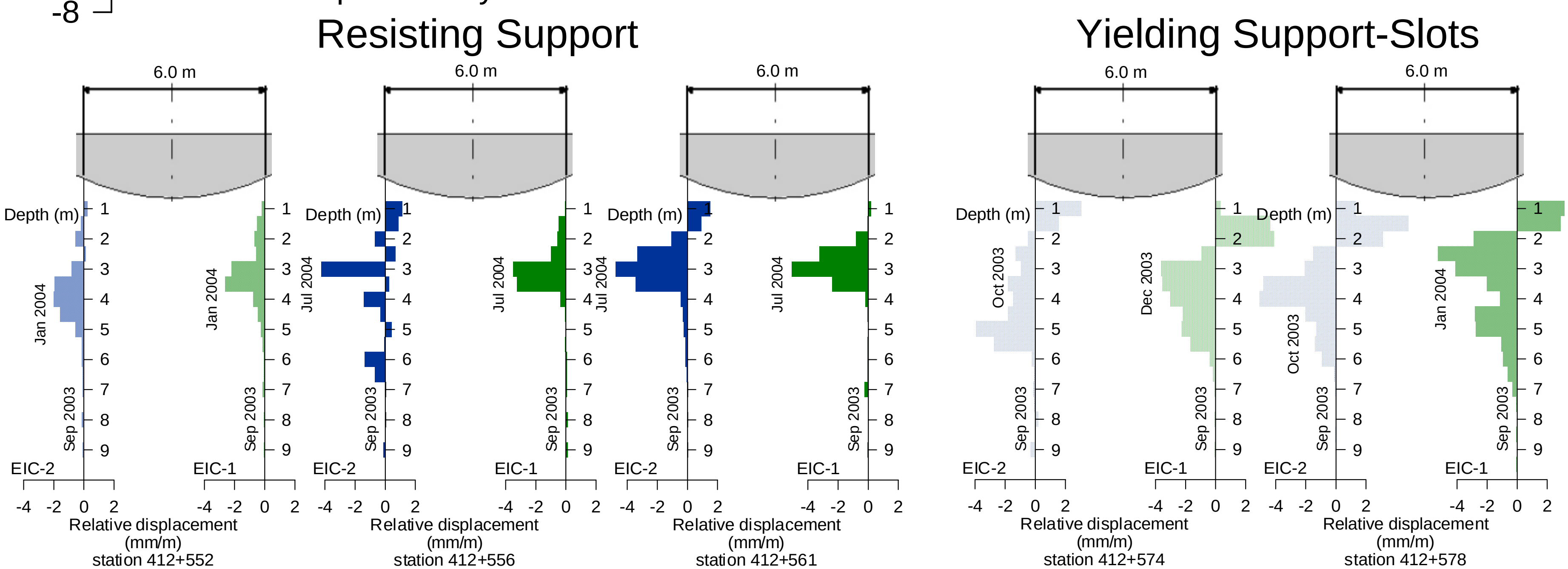
(a) resisting support



(b) yielding support-slots

Lilla Tunnel – Active Zone Below Circular Test Sections

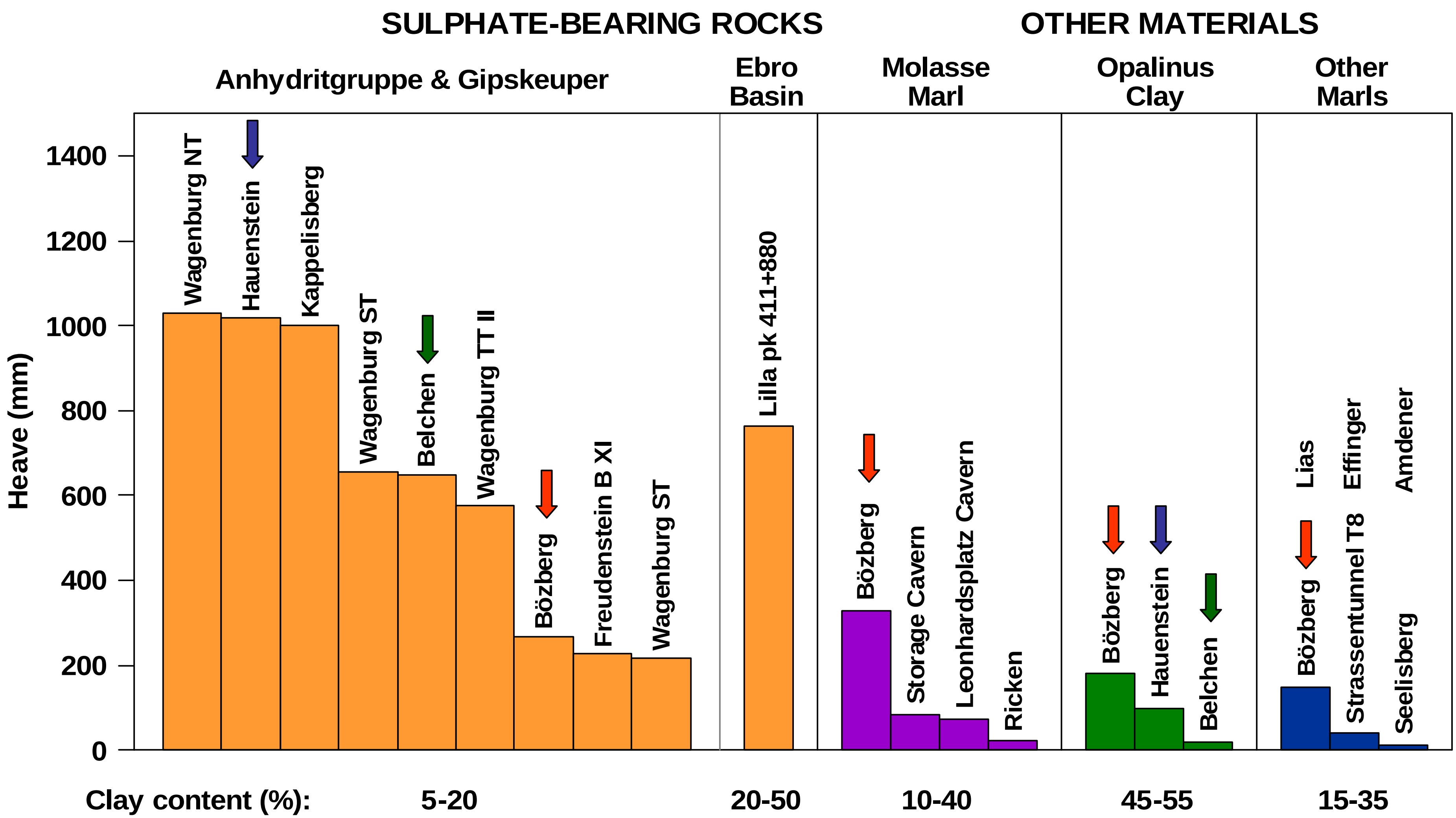




4. Swelling mechanisms in SBR

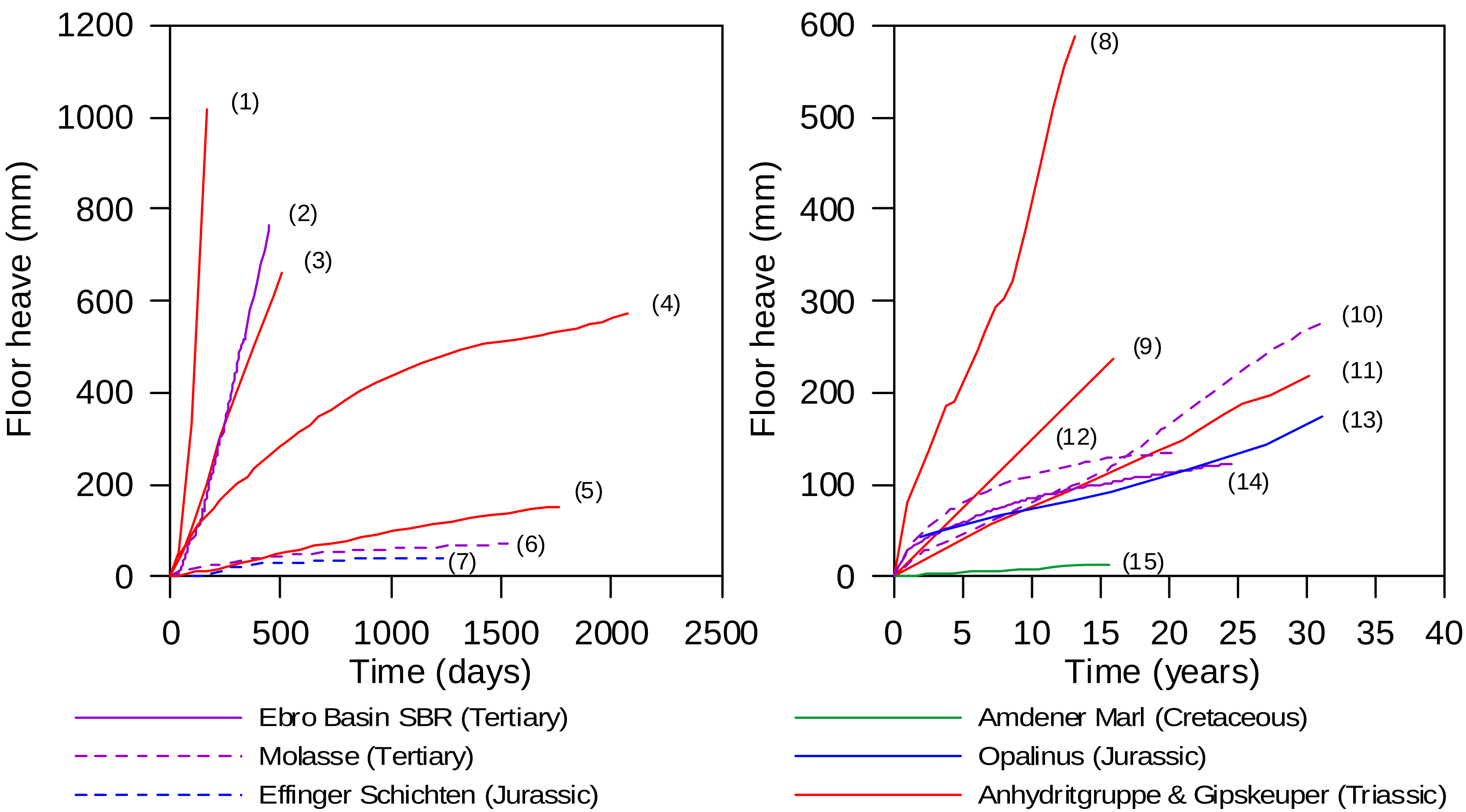
Tunnels in Expansive Rocks - Heave

Field Measurements



Tunnels in Expansive Rocks - Heave

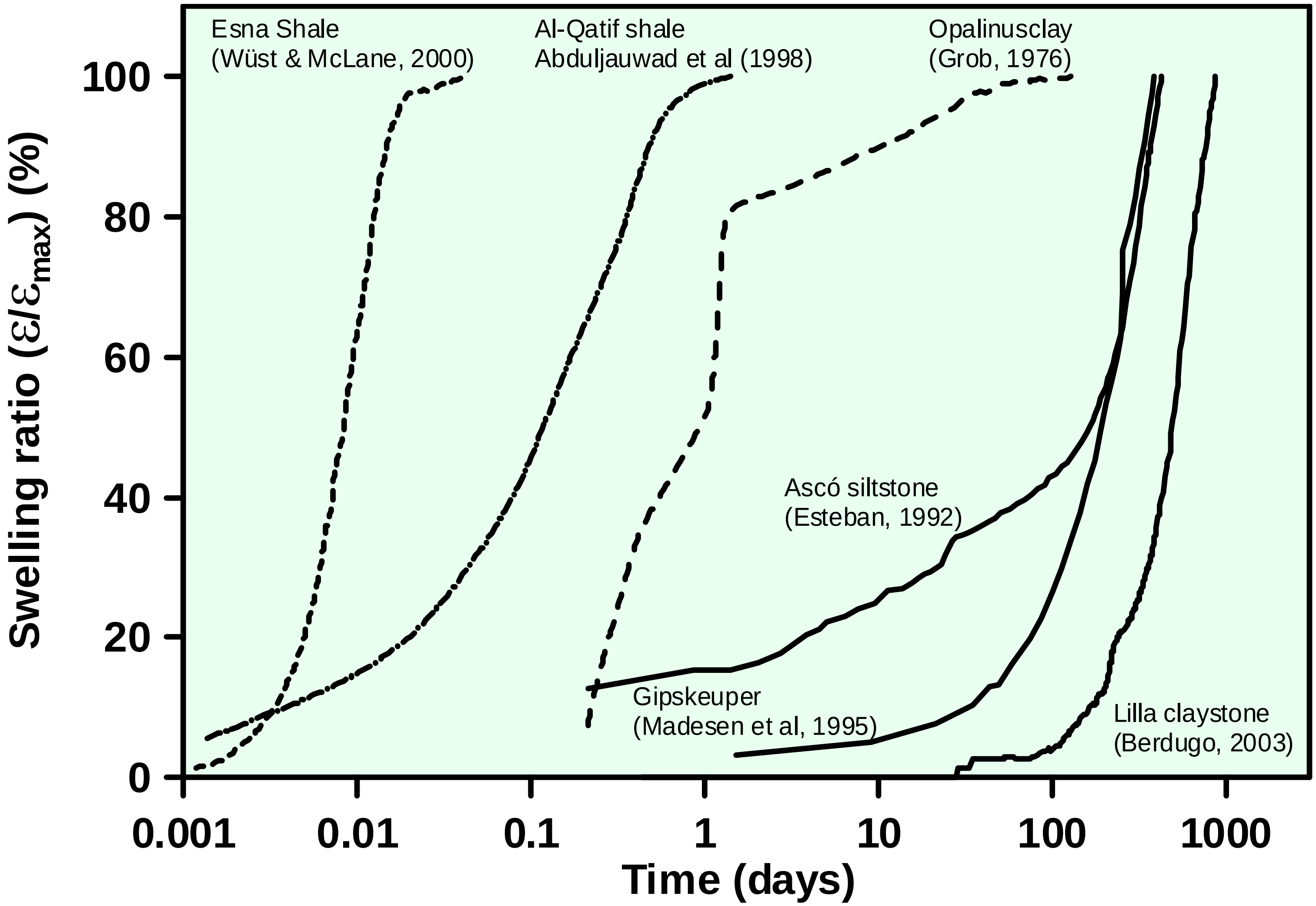
Field Measurements



(1) Hauenstein Base (Amstad & Kovári, 2001), (2) Lilla 411+880 (Alonso et al, 2004), (3) Wagenburg ST E 360 (Krause & Wurm, 1975), (4) Wagenburg TT II E 3 - wet (Nagel, 1986), (5) Freudenstein TG Block XIV (von Fecker, 1992), (6) and (12) Luftschutzanlage Leonhardsplatz (Amstad & Kovári, 2001), (7) T8 Biel-Sonceboz (Amstad & Kovári, 2001), (8) Wagenburg NT E 391 (Nagel, 1986), (9), (10) and (13) Bözberg (Grob, 1976) (11) Wagenburg ST E 387 (Paul & Wichter (1996), (14) Ascó II NPS (Berdugo, 2006), (15) Seelisberg (Amstad & Kovári, 2001)

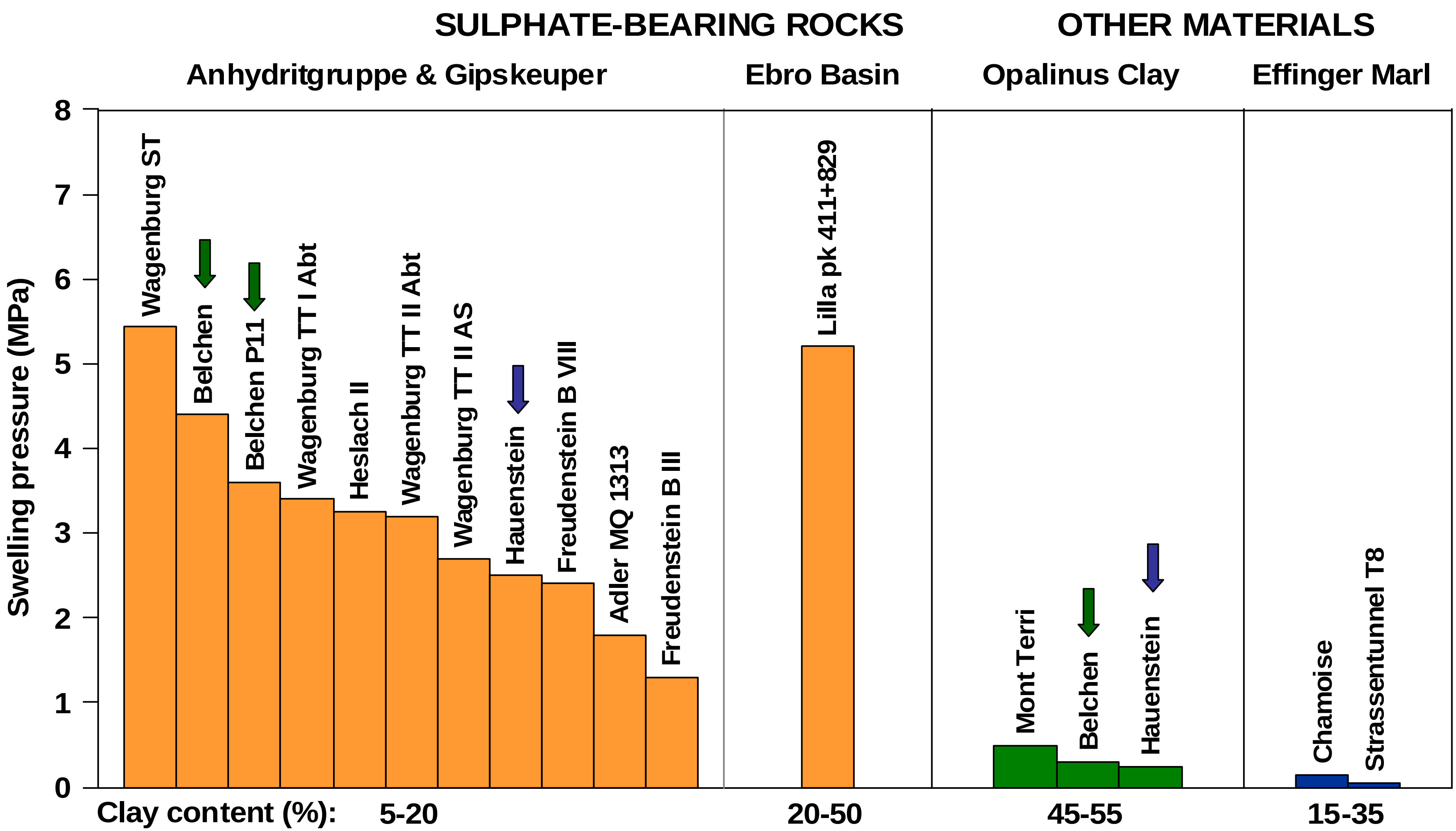
Expansive Rocks – Heave

Laboratory Tests



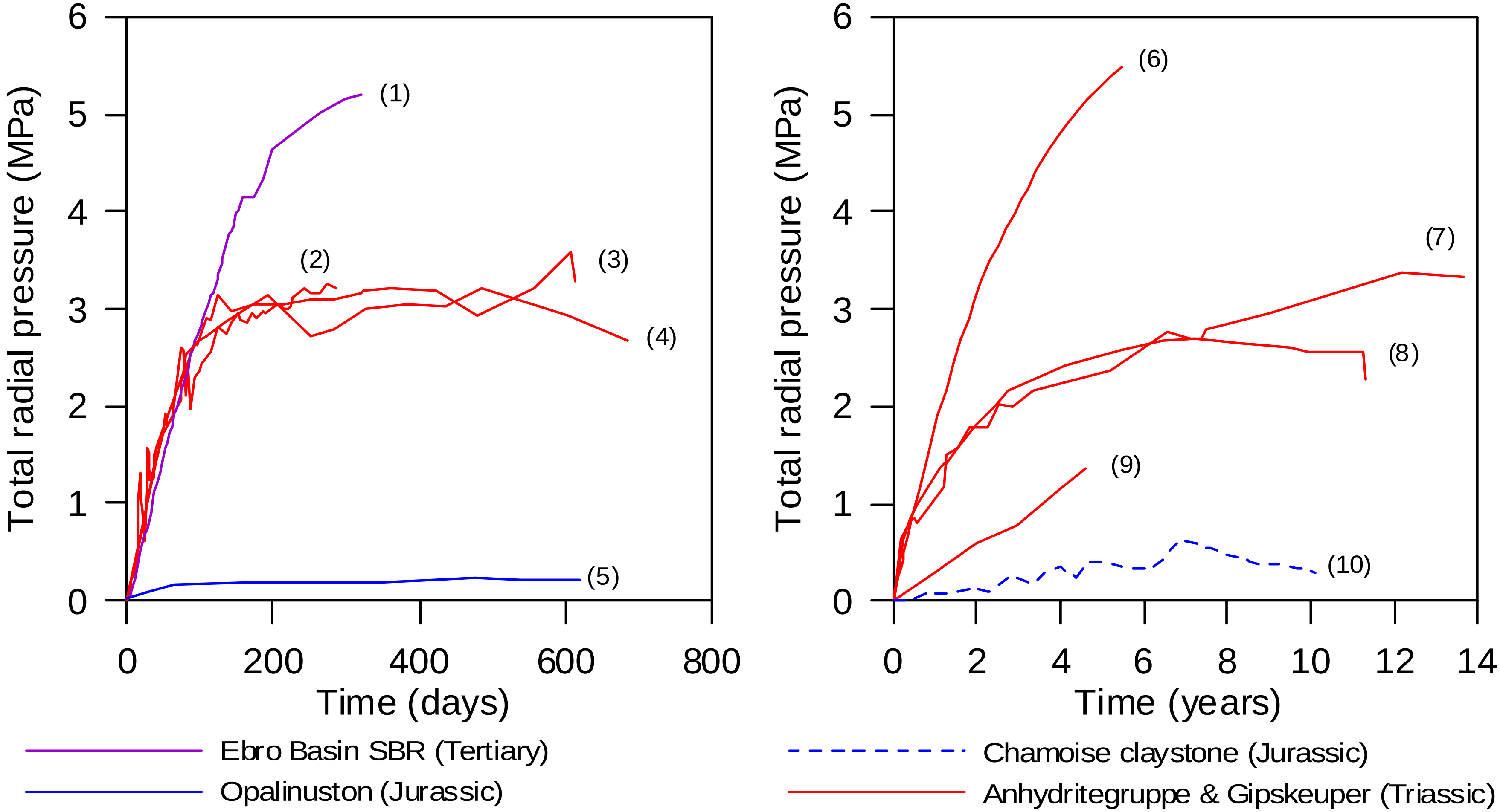
Tunnels in Expansive Rocks – Swelling Pressure

Field Measurements



Tunnels in Expansive Rocks – Swelling Pressure

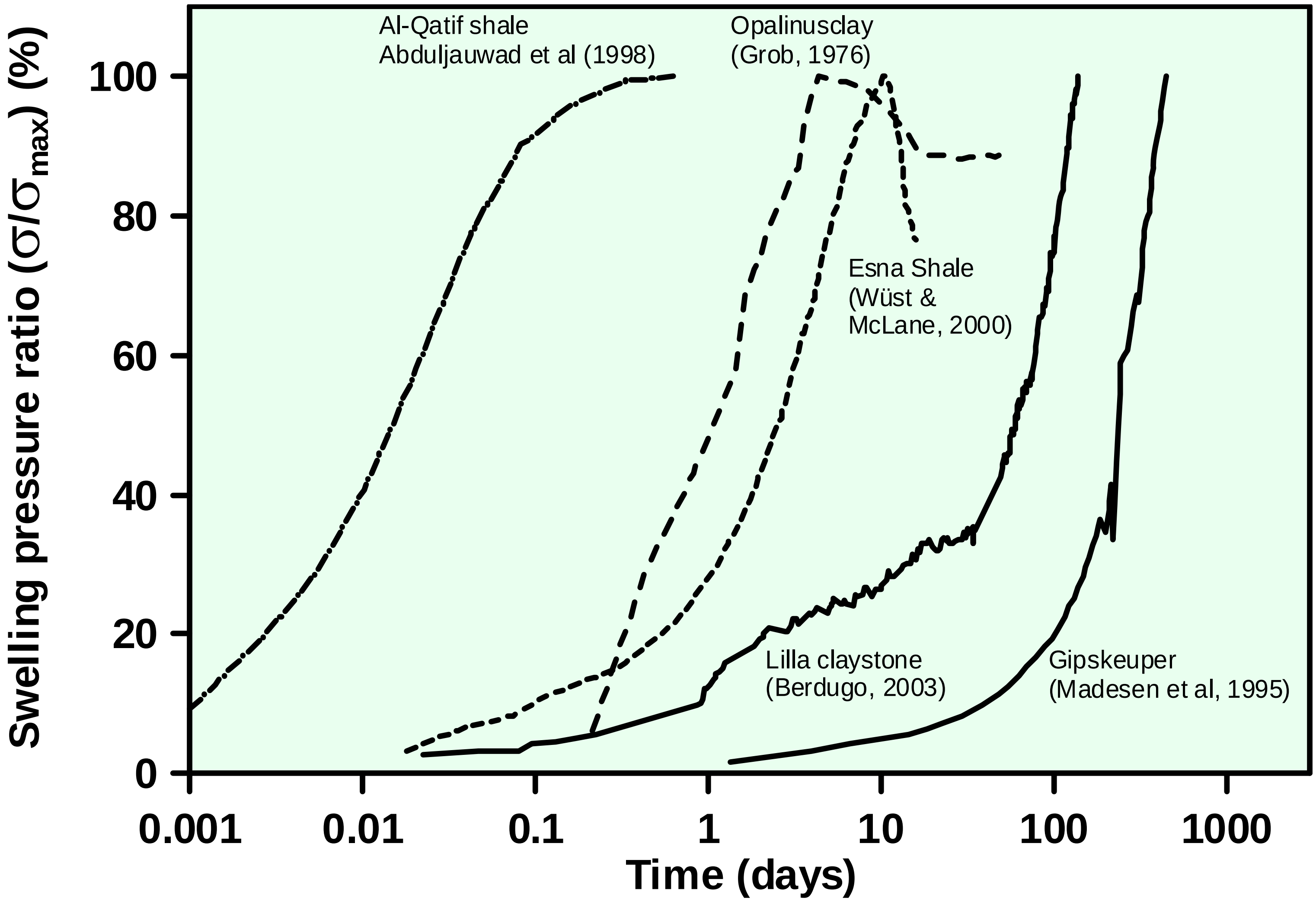
Field Measurements



(1) Lilla 411+829 (Alonso et al, 2004), (2) Heslach II (Kiehl & Wittke, 1991), (3) Belchen (Huder & Amberg, 1970), (4) Wagenburg TT II - wet (Wichter, 1985), (5) Belchen (Huder & Amberg, 1970), (6) Wagenburg ST E 409 (Paul & Wichter,1996), (7) Wagenburg TT I - dry (Wichter, 1985), (8) Wagenburg TT II - wet (Wichter, 1985), (9) Freudenstein TG Block VIII (von Fecker, 1992), (10) Chamoise (Leger, 1999).

Expansive Rocks – Swelling Pressure

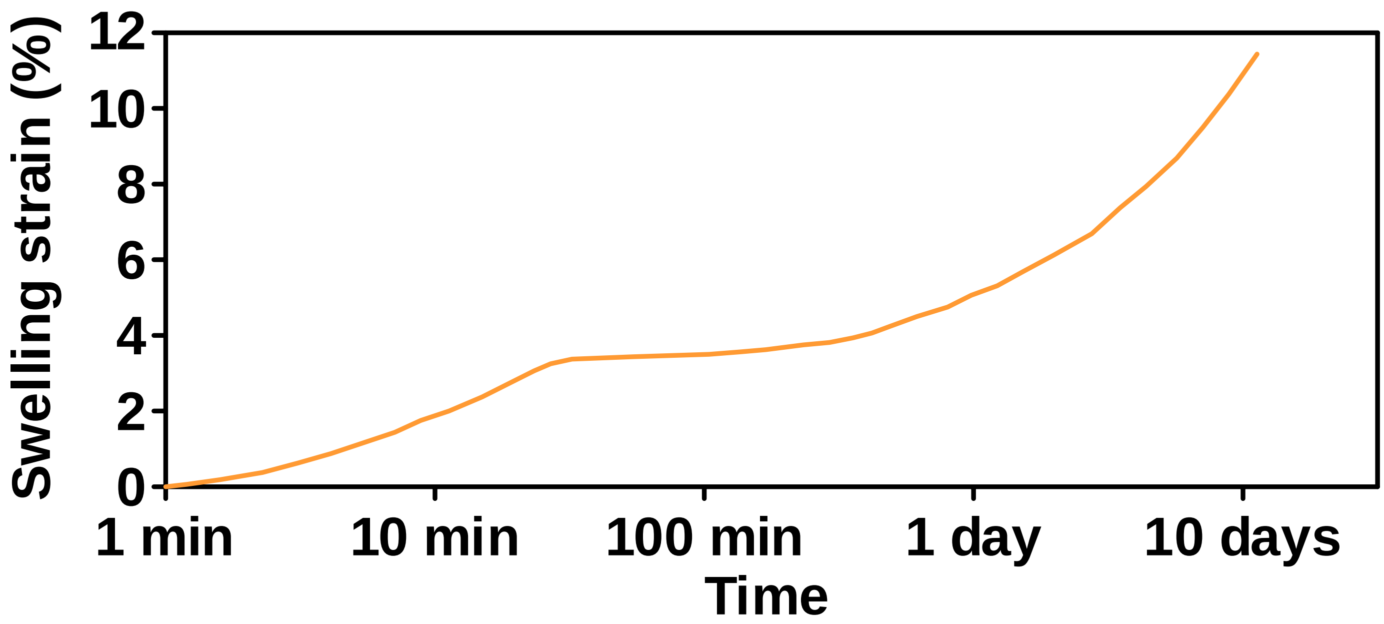
Laboratory Tests



Expansive Behaviour of SBR

THE PHENOMENOLOGY

Expansive phenomena in anhydritic-gypsiferous clayey rocks often evolved at rates that, far from slowing down, remained steady or increased with time.



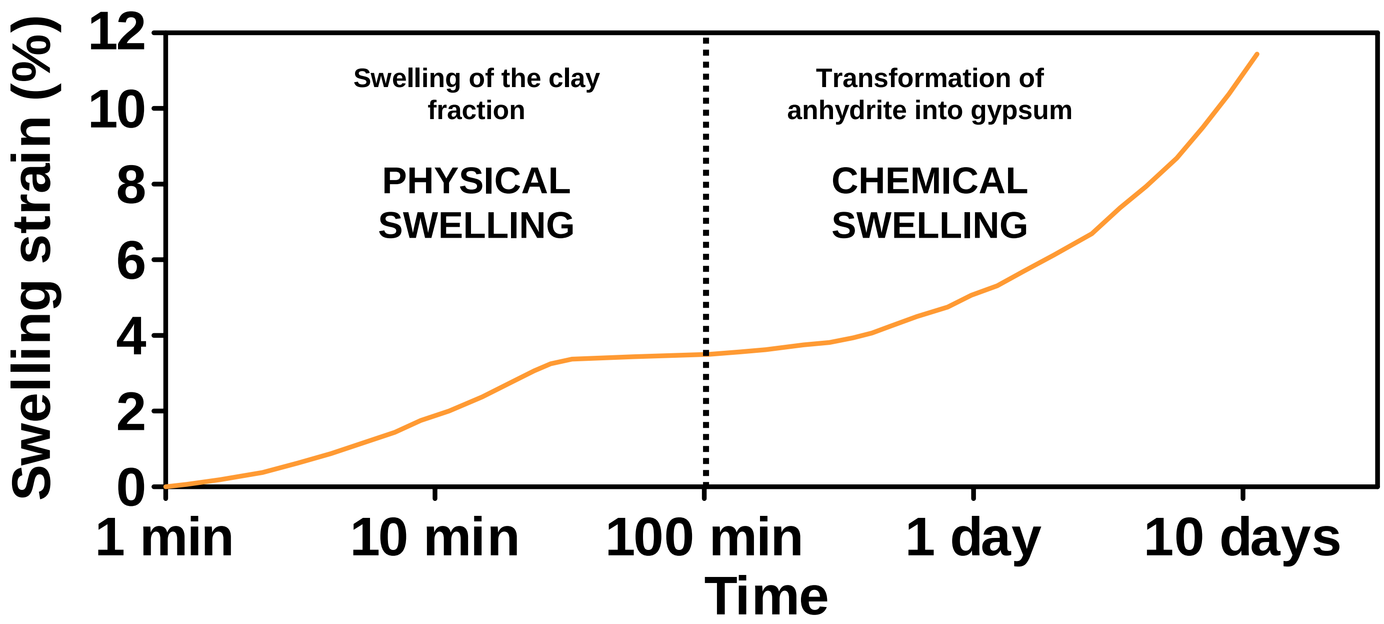
Expansive Behaviour of SBR

THE PHENOMENOLOGY

Expansive phenomena in anhydritic-gypsiferous clayey rocks often evolved at rates that, far from slowing down, remained steady or increased with time.

THE CLASSIC INTERPRETATION

Existence of a "physical swelling" -due to the expansion of clay minerals-, followed by a "chemical swelling" -due to the transformation of anhydrite into gypsum-.



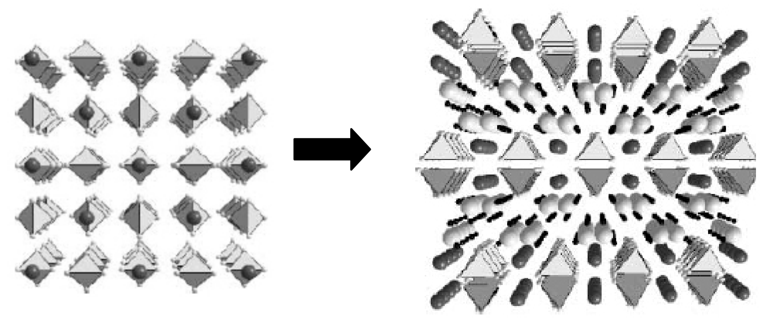
Expansive Behaviour of SBR

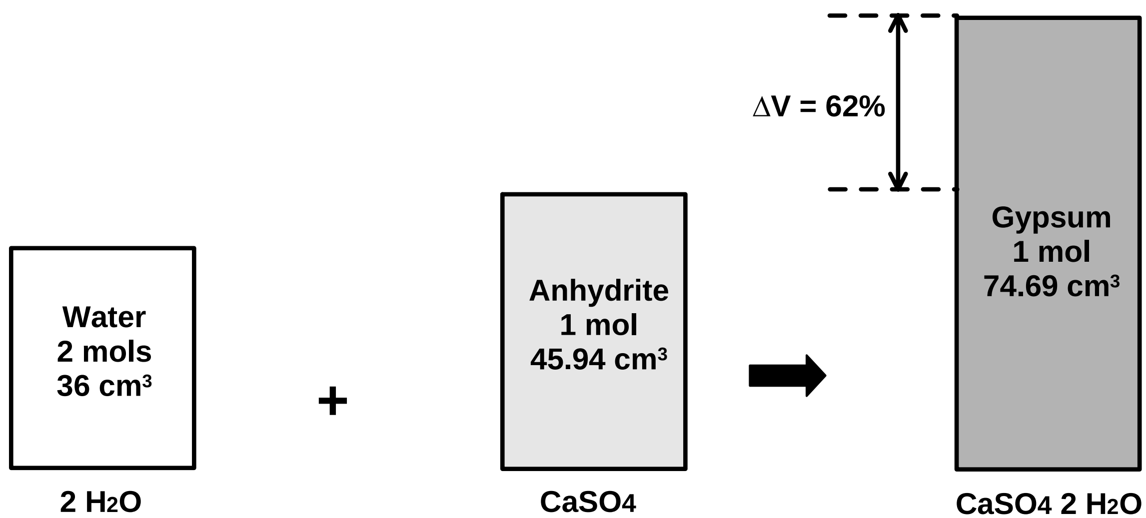
TRANSFORMATION OF ANHYDRITE INTO GYPSUM IN AN OPEN SYSTEM

Anhydrite: Gs = 2.96

Gypsum: Gs = 2.32

Orthorhombic **Monoclinic**





Expansive Behaviour of SBR

DETERMINING FACTORS IN THE CLASSIC CRITERION

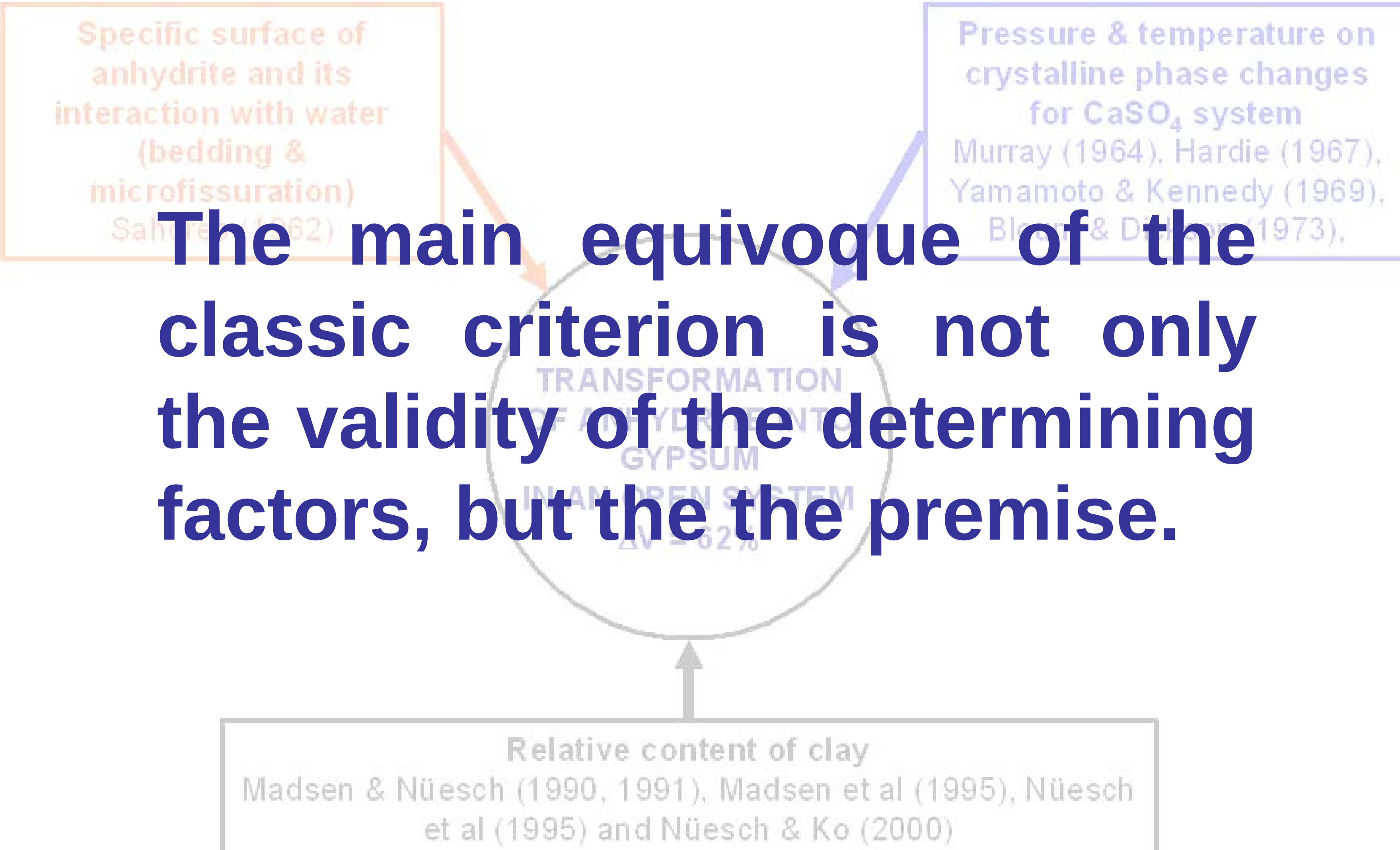
Specific surface of anhydrite and its interaction with water (bedding & microfissuration)
Sahores (1962)

Pressure & temperature on crystalline phase changes for $CaSO_4$ system
Murray (1964), Hardie (1967), Yamamoto & Kennedy (1969), Blount & Dickson (1973),

TRANSFORMATION OF ANHYDRITE INTO GYPSUM IN AN OPEN SYSTEM
$\Delta V = 62\%$

Relative content of clay
Madsen & Nüesch (1990, 1991), Madsen et al (1995), Nüesch et al (1995) and Nüesch & Ko (2000)

Expansive Behaviour of SBR



The main equivoque of the classic criterion is not only the validity of the determining factors, but the the premise.

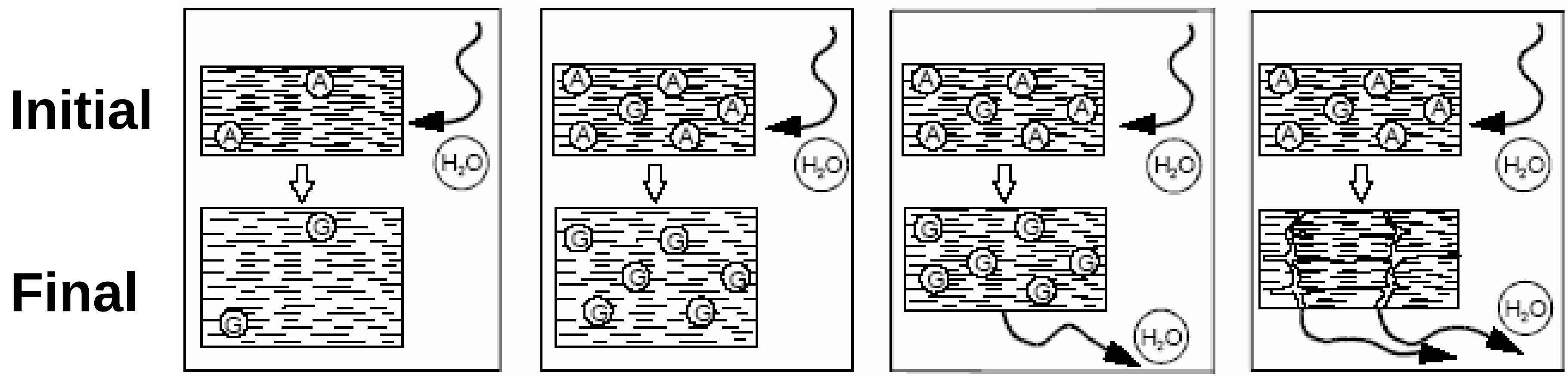
Expansive Behaviour of SBR

BASIC SHORTCOMING OF THE CLASSIC CRITERION

Theory of Isovolumetric Replacement
Holliday (1970), Ortí Cabo (1977)

The transformation of anhydrite into gypsum is an isovolumetric (isochoric) process in which anhydrite is dissolved as fast as secondary gypsum precipitates. The excess in calcium sulphate dihydrated (60 - 63% in volume) could be either transported in aqueous solution or it could precipitate partially in the form of fibrous gypsum in open discontinuities of the host rocks

The chemical composition of incoming water, the geochemical conditions for dissolution/precipitation and the water flow properties are not considered



Classical theory

Theory of isovolumetric replacement

Epitaxial Growth of Gypsum on Anhydrite

- **Formation of an impervious thin surface of gypsum on anhydrite, which generates a protective film and isolated anhydrite of the sulphate-rich water action (Steiner, 1993).**

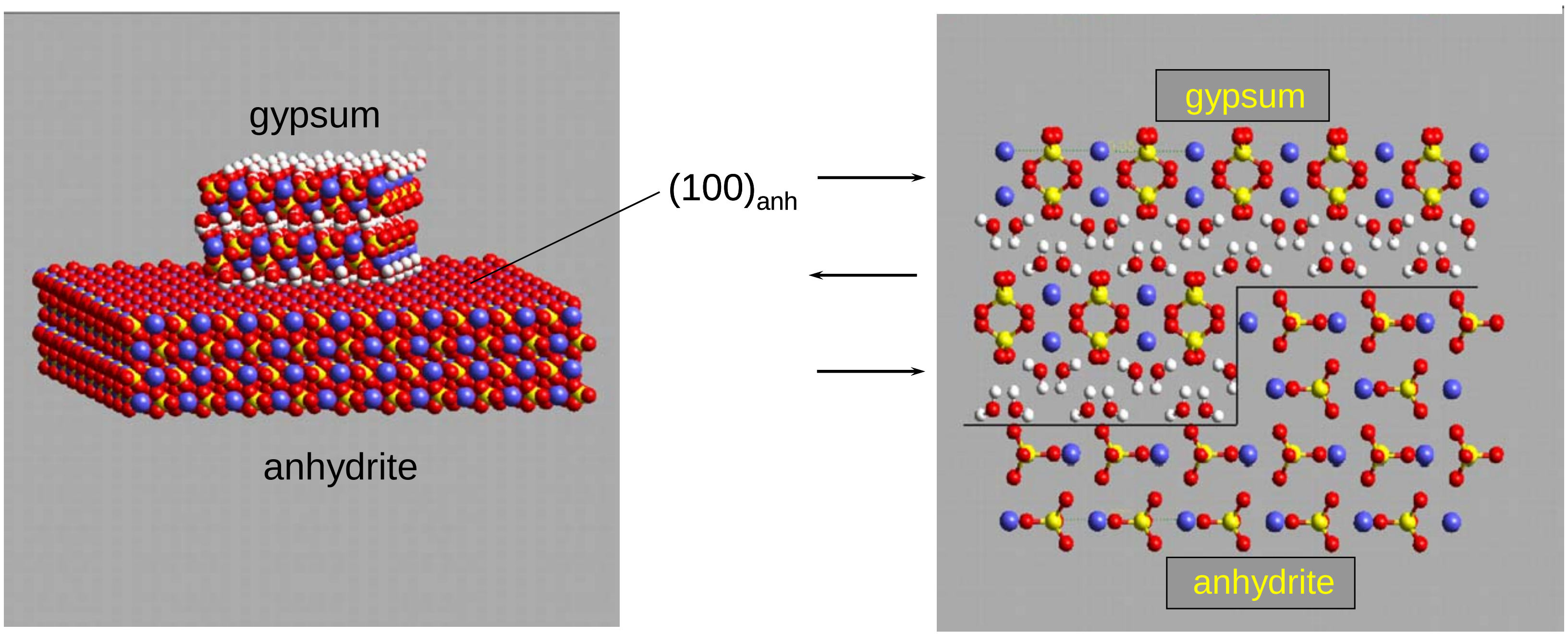
- **A monomolecular gypsum layer starts to grow from pre-existent anhydrite cleavage steps and it advances until a higher anhydrite step edge is reached. Then, a new gypsum monolayer grows in the opposite direction on top of the previous one (Pina et al, 2000).**

Expansive Behaviour of SBR

Epitaxial Growth of Gypsum on Anhydrite

GYPSUM (010) on ANHYDRITE (100)

EPITAXIAL GROWTH

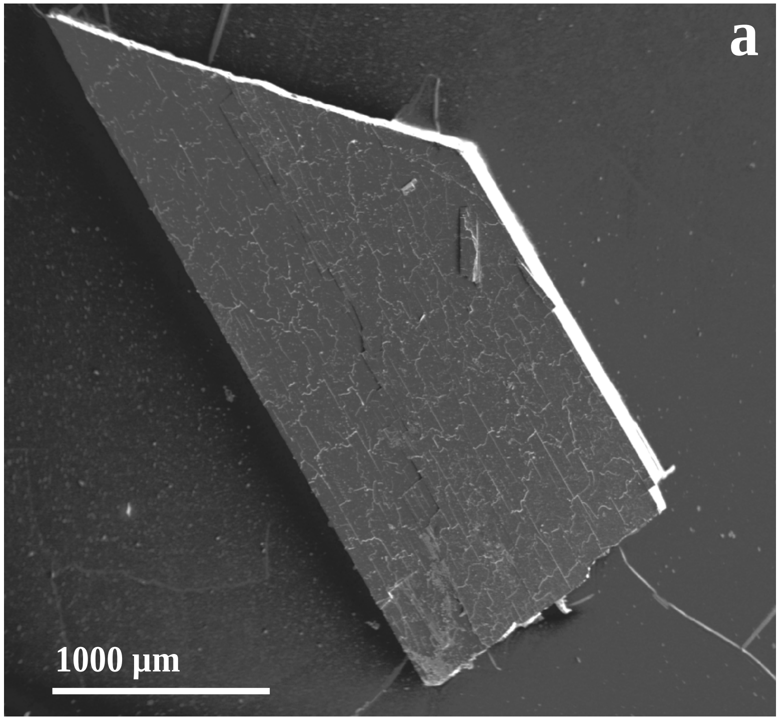


Ca S O H

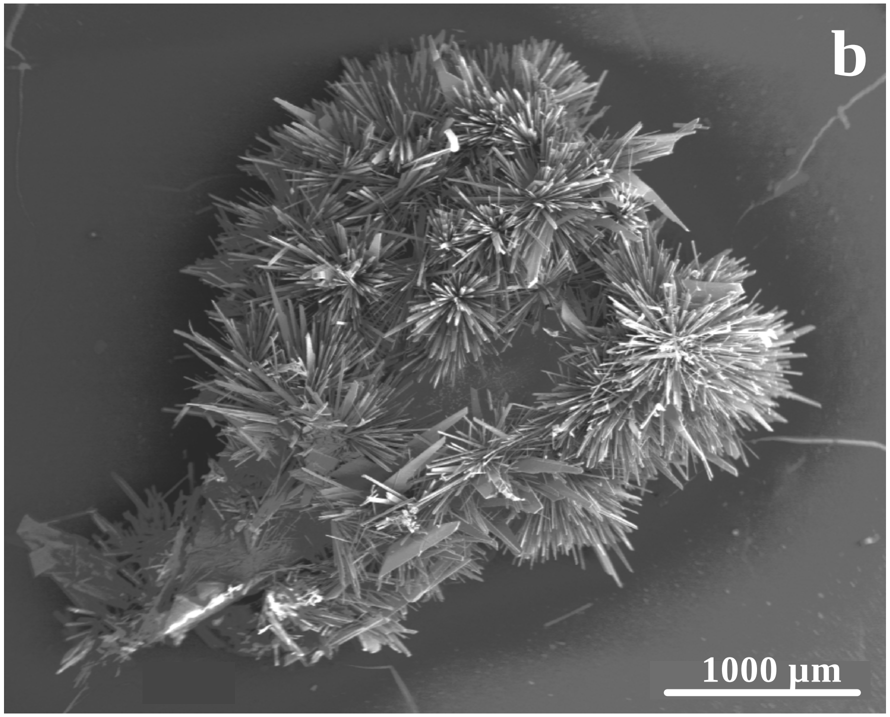
(Pina and co-workers, 2003 - personal communication)

Expansive Behaviour of SBR

Epitaxial Growth of Gypsum on Anhydrite



Undisturbed anhydrite



Anhydrite affected by epitaxial growth

(Pina and co-workers, 2006 - personal communication)

Expansive Behaviour of SBR

Epitaxial Growth of Gypsum on Anhydrite

OBSERVATIONS IN MATERIALS FROM LILLA TUNNEL
May, 2005

THE QUESTION

What mechanisms are really related to the expansive behaviour of sulphate-bearing rocks?

Swelling mechanisms in SBR: a new criterion

Hydration of Clay Minerals

Hydration of clay minerals, suction decrease, cation exchange, osmotic swelling, concentration changes, degradation of bonds, …

Crystal growth

Requires water supersaturation induced by temperature and/or vapor loss (drying under RH conditions)

$$\varepsilon_{\text{total swelling}} = \varepsilon_{\text{matrix swelling}} + \varepsilon_{\text{crystal growth}}$$

Constitutive modelling (suction, geochemical variables, stress, …)

"POINT" FORMULATION

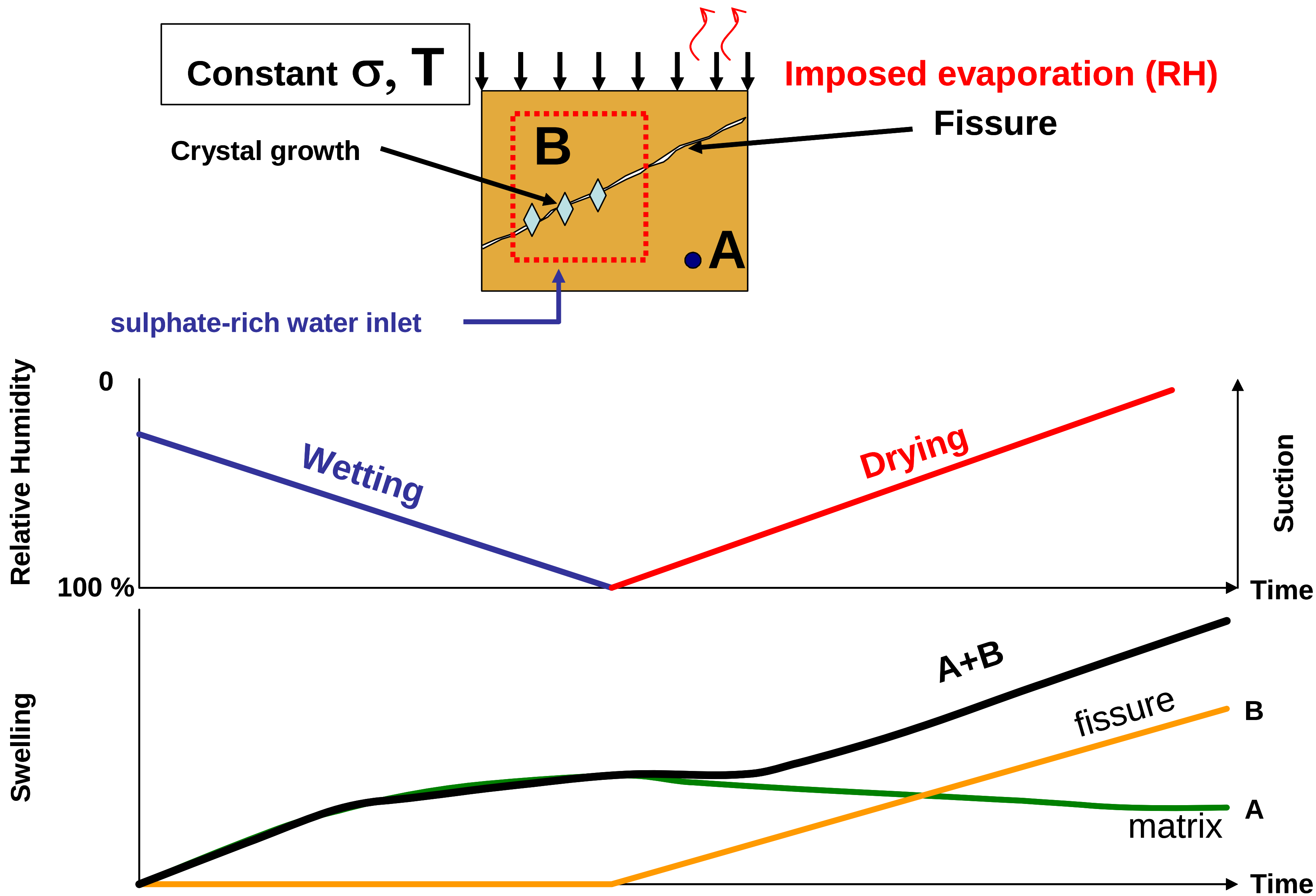
Large scale phenomenon (temperature, RH at boundaries, RH in discontinuities, …)

BOUNDARY VALUE PROBLEM

Need for THMC coupled analyses !

Swelling mechanisms in SBR: a new criterion

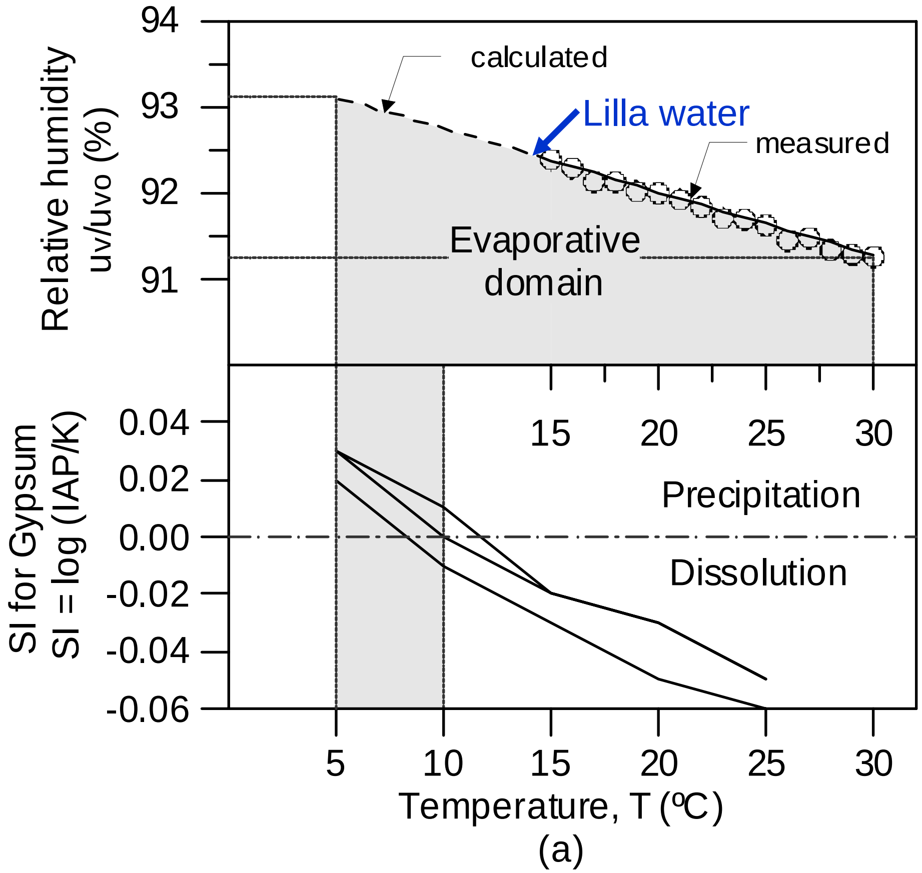
Swelling under drying



Swelling mechanisms in SBR: a new criterion

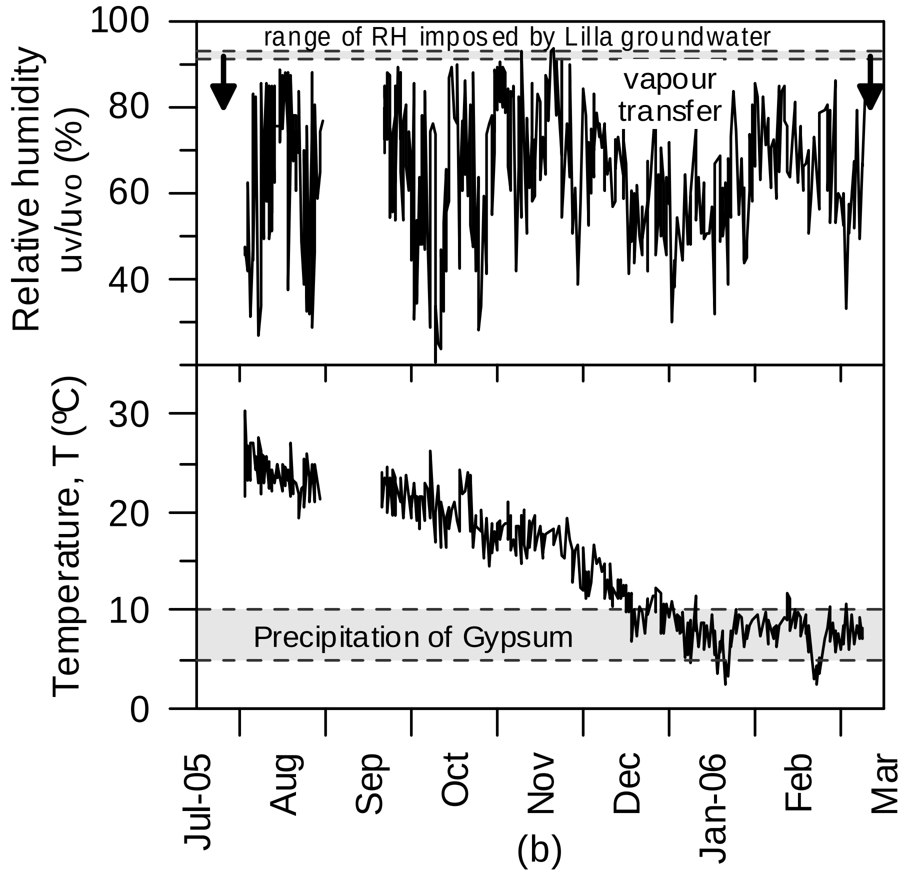
Swelling under drying

ANALYSIS OF LILLA TUNNEL



(a)

Groundwater conditions

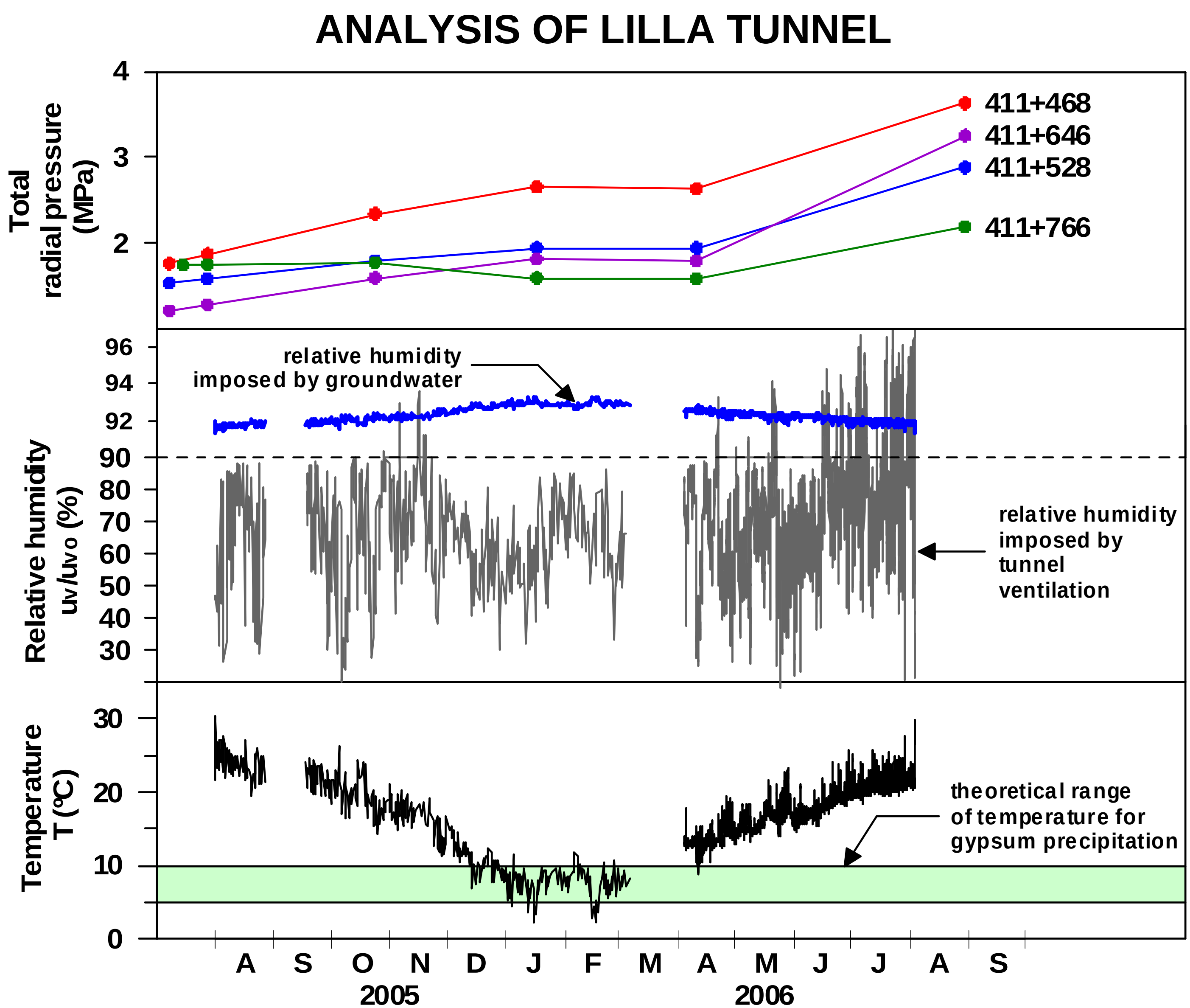


(b)

Tunnel environmental conditions

Swelling mechanisms in SBR: a new criterion

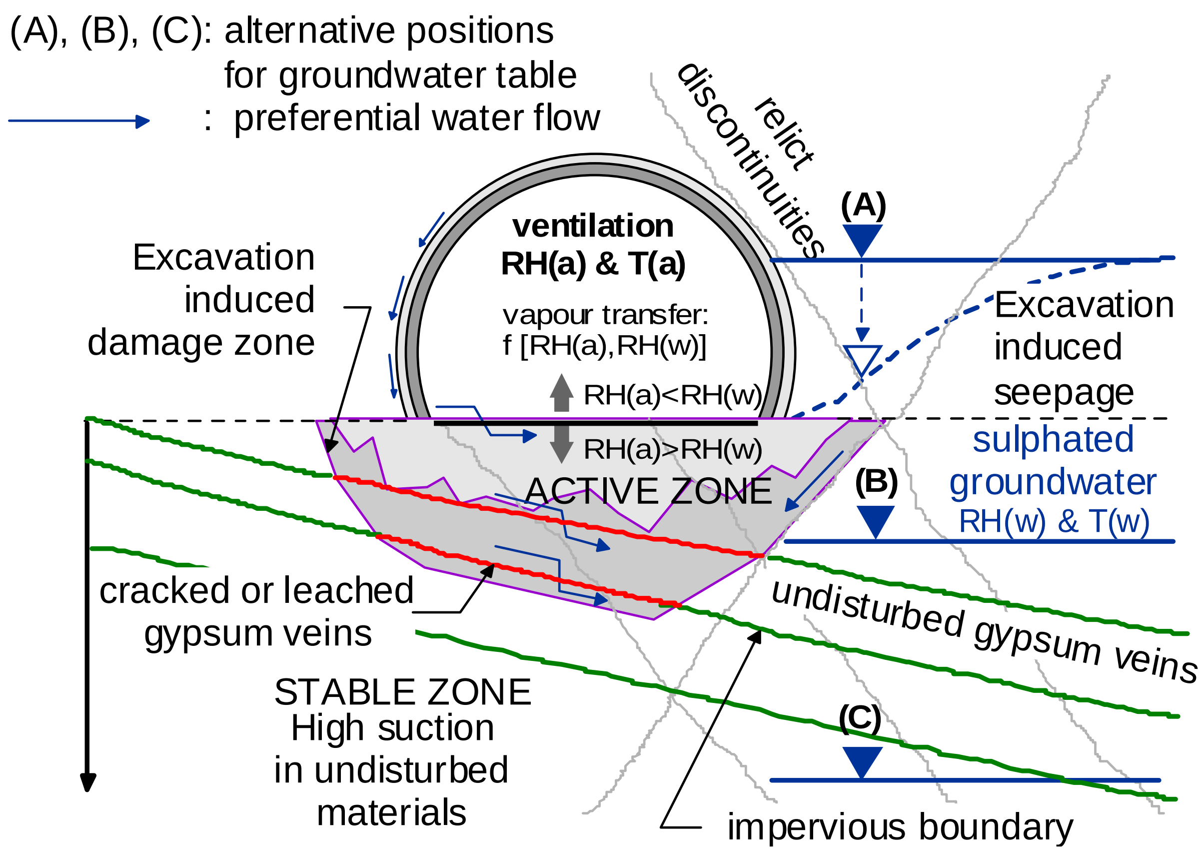
Swelling under drying



Swelling mechanisms in SBR: a new criterion

Swelling under drying

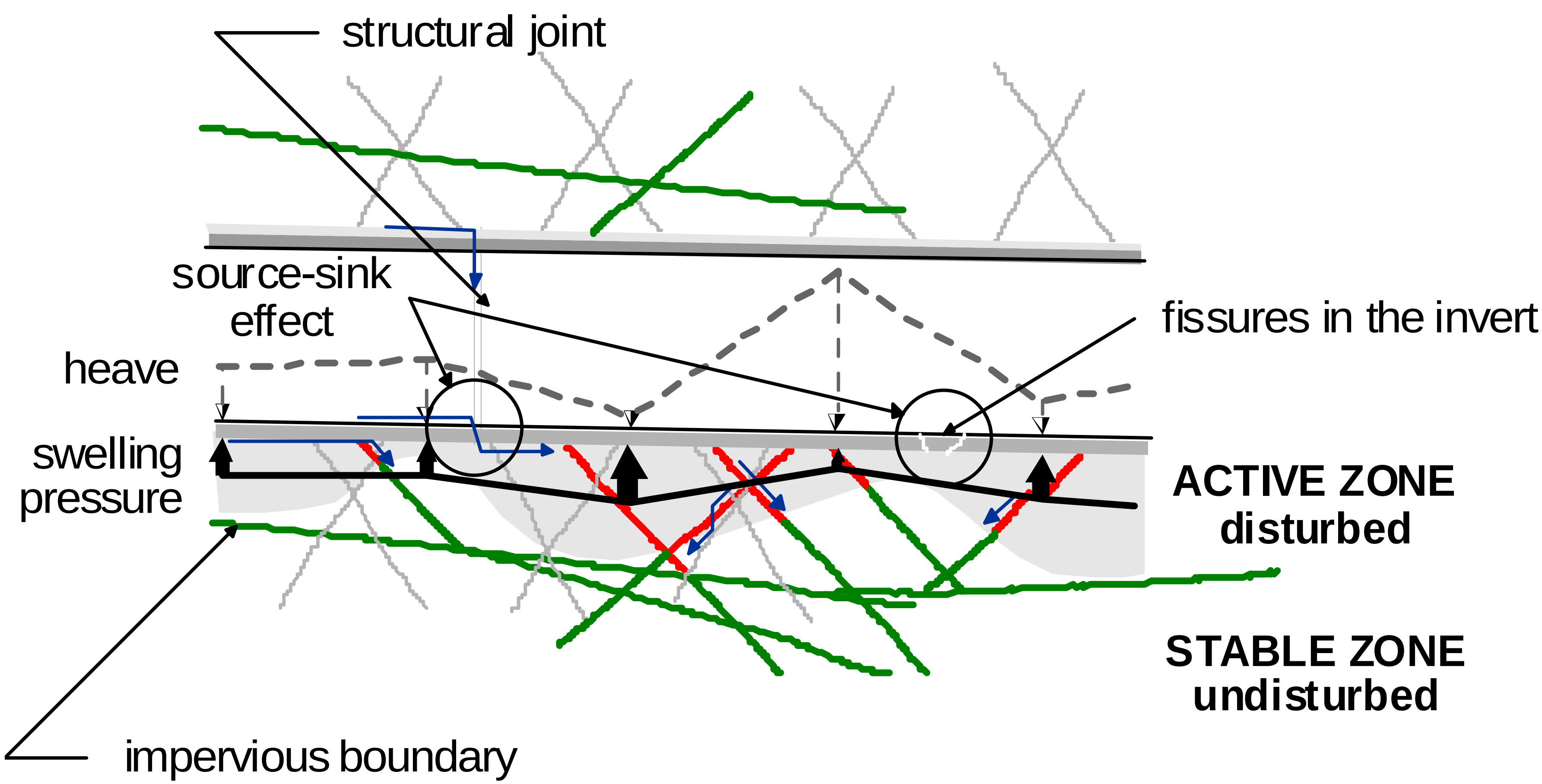
ANALYSIS OF LILLA TUNNEL



Swelling mechanisms in SBR: a new criterion

Swelling under drying

ANALYSIS OF LILLA TUNNEL



CONCLUSIONS ON TUNNELING IN SBR

- Resisting or yielding support?
  - A mechanism has been identified (swelling under drying) that predicts virtually indefinite continuing heave
  - Single tunnel with no alternative. No possibilities of major repairs
  - Preventing movements may minimize damage to the rock, limiting the increase of permeability
  - Previous experience suggest phenomena stabilisation when using resisting support (pressures) and continuing deformation when using yielding support