AEG-ASCE SHORT COURSE

TUNNELS THROUGH FAULT ROCKS AND TECTONIC MELANGES

May 31 and June 1, 2002

Gunter Riedmueller and Wulf Schubert

FROM AEG SHORT COURSE " Tunnels Through Fault Rocks and Tectonic Melanges: A Short Course for Engineering Geologists and Geotechnical Engineers", Oakland, California; June 1, 2002; Instructors: Prof. Gunter Riedmueller and Prof. Wulf Schubert, Technical University of Graz, Austria and Gruppe Geotechnik Graz

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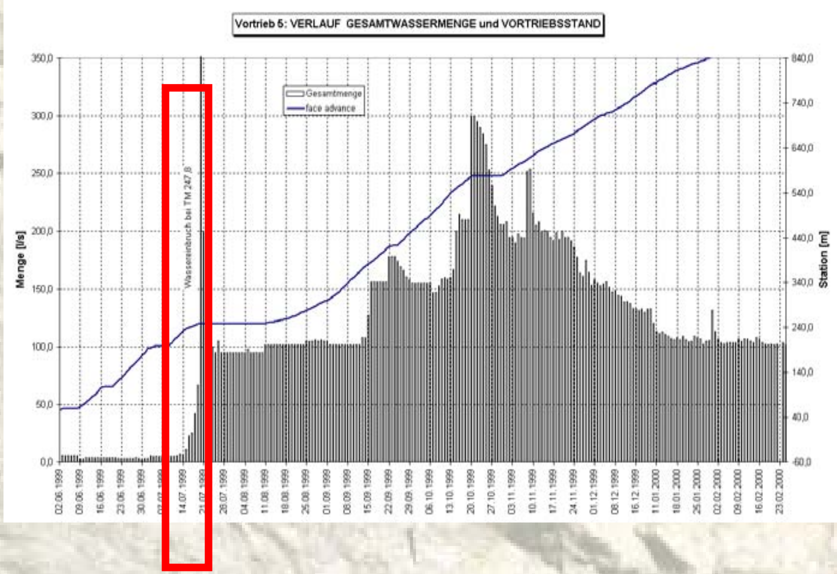
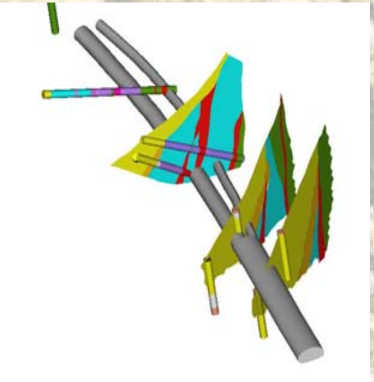
Course Outline

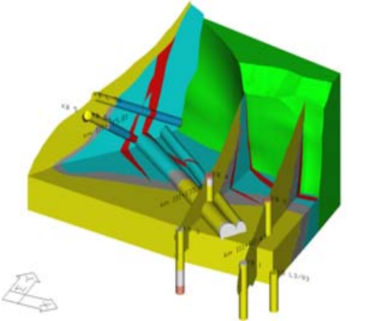
- Introduction
- Characterization and Classification
- Investigation
- State-of-the Art Method in Engineering Geological Face Mapping and Displacement Monitoring
- Prediction Ahead of the Tunnel Face
- Solving Problems with Tunneling Through Faults

Water Inflow

HEAVY WATER INFLOW
Station 247,8 m







BLISADONA TUNNEL (Austria, 1999, 500l/s)

Water Inflow

KAPONIG TUNNEL (Austria, 1993, 300l/s)

Water Inflow

BASO CHHU TUNNEL (Bhutan, 1999, 450 l/s)

Tunnel Collapse

Herzogberg Tunnel, Austria

Tunnel Collapse

Herzogberg Tunnel, Austria

Tunnel Collapse

Herzogberg Tunnel, Austria

Tunnel Collapse

Herzogberg Tunnel, Austria

Tunnel Collapse

Galgenberg Tunnel, Austria

Case Studies

- Pinglin Tunnel, Nangkan – Ilan Motorway, Taiwan
- Tunnels of the Malakasi section,

  Egnatia Motorway, Greece

Two spectacular examples showing that an inadequate geological understanding of fault rocks and tectonic melanges causes severe geotechnical problems during tunneling

Case Studies

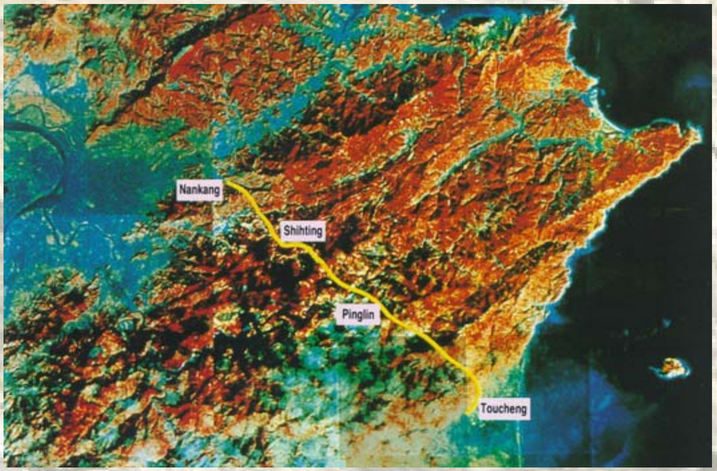
Project Summary

- Length: 12.9 km
- Twin-tube tunnel with tubes 60 m apart
- Outside diameter of tubes 11.8 m
- Pilot tunnel (diameter 4.8 m) between main tunnel tubes
- 28 cross connections between tubes
- Three ventilation shafts (diameters 6.0 m, 6.5 m, depths 355 m, 252 m, 459 m)
- Three interchange stations

- **Construction method:** two 750 m sections at the two portals should have been excavated by D&B method. The remaining 11.4 km (main tunnels and pilot tunnel) should have been constructed by using TBM
- **Construction schedule**: Construction of the pilot tunnel was commenced in July 1991. Completion of the whole project was expected by the end of 1999

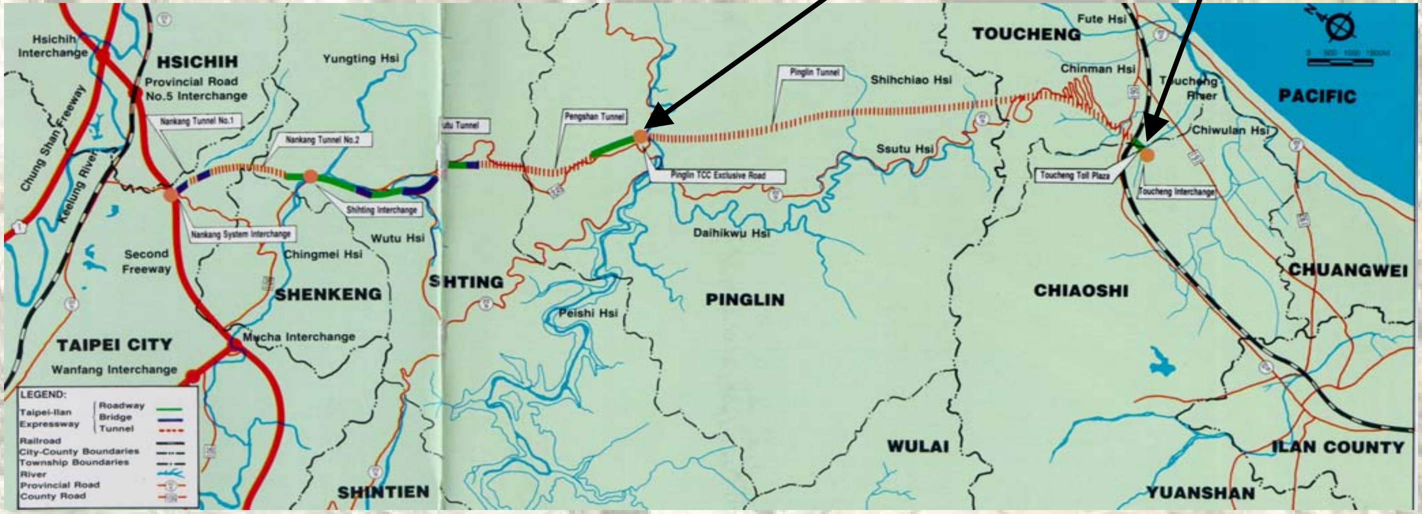
Pinglin Tunnel

Case Studies



TAIPEI-ILAN - EXPRESSWAY

Pinglin Tunnel
(12.9 km)



Pinglin Tunnel

Introduction

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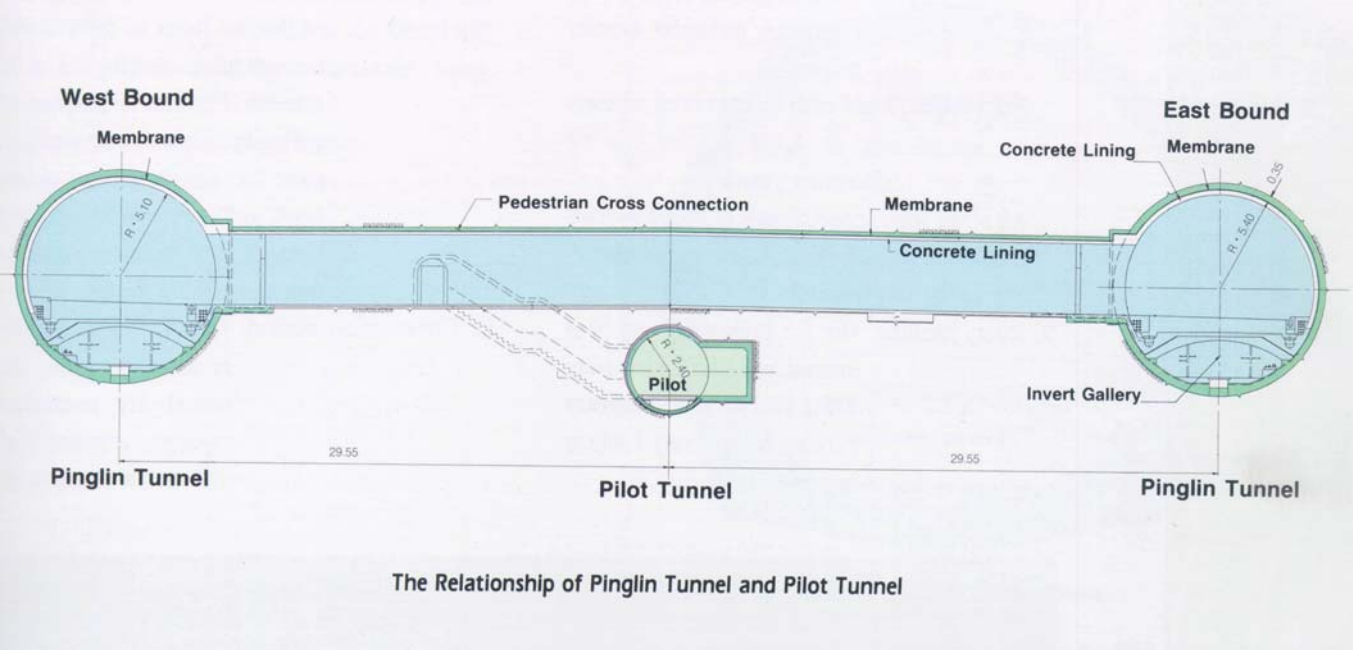
Case Studies

Artist‘s Perspective View

Pinglin Tunnel

Case Studies

Cross Section of Main Tunnels,
Pilot Tunnel and Pedestrian Connection

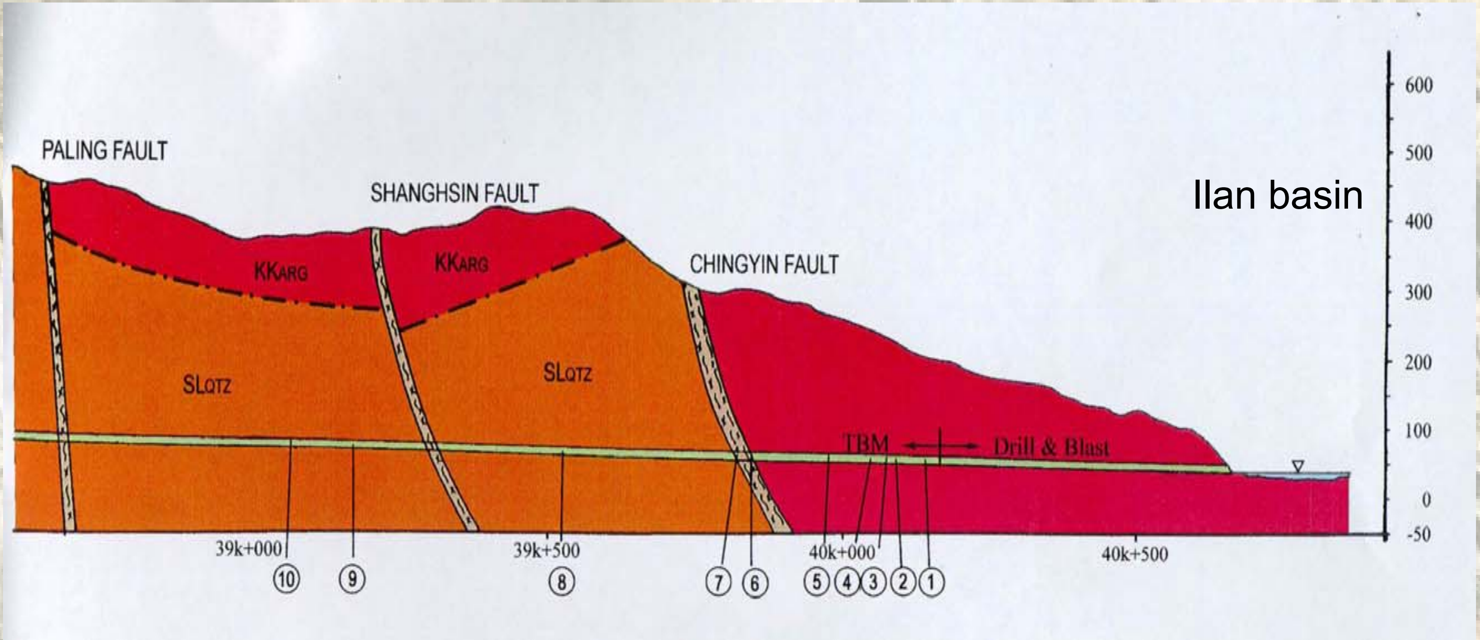


The Relationship of Pinglin Tunnel and Pilot Tunnel

Case Studies

Pinglin Tunnel, East Section

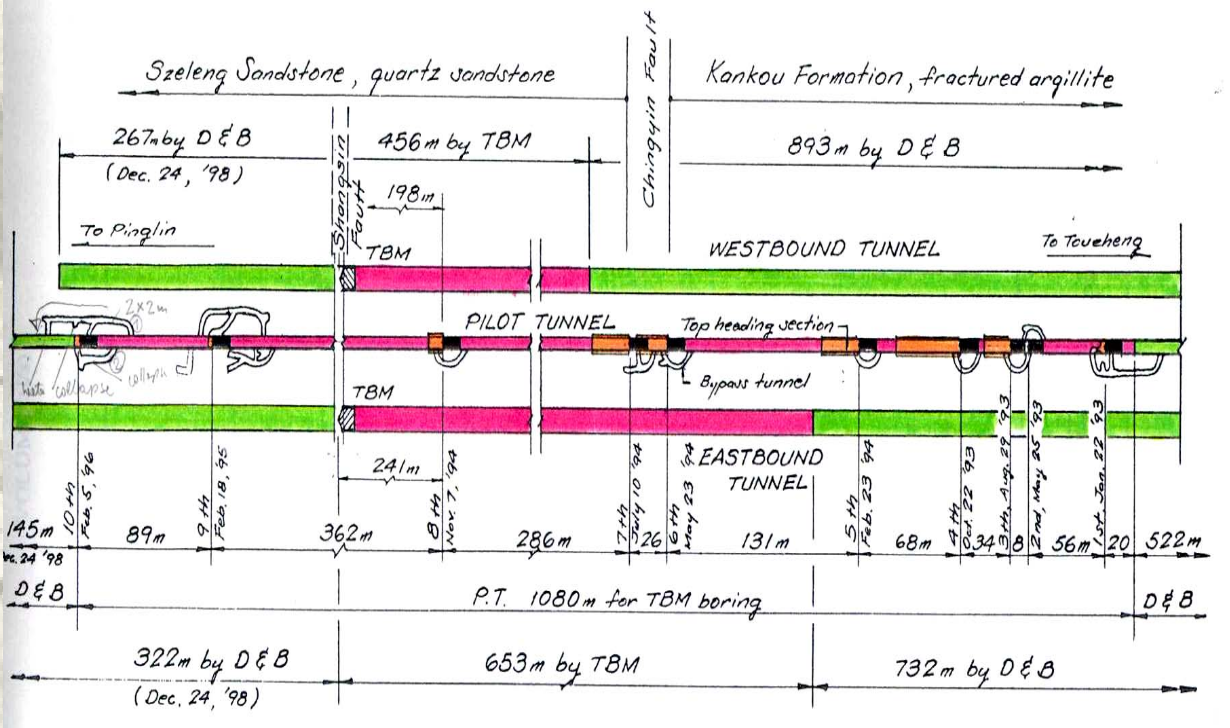
Fractured, open jointed rock mass
due to extensional faulting



10 stoppages of pilot tunnel TBM

Case Studies

Locations of TBM Stoppages (December 1998)

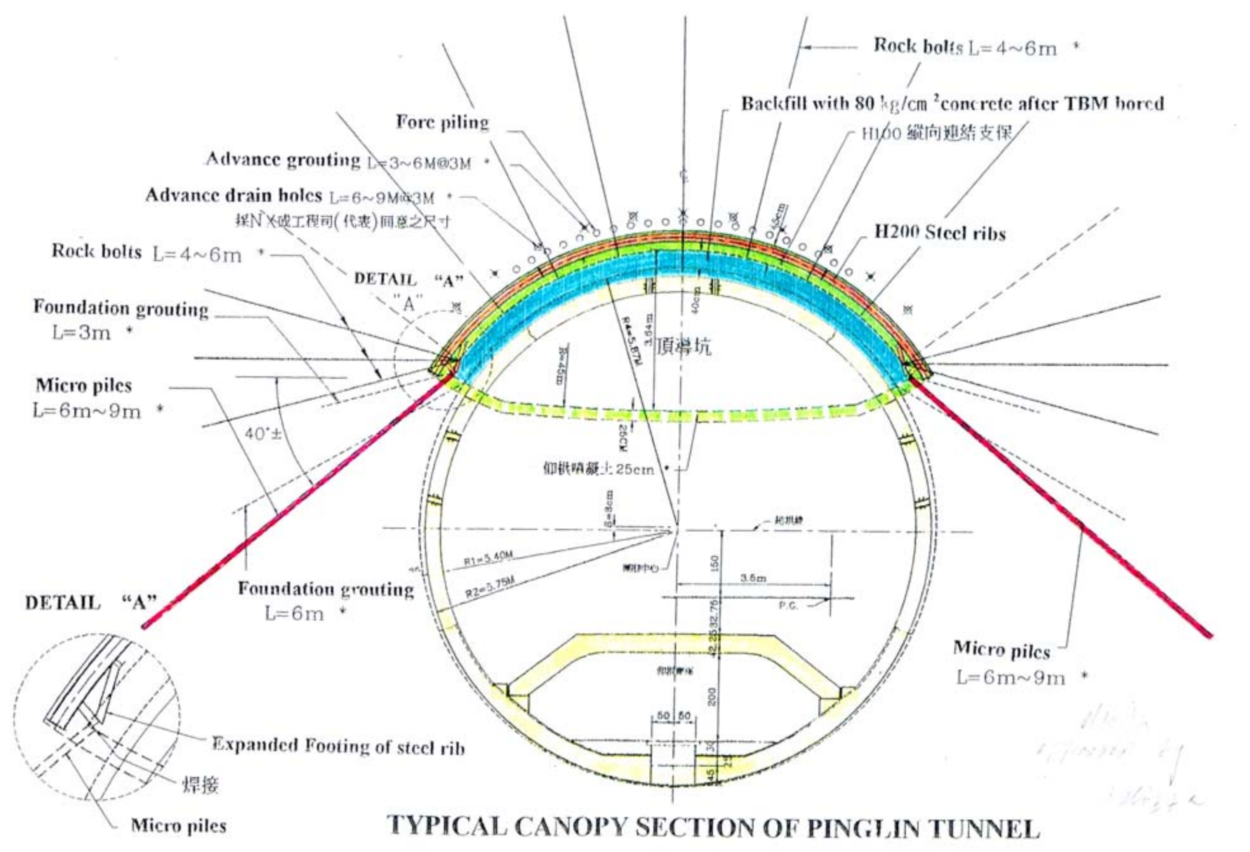


Westbound T.: 893 m D&B, 456 m TBM, 267 m D&B ahead of the face
Eastbound T.: 732 m D&B, 653 m TBM, 322 m D&B ahead of the face
Pilot Tunnel: 522 m D&B, 1080 m TBM, 145 m m D&B ahead of the face

Pinglin Tunnel

Case Studies

Design for Excavation Ahead of the TBM
(“Canopy Section“)



TYPICAL CANOPY SECTION OF PINGLIN TUNNEL

Pinglin Tunnel

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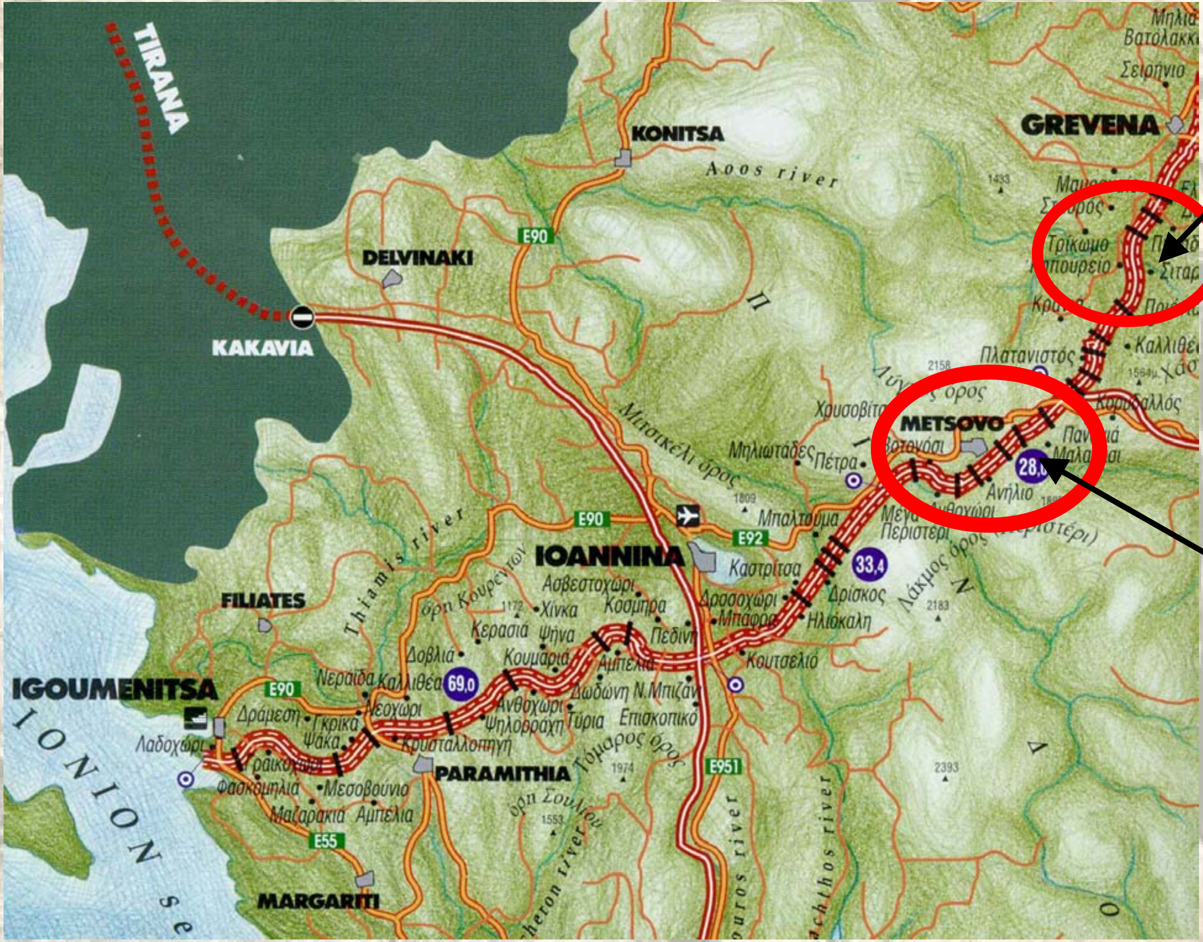
Location



Tunnels in a tectonic melange and olistostrome

Tunnels in thrust duplexes

Egnatia Motorway

Introduction

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Malakasi Section

- Alpine forearc region, containing **chaotic rock mass** of predominantly shale, sandstone, siltstone, limestone and ophiolitic lithologies
- The chaotic deposits include **olistostromes** and **tectonic melanges**, which characteristically contain a chaotic arrangement of competent blocks (limestone and ophiolitic olistoliths and/or phacoids) in an irregularly sheared weak matrix consisting of shale, sandstone, siltstone and gouge
- This chaotic rock mass from different geological environments can be characterized from the engineering perspective as **„block-in-matrix rocks“**

Case Studies

Damaged West Portal Pre-Cut of Tunnel M2

Egnatia Motorway

Significance of Fault Zones

Geotechnical Relevant
Characterization of Brittle Faults

- Faults are elongated complex zones of deformation, ranging from decimeters to kilometers in magnitude
- A significant internal structure of shear and extensional fractures has developed, reflecting the geometry of the strain field and, consequently, the orientation of the principal stresses
- The brittle deformation, such as particle size reduction by crushing of grains and reorientation of grains by shearing, generates the characteristic fine-grained gouge
- Low-temperature solution transfer contributes substantially to the alteration of fault rocks, in particular of gouge, through transformation and neoformation of clay minerals

FROM AEG SHORT COURSE " Tunnels Through Fault Rocks and Tectonic Melanges: A Short Course for Engineering Geologists and Geotechnical Engineers", Oakland, California; June 1, 2002; Instructors: Prof. Gunter Riedmueller and Prof. Wulf Schubert, Technical University of Graz, Austria and Gruppe Geotechnik Graz COPYRIGHT OF 3G - Gruppe Geotechnik Graz www.3-g.at REPRODUCED AND PROVIDED WITH THE PERMISSION OF AEG and 3G CONTACT: Dr. Alfred Fasching, CEO and Managing Director: fasching@3-g.at

Significance of Fault Zones

Geotechnical Relevant
Characterization of Brittle Faults

- The significant geotechnical feature is a substantial heterogeneity, reflected by the occurrence of more or less undeformed competent blocks which are typically surrounded by a fine-grained matrix consisting of gouge and highly fractured rocks. The matrix appears to be flowing around the blocks in an anastomosing pattern

- The mainly lozenge shaped blocks exhibit a fractal distribution of dimensions, ranging from the microscale to hundreds of meters in length. Fault structures are scale independent

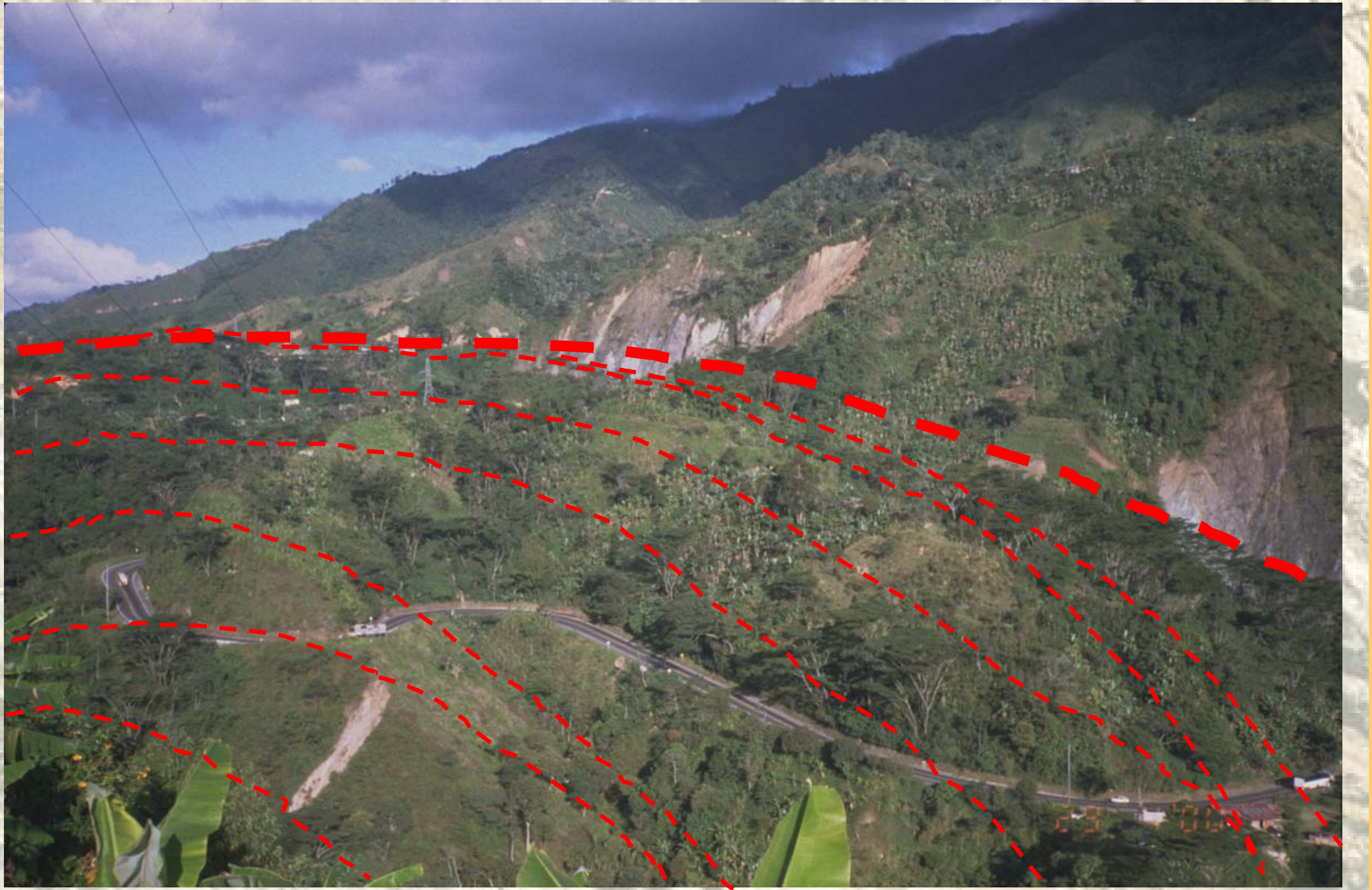
- A considerable heterogeneity of the stress field may exist. Variations in the stress field might be an important cause of segmentary fault zone formation

- Groundwater conditions are also highly variable. Water pressures and flow directions may change dramatically across fault zones. A fault zone acts as aquifer, aquitard and aquiclude

Fault Morphology

North Anatolian Fault Zone, Turkey
Fault Escarpment of Active Segment, near Bolu Tunnel

Fault Morphology



Normal Faults, La Linea Tunnel, Colombia

Case Studies

Project Data

- Rock Fill Dam (Height 120 m)
- Headrace Tunnel (Length 19.5 m, Diameter 3.5 m
- Penstock (Length 2.6 km)
- Gross Head 1.053 m
- Total Capacity 120 MW
- Tailrace Water Canal
- Compensation Reservoir
- Treatment Plant
- Potable Water Conduit
- Irrigation Canals

HPP Misicuni, Bolivia

Case Studies

Project History

- Construction problems (TBM excavation) of the headrace tunnel due to inadequate geotechnical characterization of fault zones

- The 19.5 km long tunnel penetrates Ordovician quartzitic sandstone and slate. Faults were only identified as individual planar elements

- As a consequence of the inadequate fault model inappropriate equipment was selected which, in combination with insufficient planning and construction shortcomings, caused unforeseen stoppages of the TBM excavation due to tunnel collapse and water inflow

- The total costs for remedial work and effective time of immobilized equipment are US$ 3 million

HPP Misicuni, Bolivia

Case Studies

Strike – Slip Fault, Misicuni Tunnel, Bolivia
Bocatoma Portal, Intermediate Shaft

HPP Misicuni, Bolivia

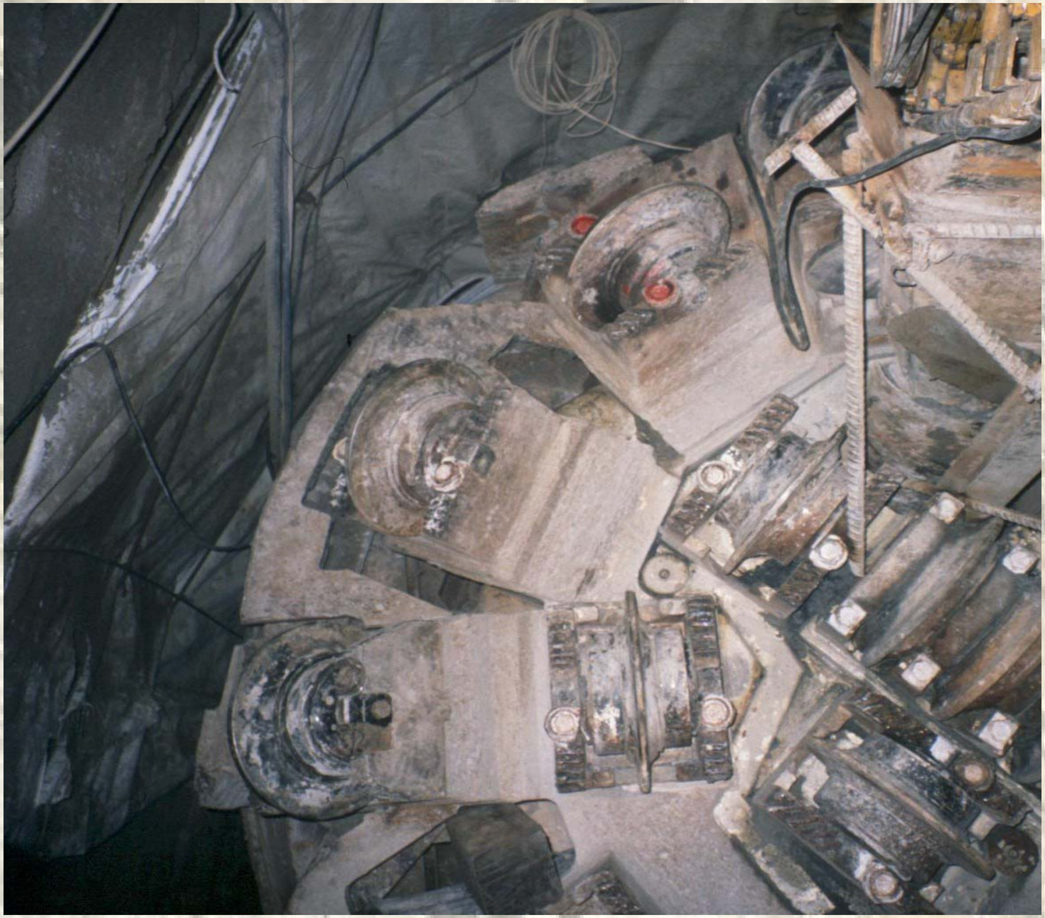
Case Studies

HPP Misicuni, Headrace Tunnel, Calio - Portal

HPP Misicuni, Bolivia

Case Studies

Cutter Head of Buried TBM at km 18 + 513.70
Calio Heading on May 03, 1999



HPP Misicuni, Bolivia

Case Studies

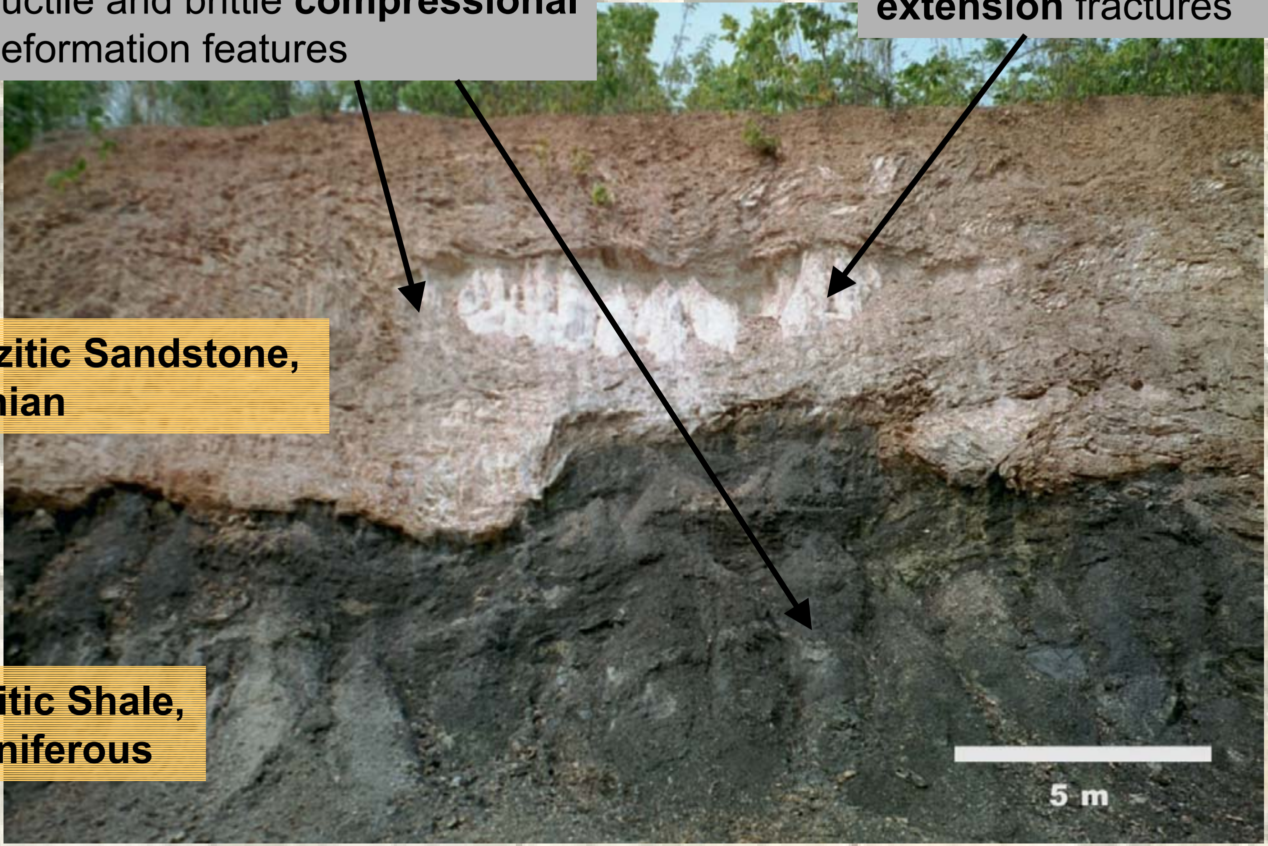
Excavation Ahead of the TBM Using Marciavantis, Steel Ribs and Shotcrete

HPP Misicuni, Bolivia

Fault Structures

- The analysis of the internal fault structure gives evidence of the displacement field during faulting and indicates the orientation of principal stresses (paleostress analyses)
- From the geotechnical point of view the differentiation of extensional and compressional faults is important

Fault Structures



Foliated **soft matrix** showing ductile and brittle **compressional** deformation features

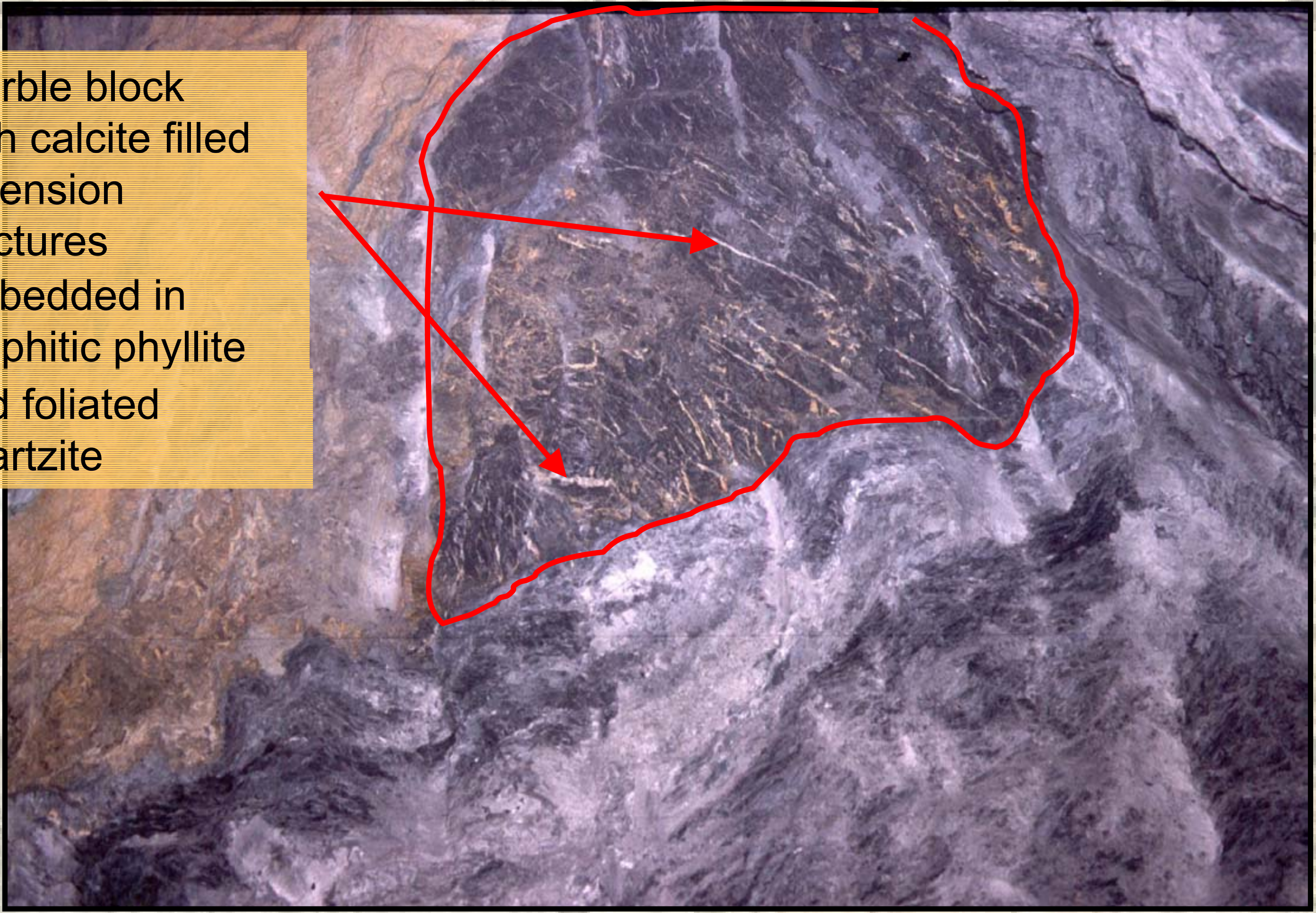
Lenticular **stiff block** showing **extension** fractures

Quartzitic Sandstone, Devonian

Graphitic Shale, Carboniferous

Formation of Melange in an Foreland Basin Overthrust Setting, Main Tunnel, Mae Kuang Irrigation Project, N – Thailand

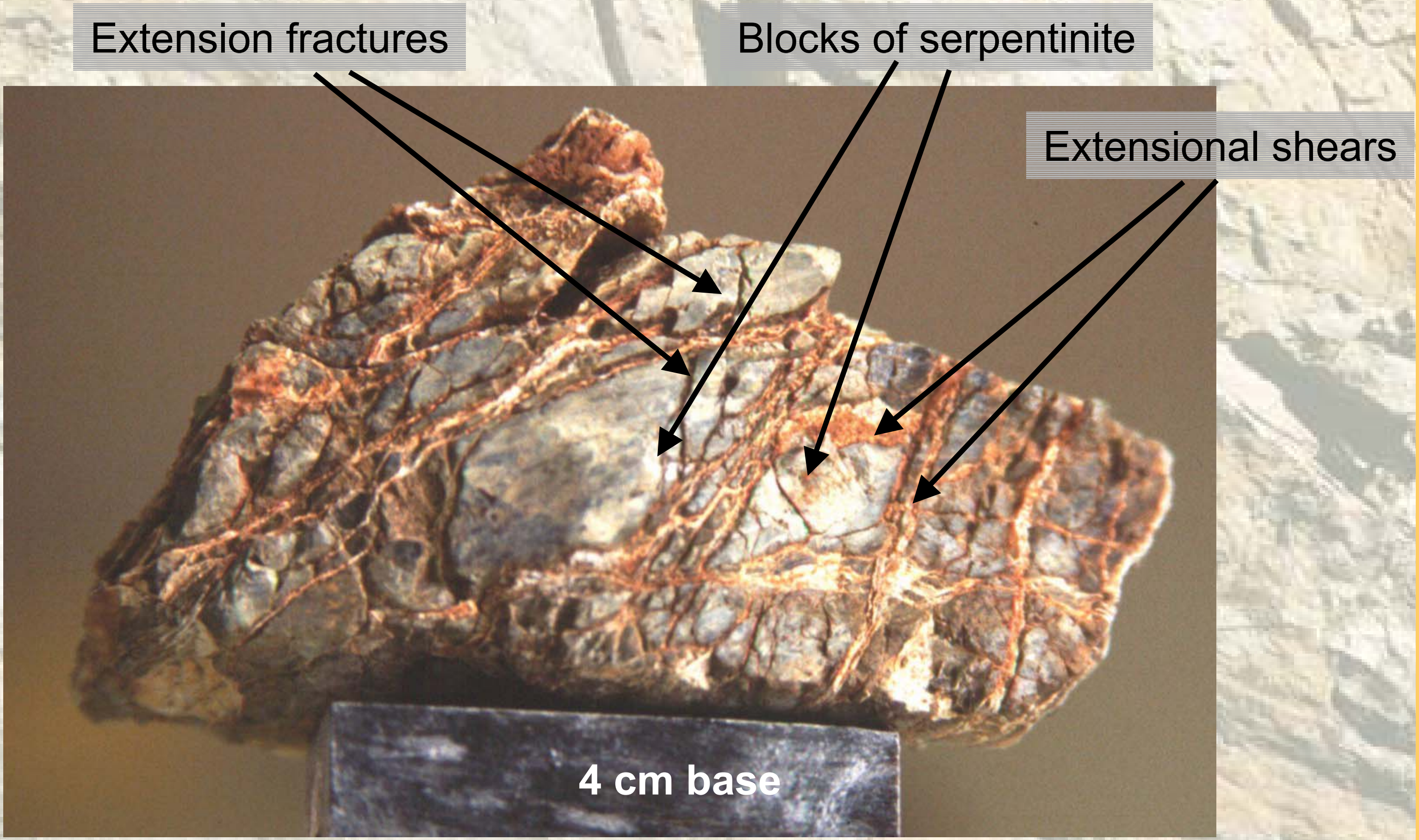
Fault Structures



Marble block with calcite filled extension fractures embedded in graphitic phyllite and foliated quartzite

Tectonic Melange in an Alpine Thrust Setting
Semmering Motorway, Tunnel Steinhaus, Austria

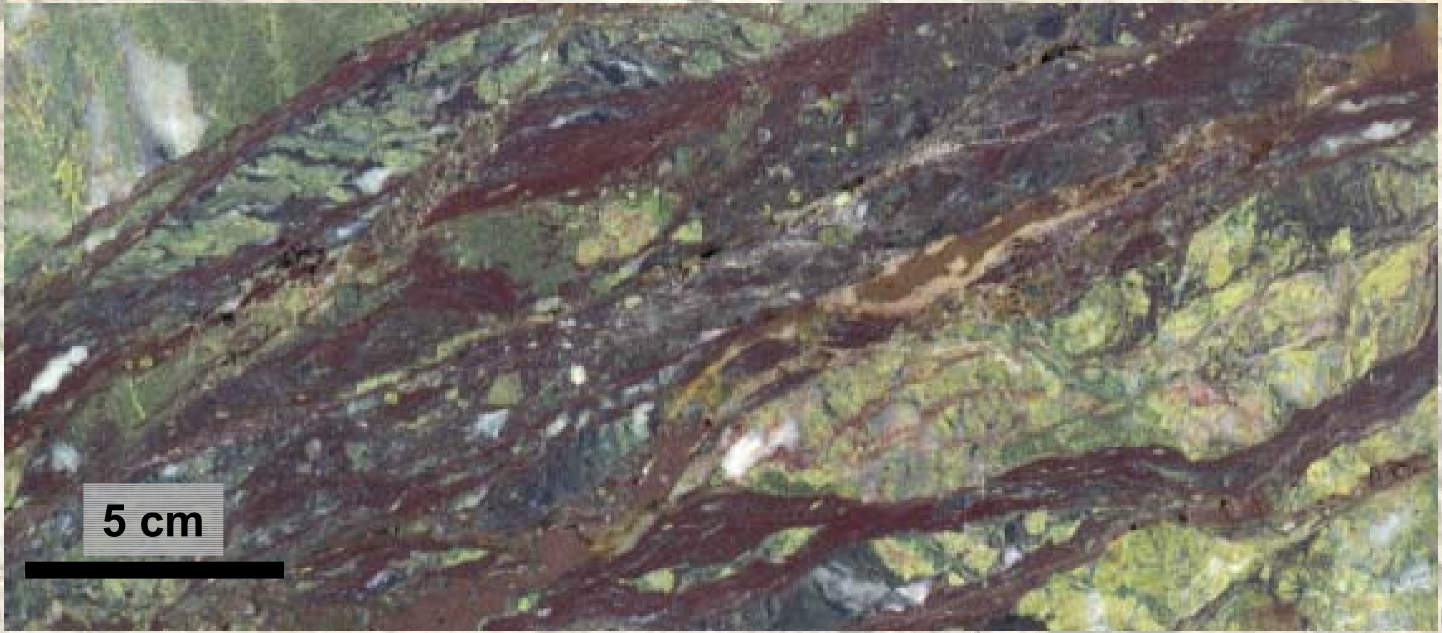
Fault Structures



Typical Structure of Ophiolitic Melange in Mesoscale

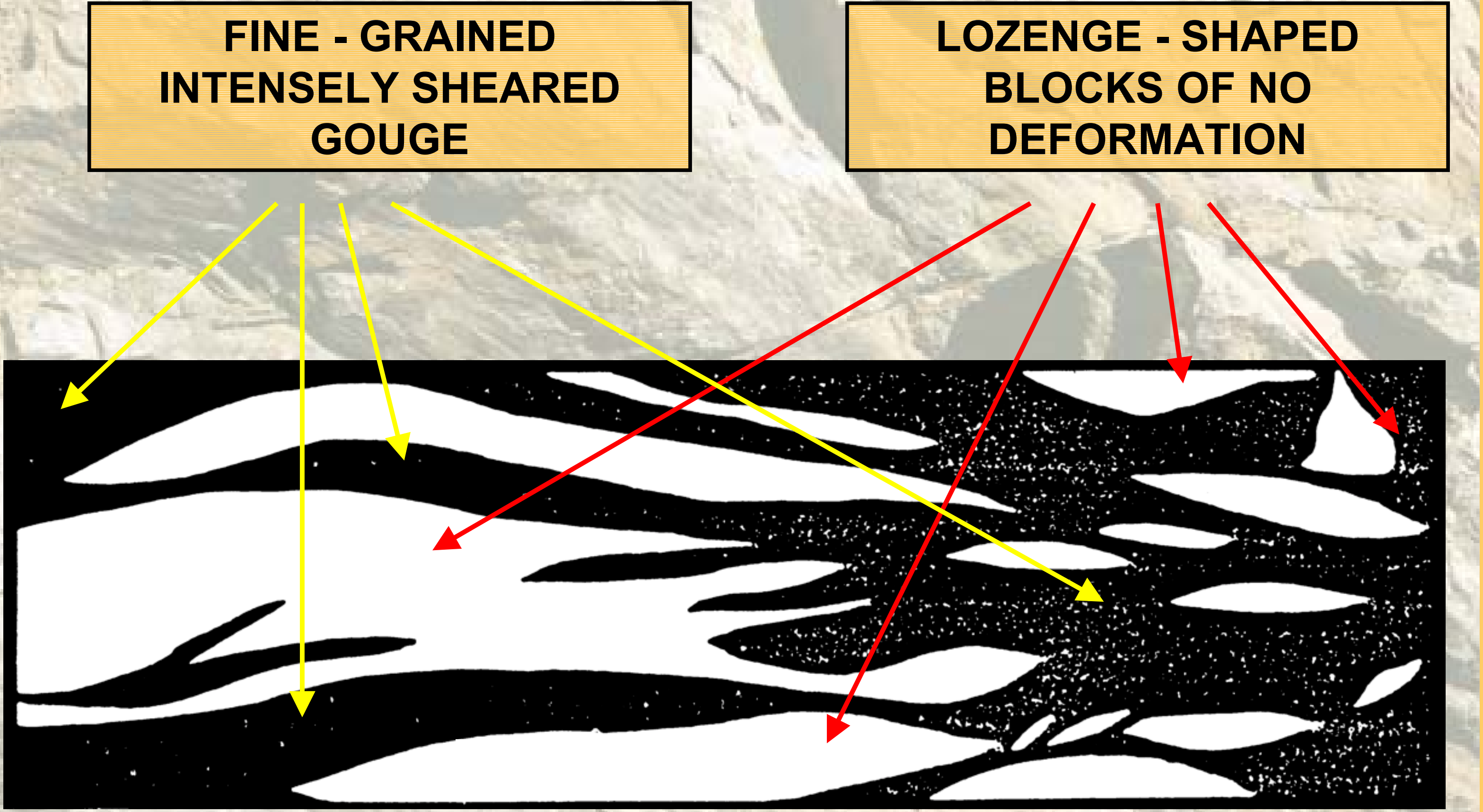
Egnatia Motorway, N-Greece

Fault Structures



Significantly Anisotropic Melange (Mesoscale)
Diverse Elongate Blocks (Phacoids) in Foliated Matrix

Fault Structures



FINE - GRAINED INTENSELY SHEARED GOUGE

LOZENGE - SHAPED BLOCKS OF NO DEFORMATION

Fault Zone Model, Blocks Show Fractal Dimensions, from the Micro – to the Megascale

Fault Structures

RESEARCH ON "BIMROCKS"

- **Lindquist (1994):**

  The strength and deformation properties of melange.

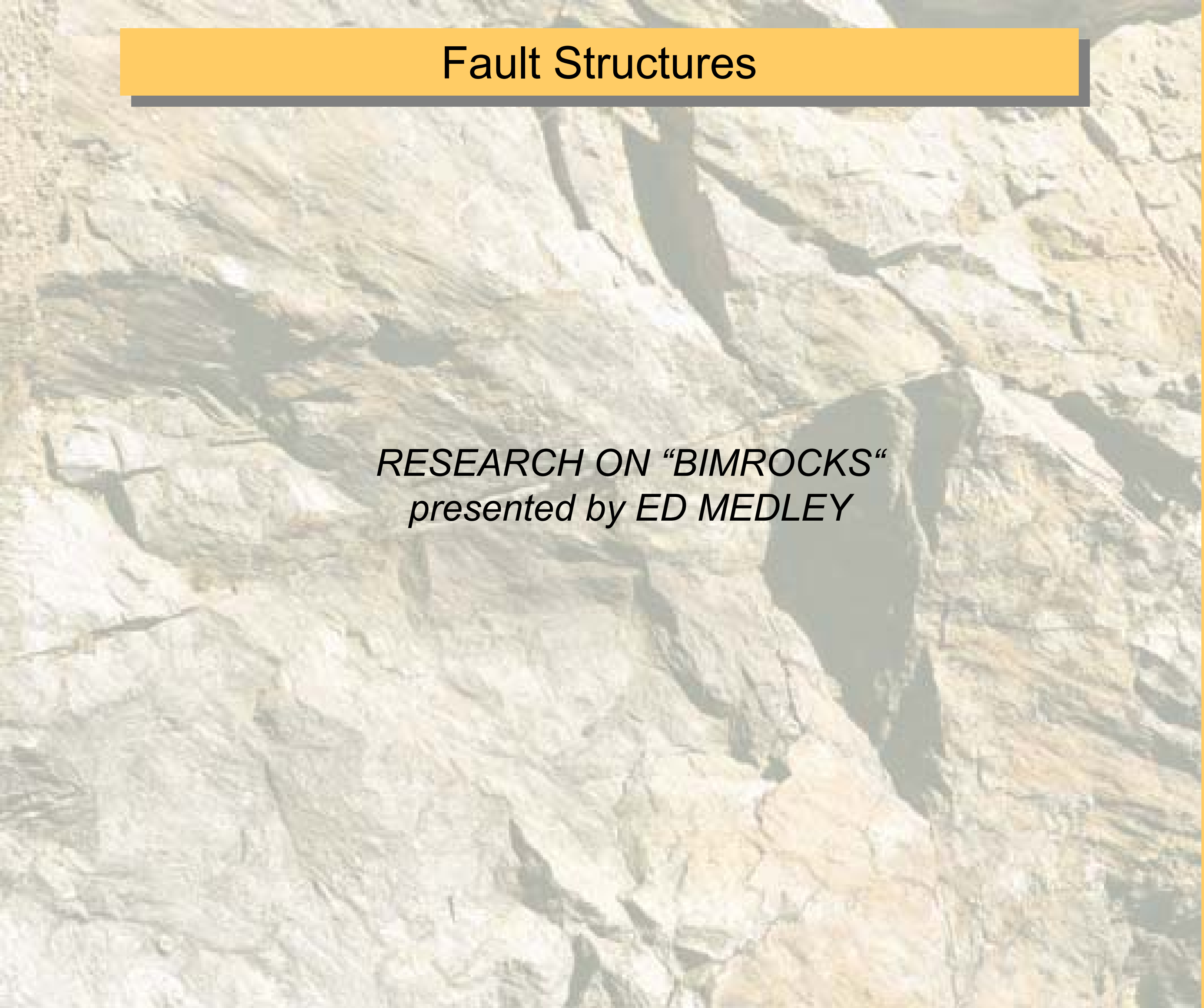
  PhD dissertation, Univ. Calif. Berkeley

- **Medley (1994):**

  The engineering characterization of melanges and similar Block-in-Matrix Rocks (Bimrocks).

  PhD dissertation, Univ. Calif. Berkeley

Fault Structures



RESEARCH ON “BIMROCKS“
presented by ED MEDLEY

Exponent™

Failure Analysis Associates

Fundamental Concepts to Consider When Characterizing Melanges and Other Bimrocks

Dr. Edmund Medley PE, CEG

Exponent Failure Analysis Associates, Menlo Park, CA

AEG Short Course: Tunneling Through Fault Rocks and Tectonic Melanges: A Short Course for Engineering Geologists and Geotechnical Engineers

Saturday June 1, 2002: Oakland California

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Melange and Similar Bimrocks

- **Bimrocks:** block-in-matrix rocks
  - a mixture of rocks composed of geotechnically significant blocks within a bonded matrix of finer texture

- **Melanges:** UNCHILE geological mixtures of competent blocks composed of sedimentary/ metamorphic blocks in weaker matrix of sheared shale /serpentinite
- **Similar Bimrocks**: Fault Rocks, Breccias, Lahars, Tillites, etc.

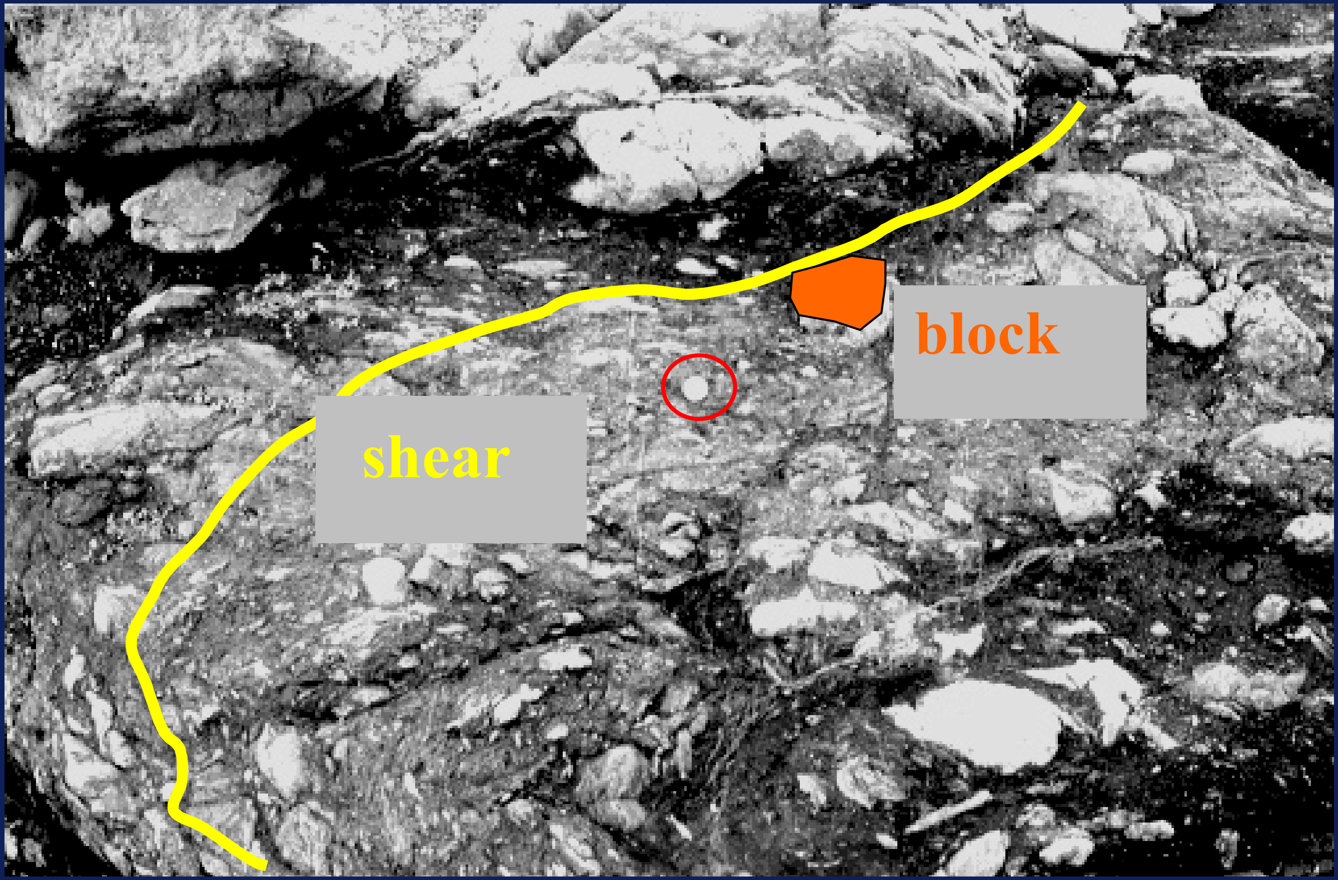
Melange: geological mixture with polylithologic blocks ranging in size from sand to mountains: Blocks in the Gwna melange, Anglesey, North Wales

Gwna Melange, North Wales

Franciscan Complex,

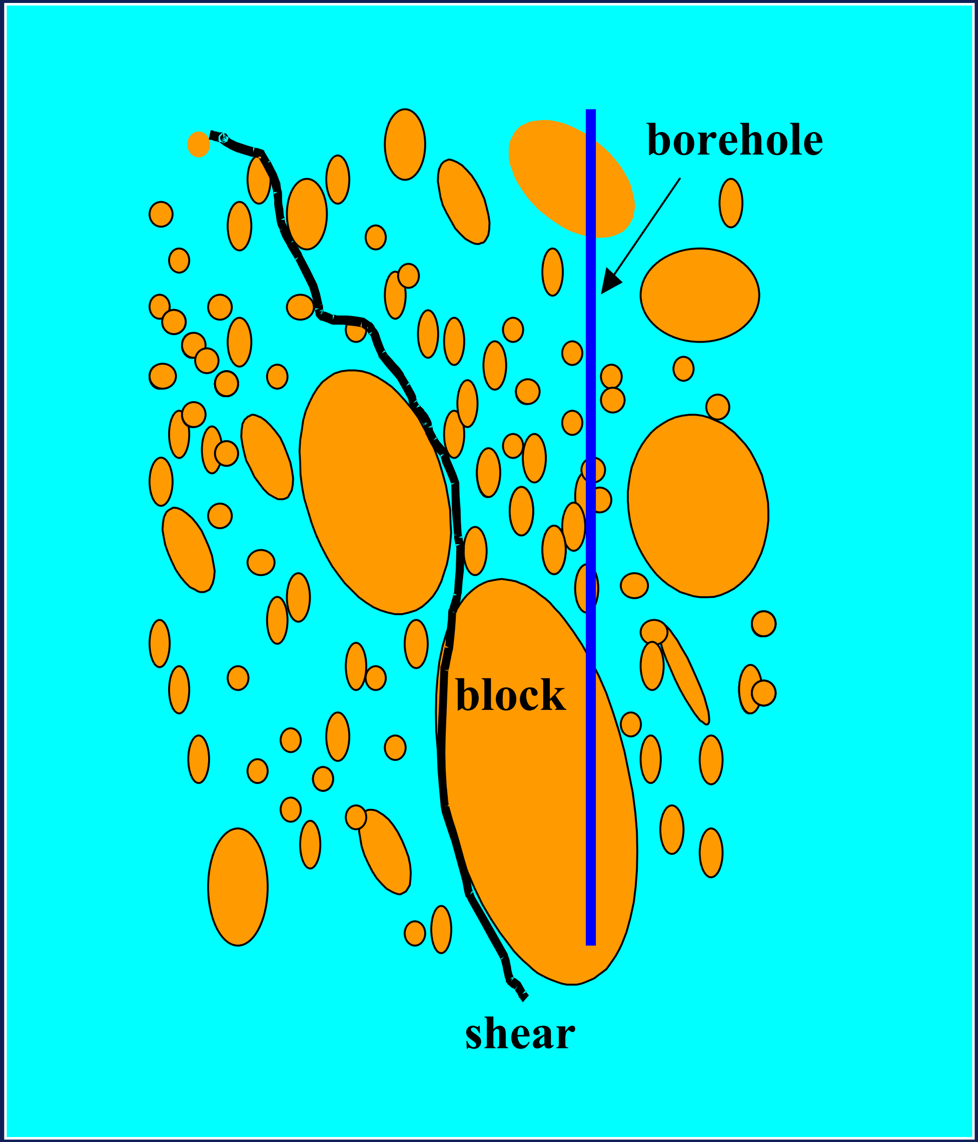
El Cerrito, California

Franciscan Complex melange (Point Delgada, California)

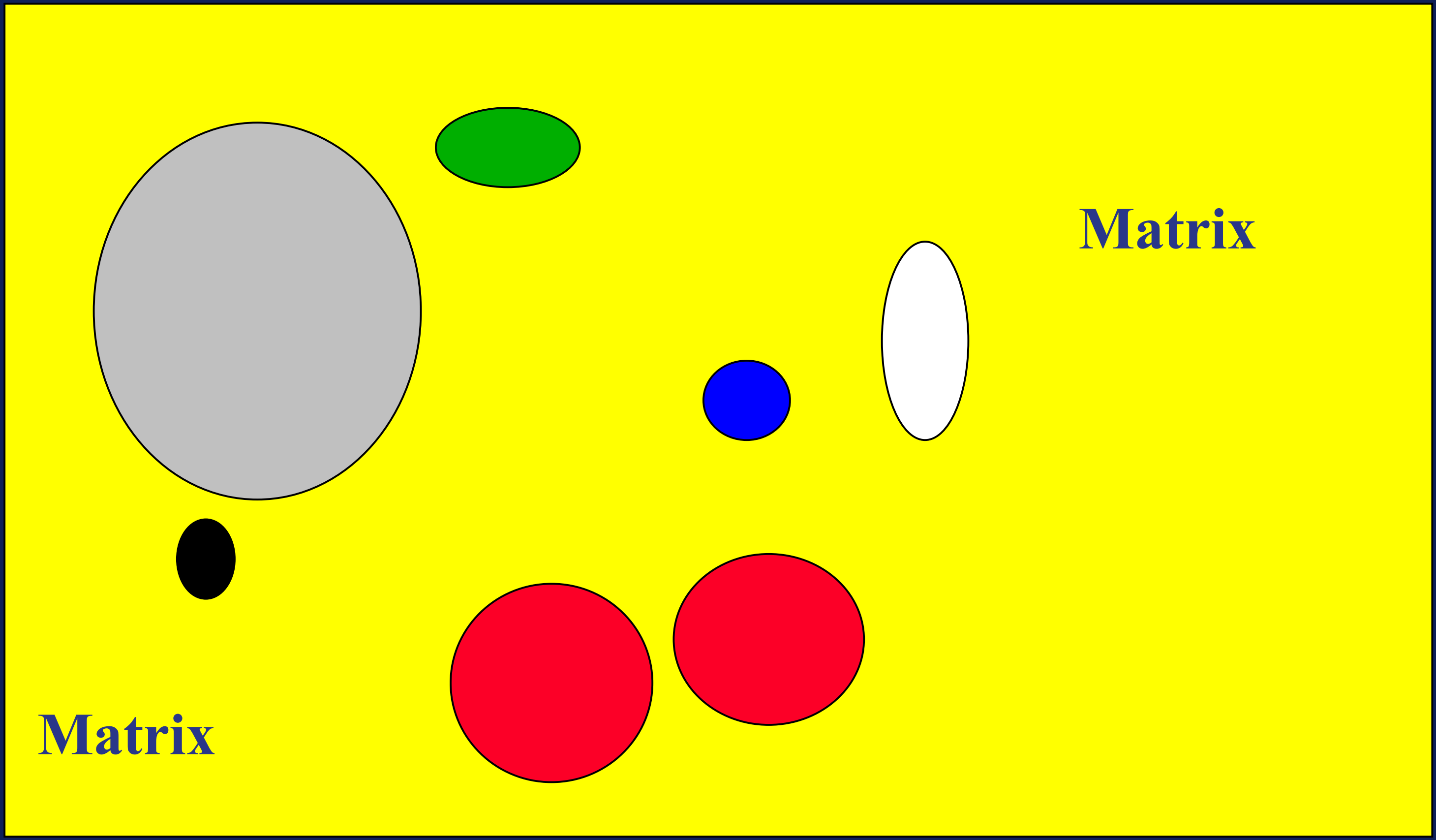


A real problem !!

We can only characterize three-dimensional chaos with one-dimensional boreholes and two-dimensional plans and cross-sections……

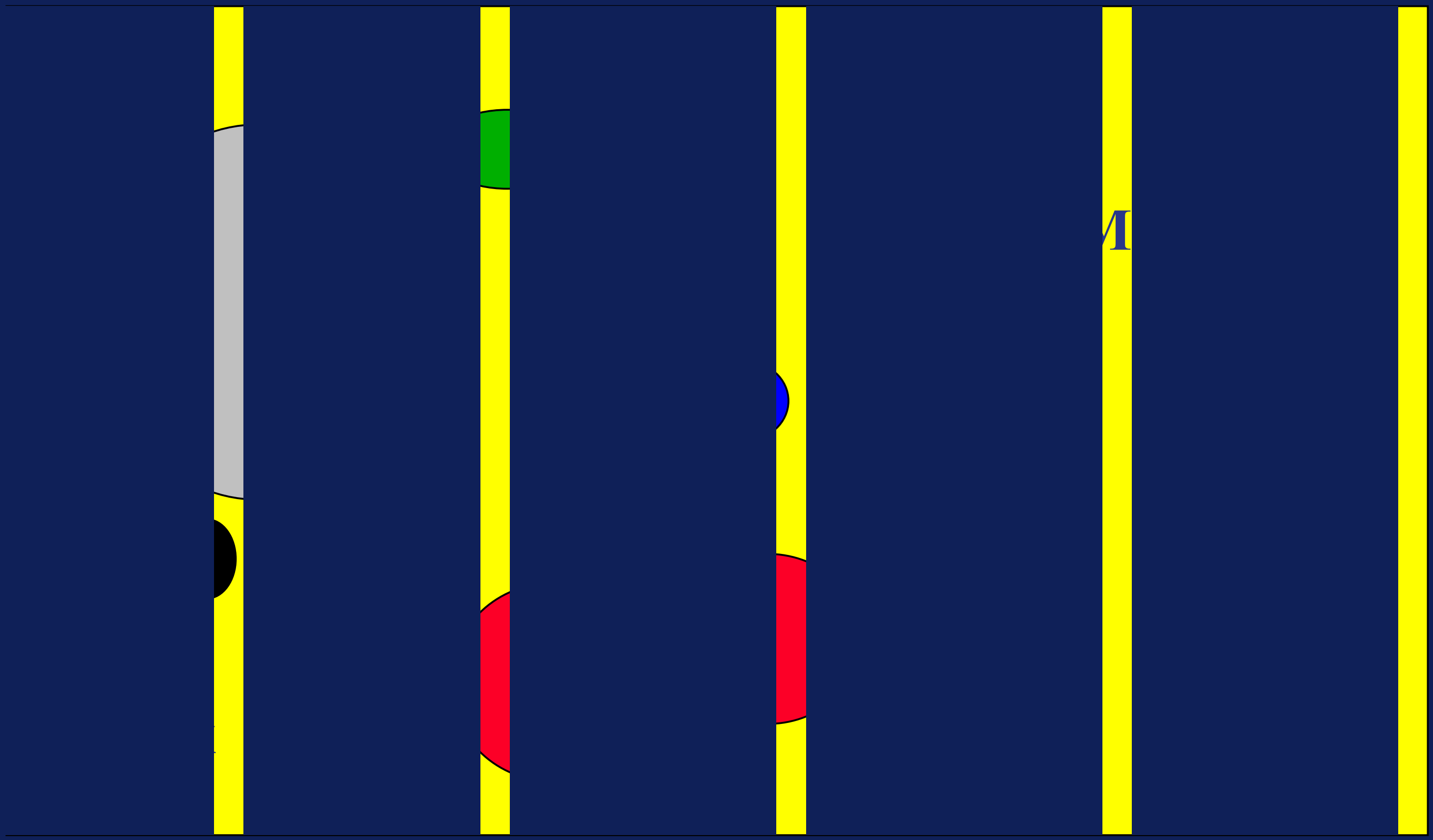


Exploring Bimrocks is NOT a piece of cake….



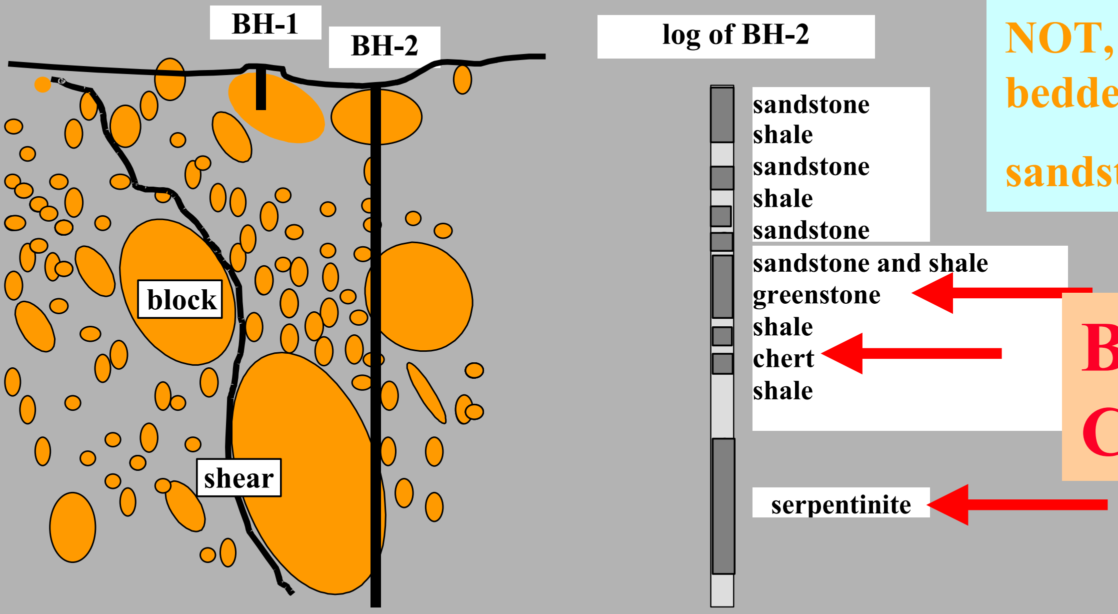
Willis, 2000; after Medley, 2000

Bimrocks as Mapped, or as drilled and cored



Willis, 2000

Exploring melanges: they are obvious!!!



Looks like, but IS NOT, “inter-bedded shales and sandstones”*

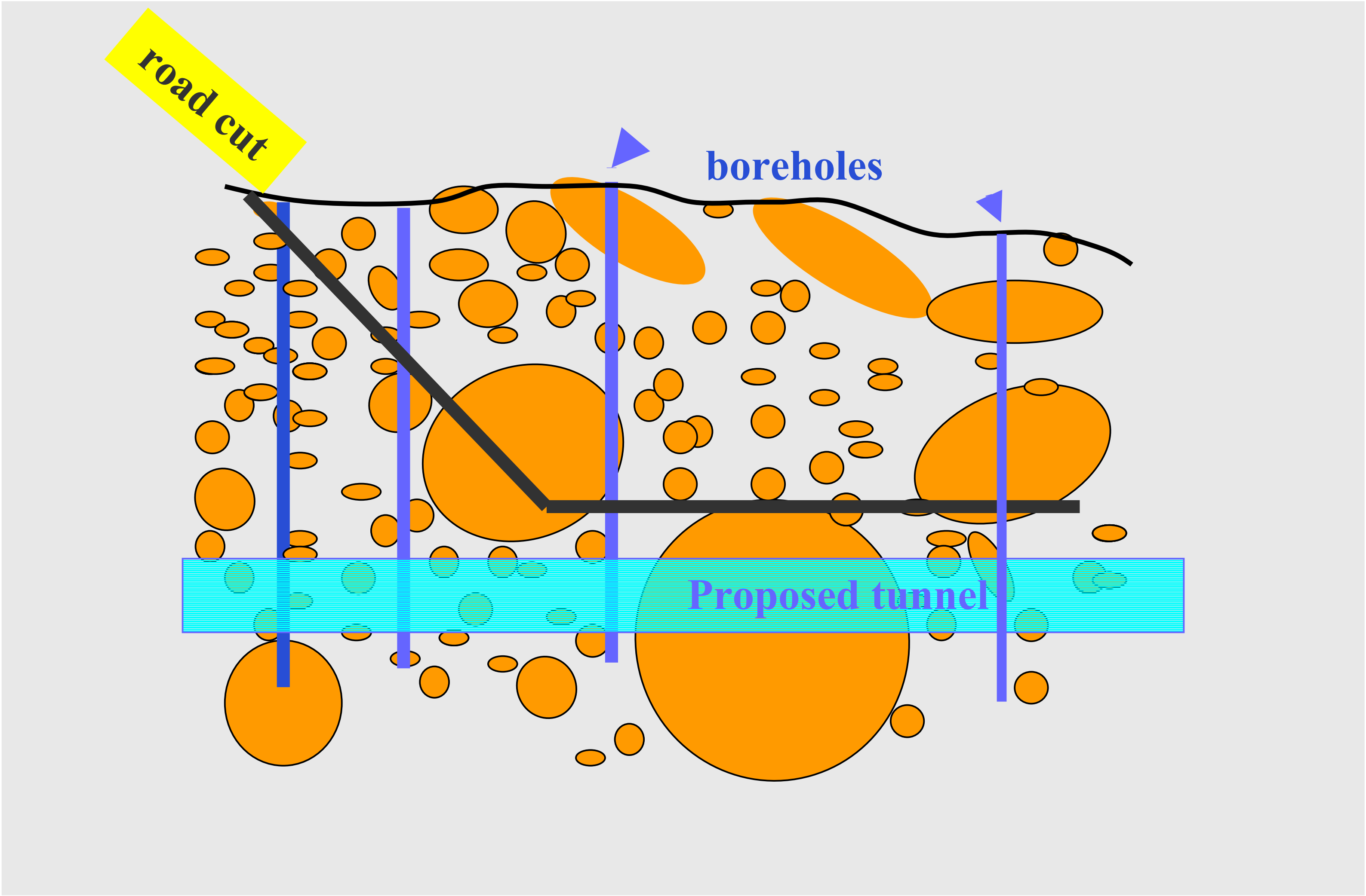
Big Clues

*Also beware terms like: “soil with boulders”. “miscellaneous soils”

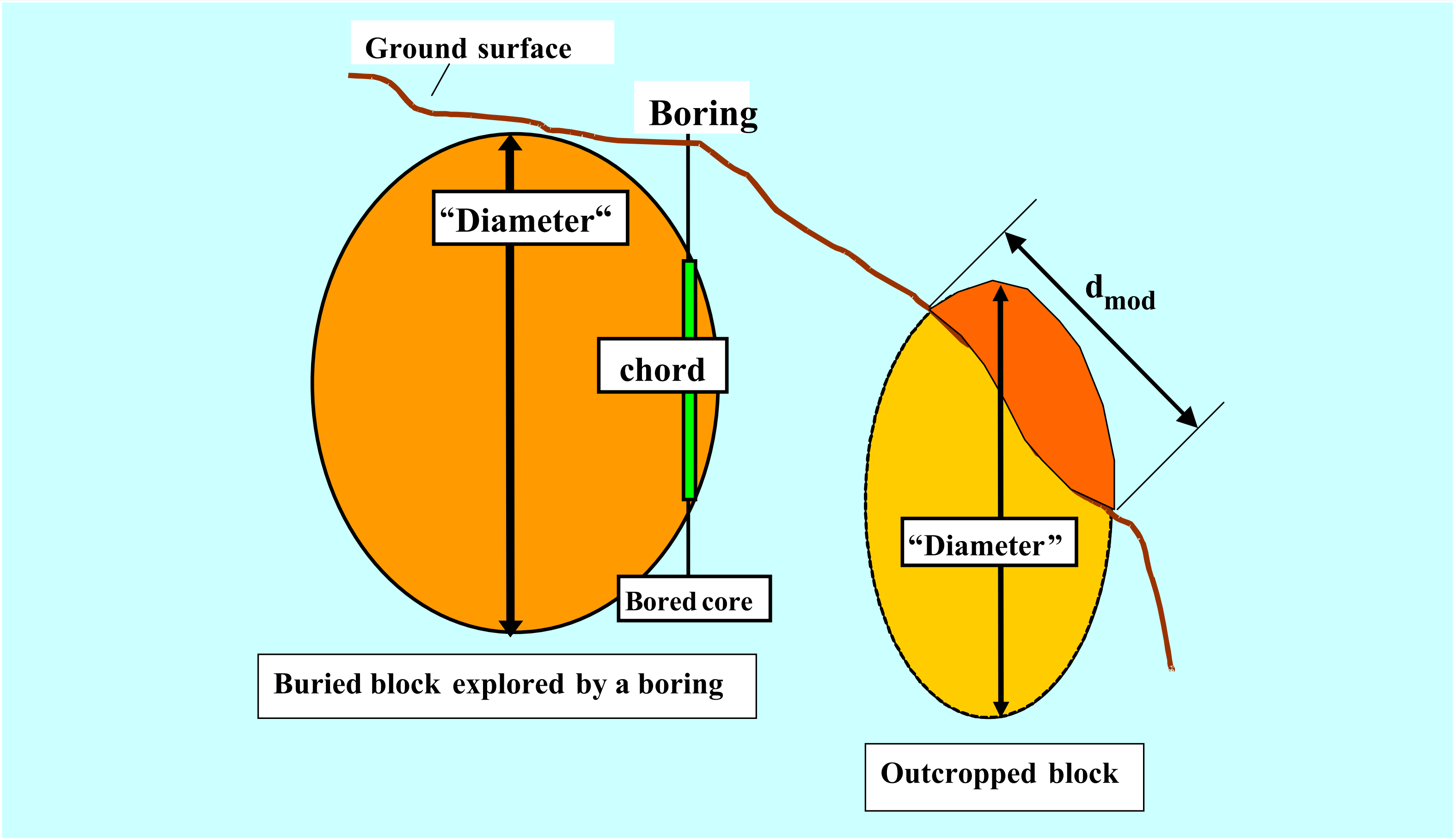
The complexity of a turbidite sequence - **REAL** interbedded sandstones and shales

(Devil’s Slide, Pacifica, California)

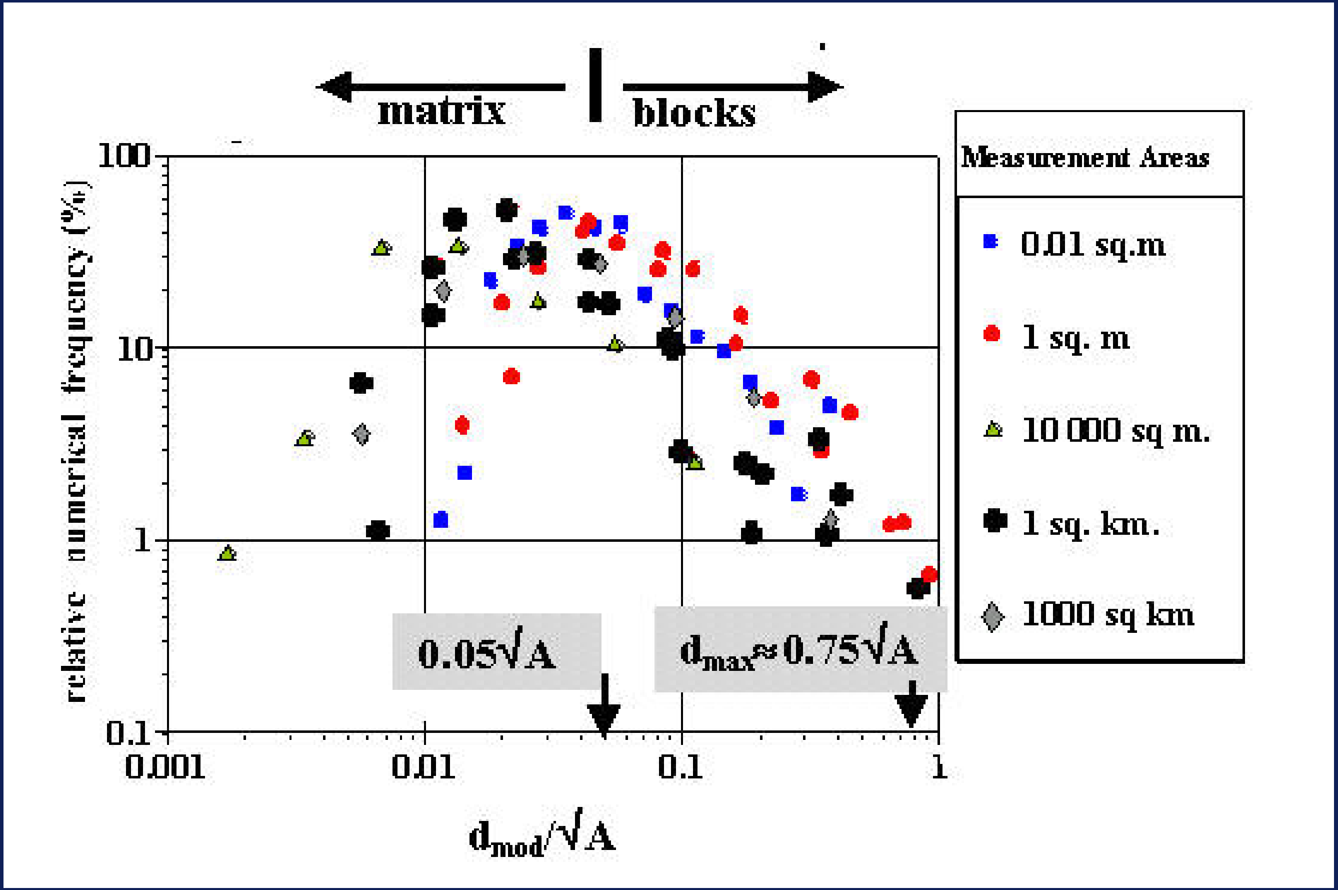
When investigating think BLOCKS!!



The "size" of blocks



Scale-independent block size distributions of Franciscan melanges



Medley, 1994

Q: What is Block/What is Matrix?

For any rock volume use an appropriate scale to determine block/matrix threshold, such as

- $\sqrt{A}$
- Size of largest mapped block (d_{max})
- Some *characteristic engineering dimension* (L_c)

(tunnel diameter; thickness of landslide; diameter of laboratory specimen, etc.)

Use these guidelines at *any scale of interest*

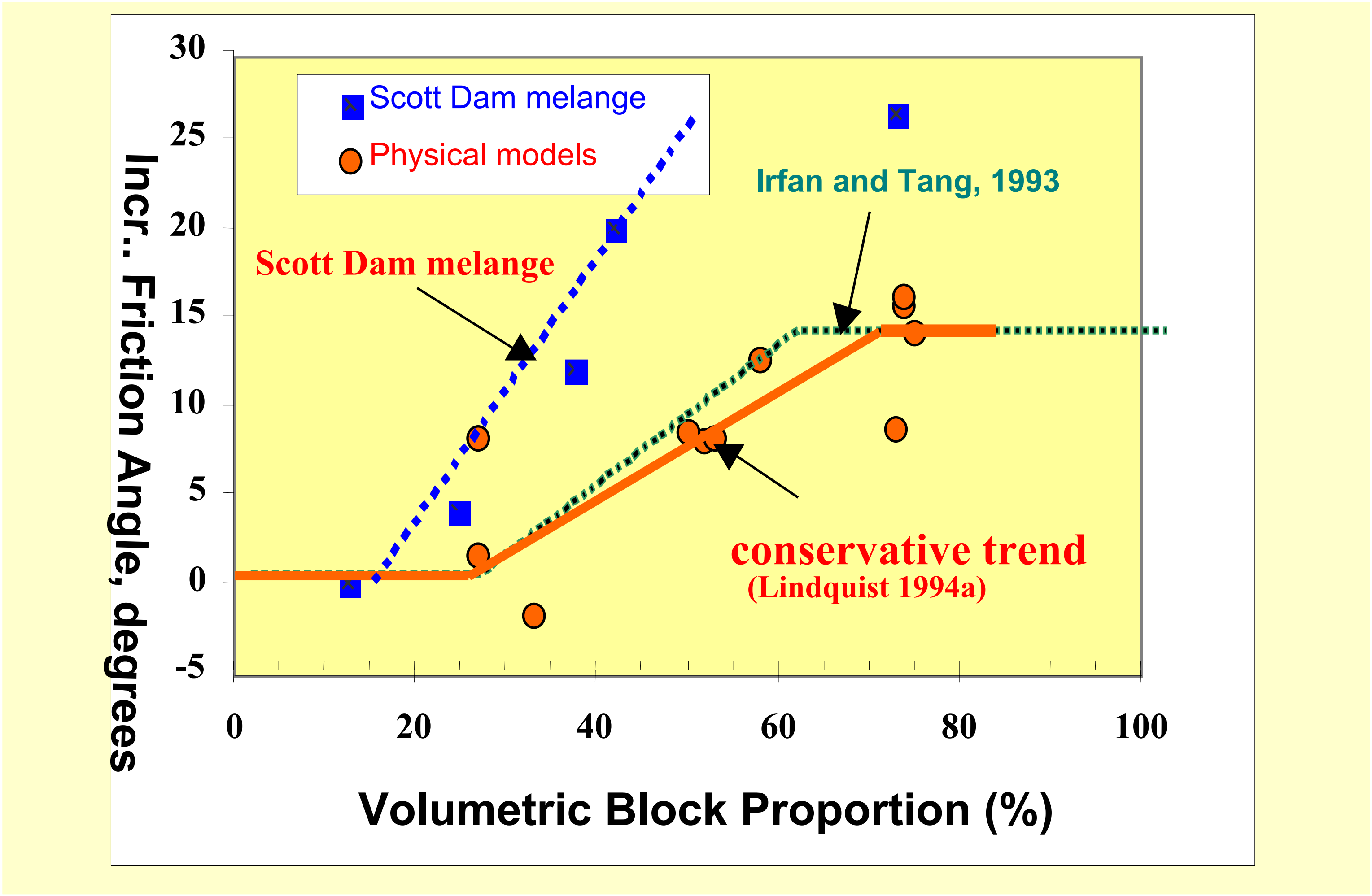
- **smallest blocks** are:

  0.05L_c or 0.05 $\sqrt{A}$ or 0.05d_{max}

- **largest block is:**

  0.75 $\sqrt{A}$ or 0.75Lc or 0.05d_{max}

Strength of bimrock depends on volumetric block proportion

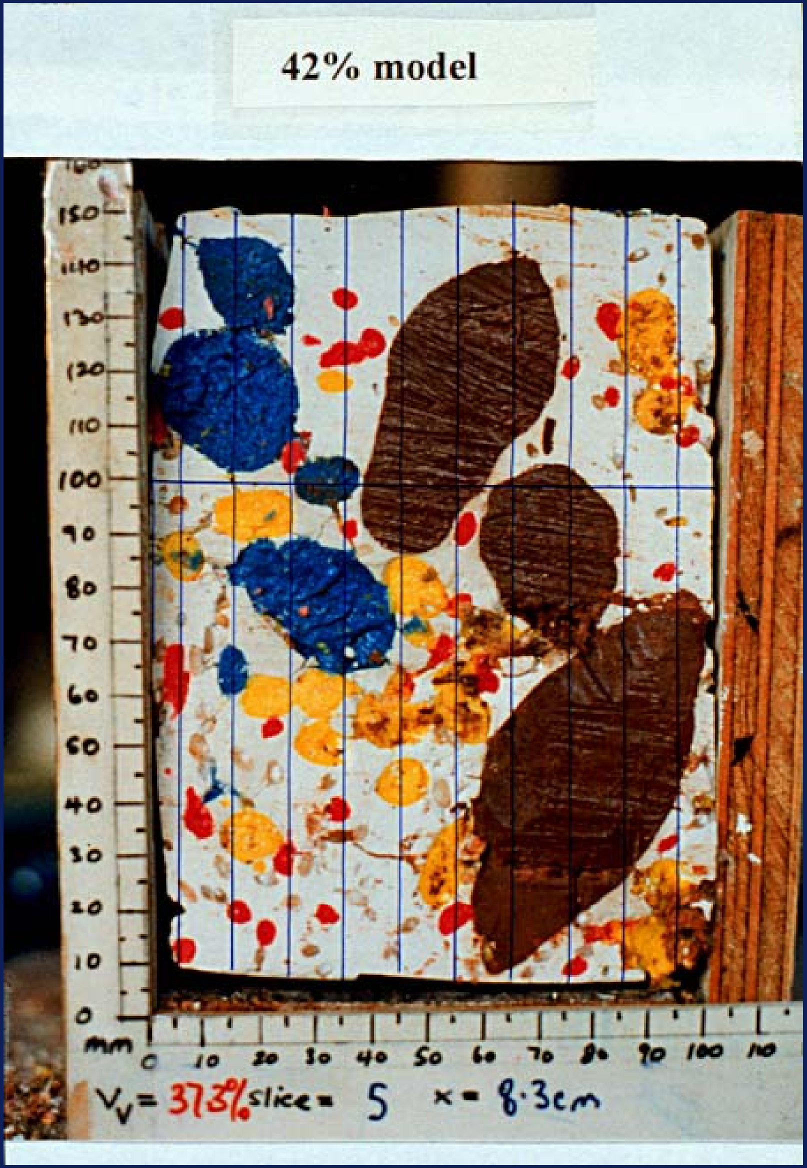


Estimation of volumetric block proportions

- Determine linear proportion from drill core
- Apply stereological principle:

linear proportion = volumetric proportion

- **TRUE ONLY** when you perform lots drilling/$$$) so beware uncertainty (error)

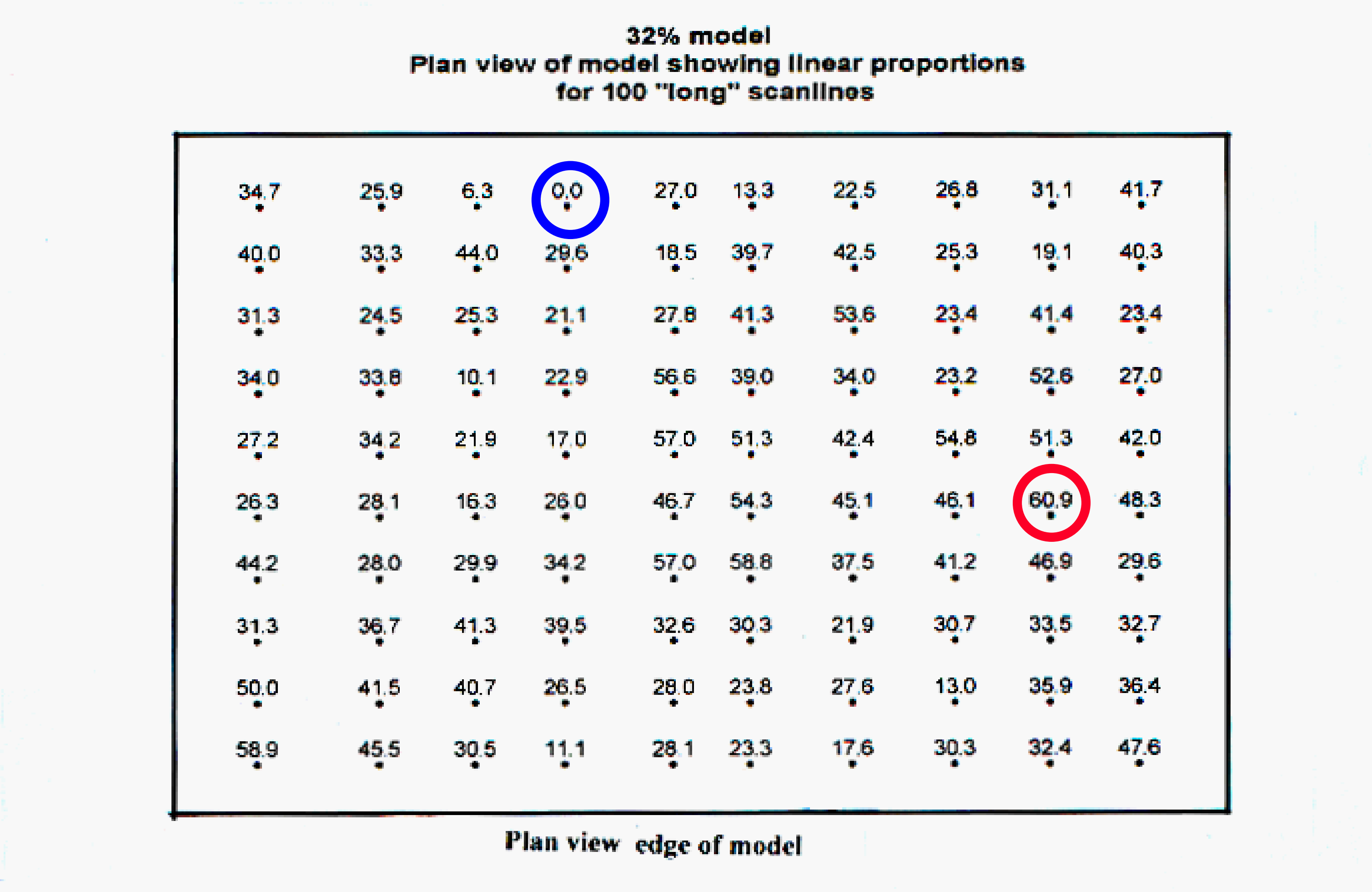


Estimating volumetric block proportion: how true is our estimate using a few boreholes?

Slice of a physical model bimrock with a known volumetric block proportion and block size distribution, explored by model boreholes.

……. or, how wrong can we be?

Actual volumetric proportion is 32%



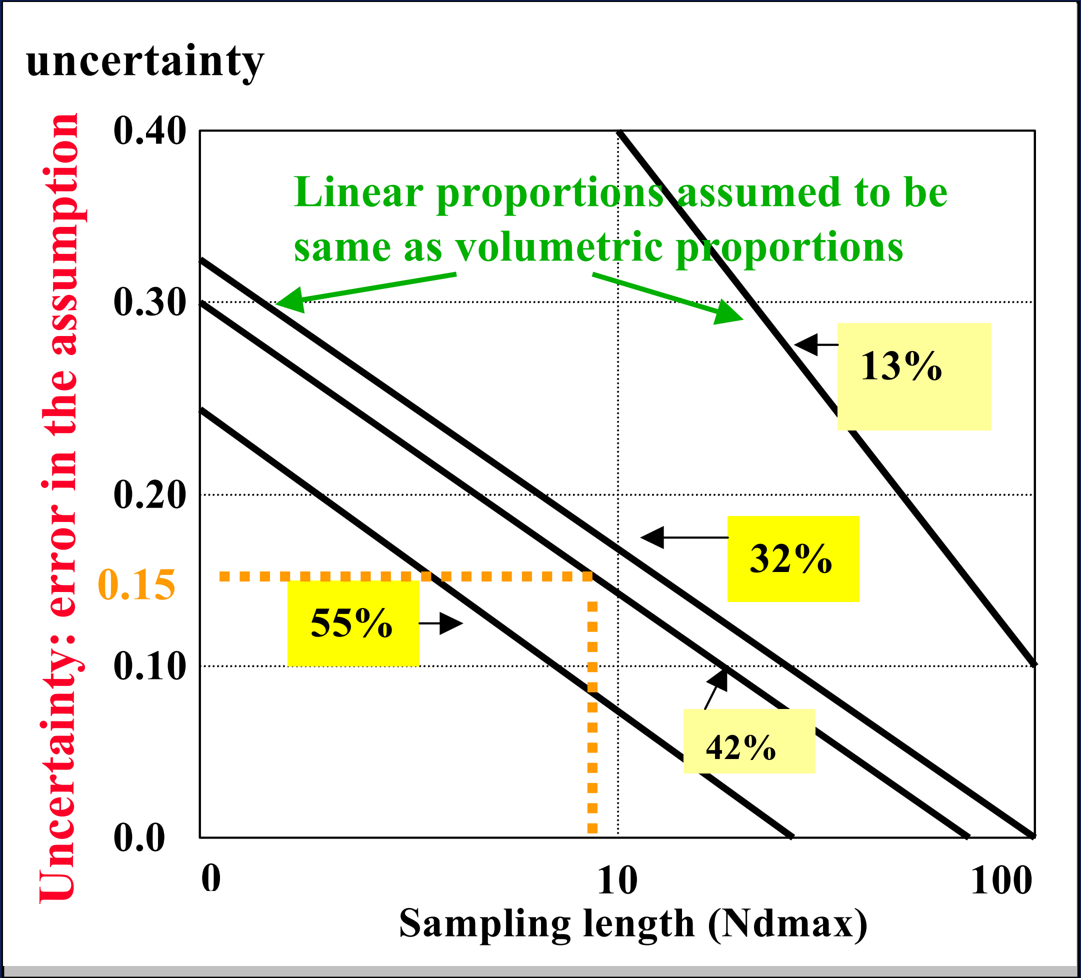
32% model
Plan view of model showing linear proportions
for 100 "long" scanlines

34.7	25.9	6.3	0.0	27.0	13.3	22.5	26.8	31.1	41.7
40.0	33.3	44.0	29.6	18.5	39.7	42.5	25.3	19.1	40.3
31.3	24.5	25.3	21.1	27.8	41.3	53.6	23.4	41.4	23.4
34.0	33.8	10.1	22.9	56.6	39.0	34.0	23.2	52.6	27.0
27.2	34.2	21.9	17.0	57.0	51.3	42.4	54.8	51.3	42.0
26.3	28.1	16.3	26.0	46.7	54.3	45.1	46.1	60.9	48.3
44.2	28.0	29.9	34.2	57.0	58.8	37.5	41.2	46.9	29.6
31.3	36.7	41.3	39.5	32.6	30.3	21.9	30.7	33.5	32.7
50.0	41.5	40.7	26.5	28.0	23.8	27.6	13.0	35.9	36.4
58.9	45.5	30.5	11.1	28.1	23.3	17.6	30.3	32.4	47.6

Plan view edge of model

Guidelines for estimating block volumetric proportion

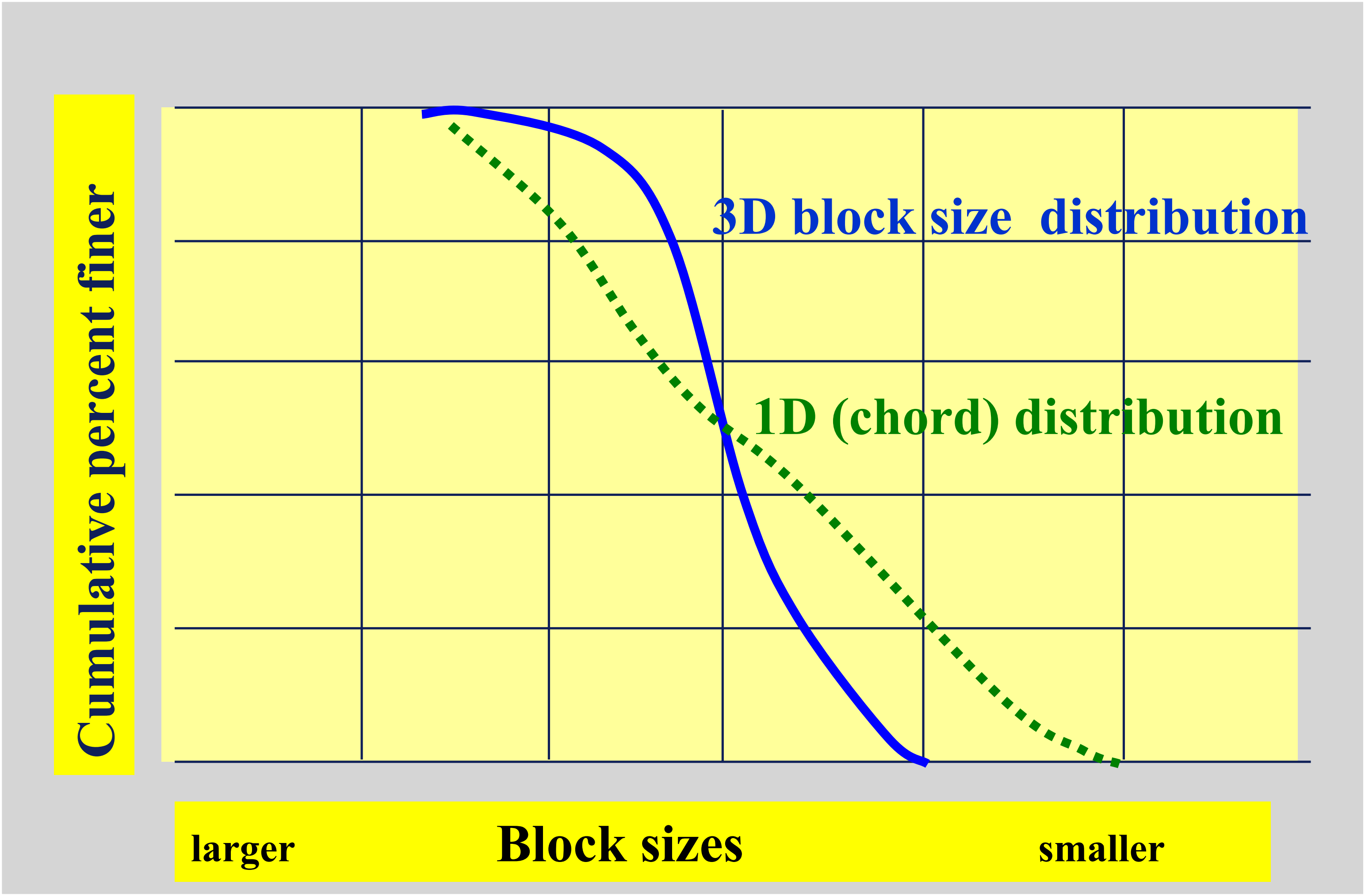
- Measure at least 10* d_{max} of drill core (e.g.: $7.5\sqrt{A}$)
- Take uncertainty into account, and:
  - adjust vol% estimate downwards for strength
  - adjust vol% estimate upwards for construction excavation purposes



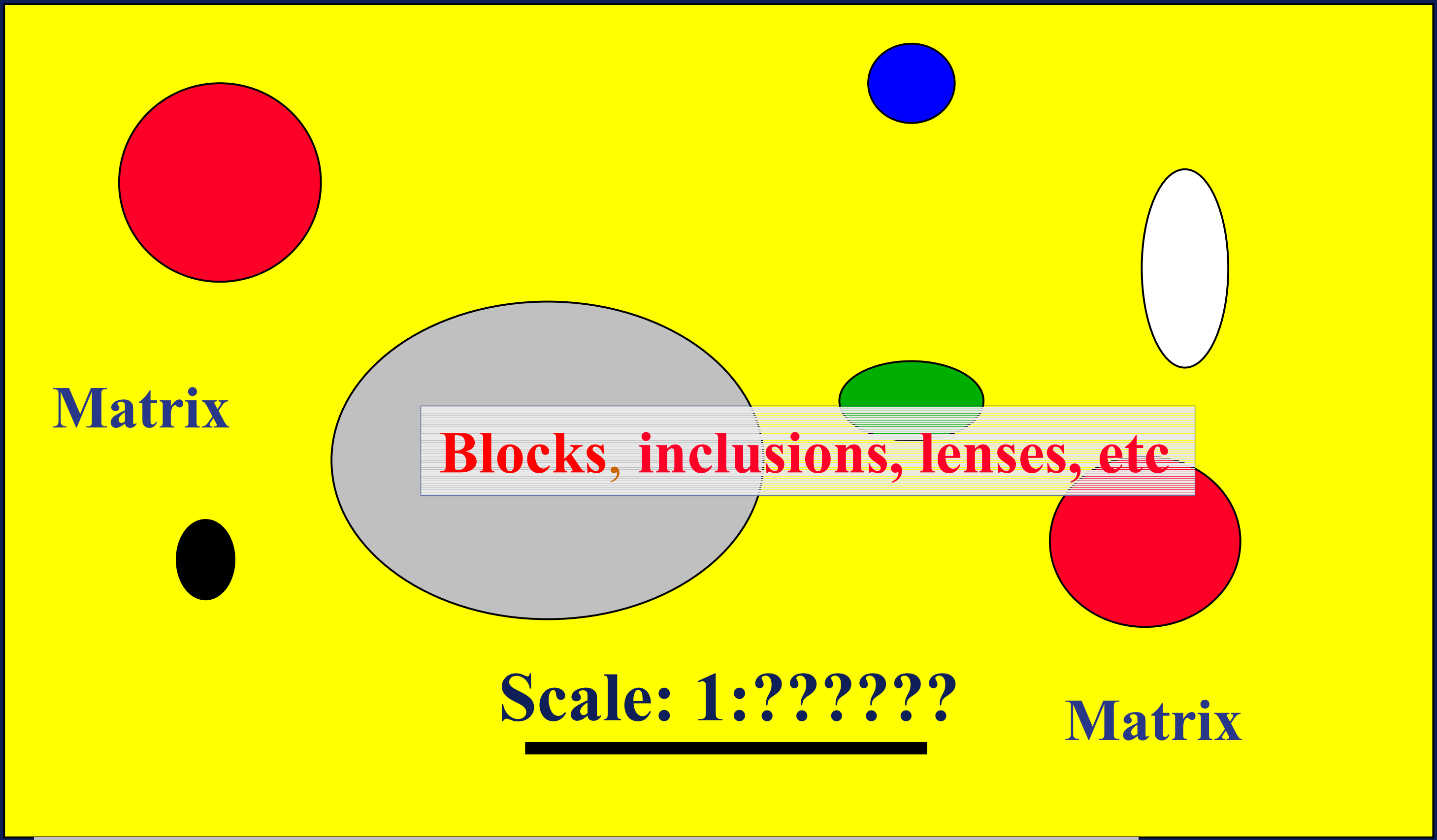
Estimating volumetric properties on the basis of linear boring measurements

0.15x40% = 6%: use 34% block proportion

3D and 1D Block Size Distributions

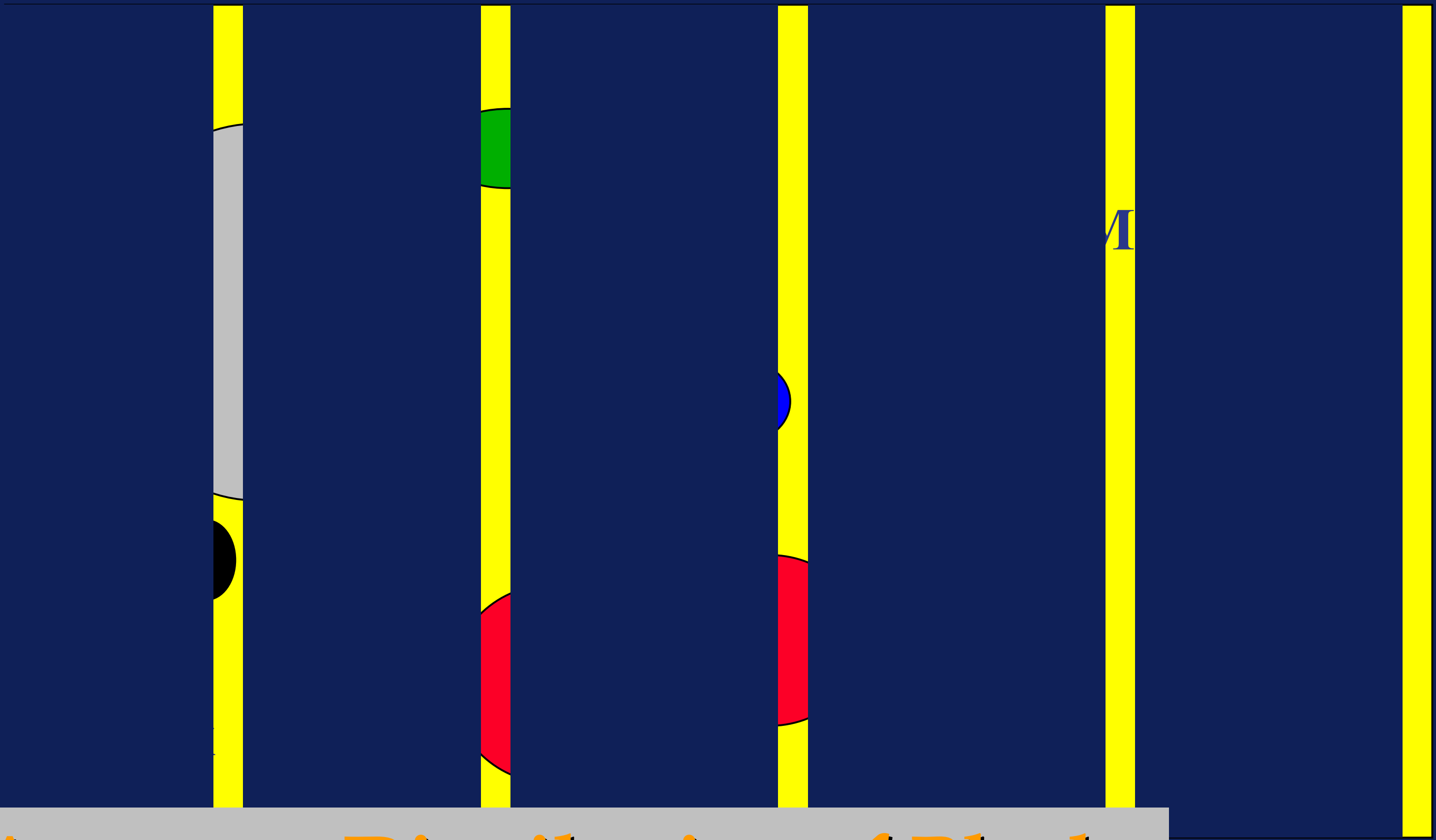


BIG CONCLUSION 1: Remember this picture!!!



Actual Distribution of Blocks

BIG CONCLUSION 2:
Remember this picture as well!!!



Apparent Distribution of Blocks

Willis, 2000

Formation of Clay Minerals

Clay Mineral Neoformation and Transformation in Fault Zones

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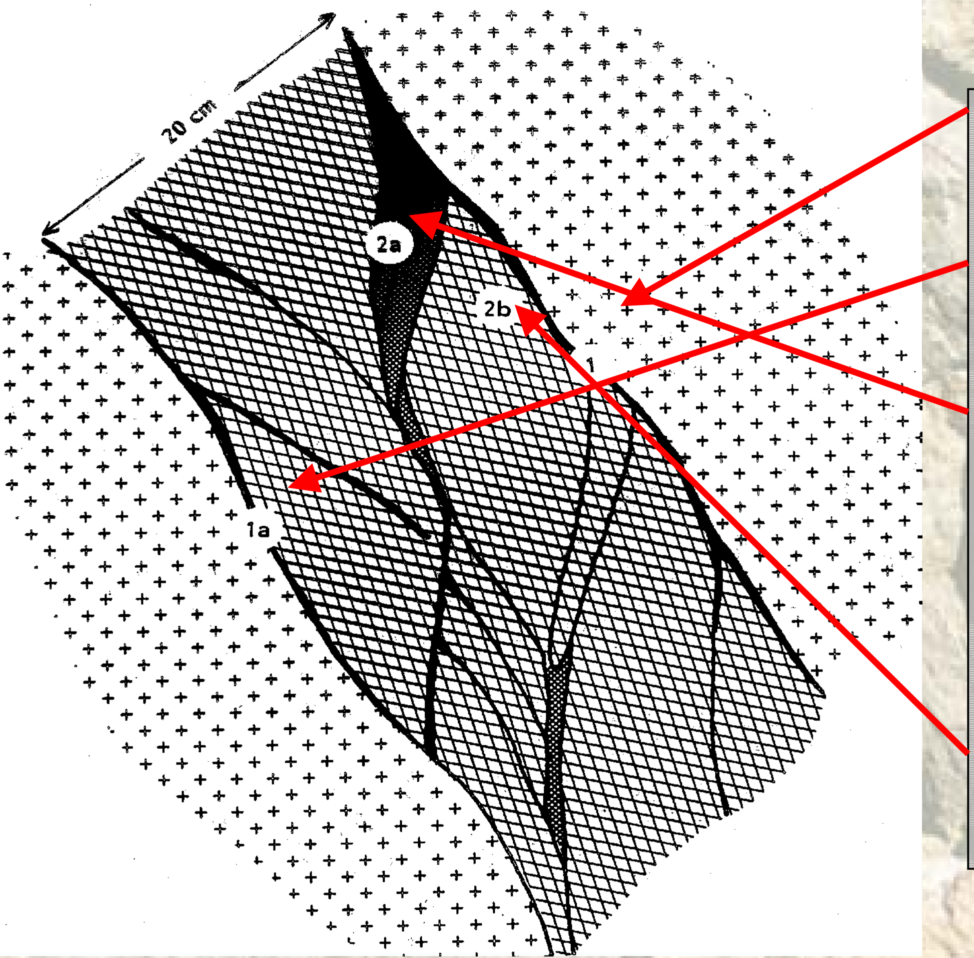
Formation of Clay Minerals



Sample 1: Smectite 92%
Illite 8%

Sample 1a: Smectite 87%
Illite 13%

Sample 2a: Smectite 77%
Mixed Layer
3%
Kaolinite 17%
Illite 3%

Sample 2b: Sample 40%
Kaolinite 50%
Illite 10%

Fault Zone in Gneiss („Zentralgneis“)
HPP MALTA – Gößß Tunnel, Km 4,615

Characterization

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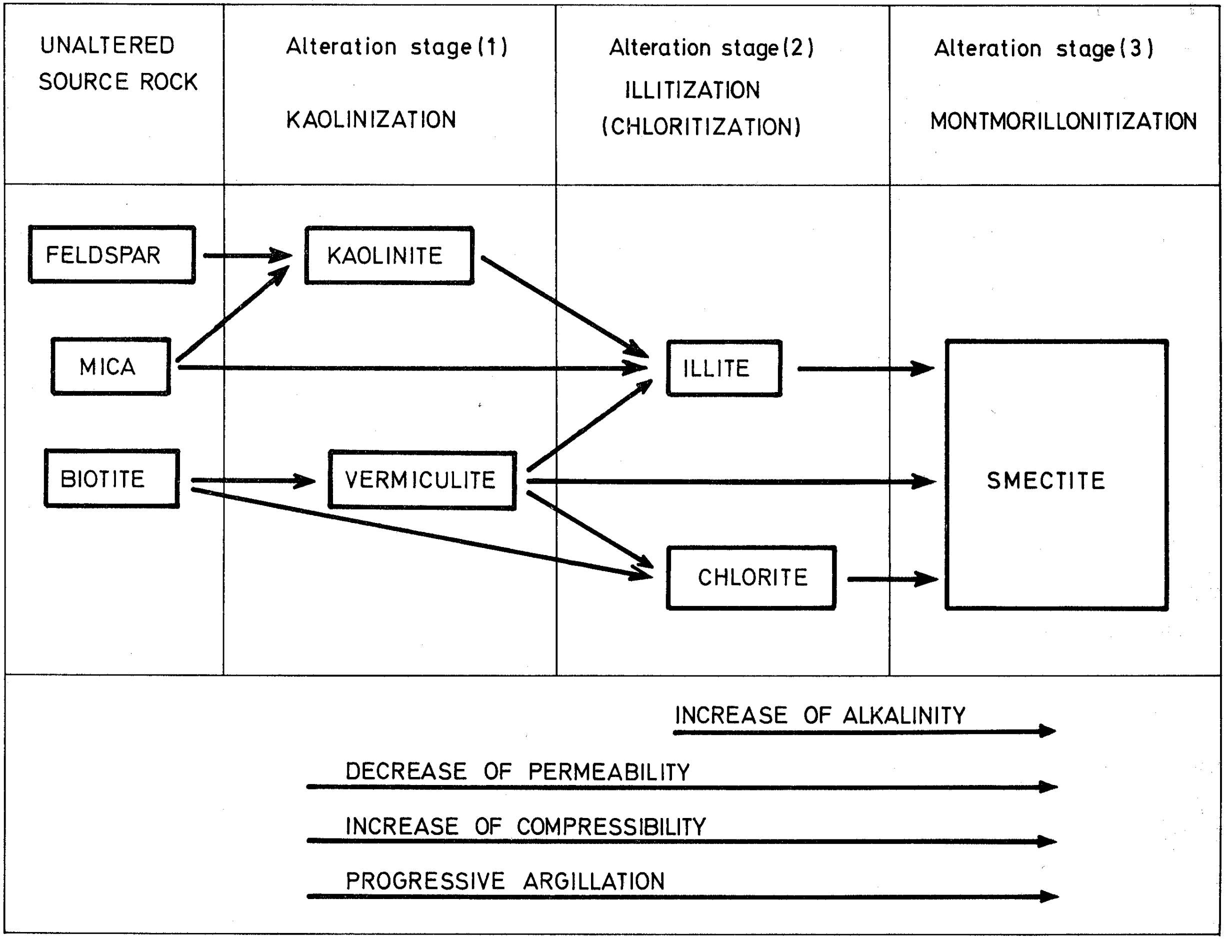
Formation of Clay Minerals

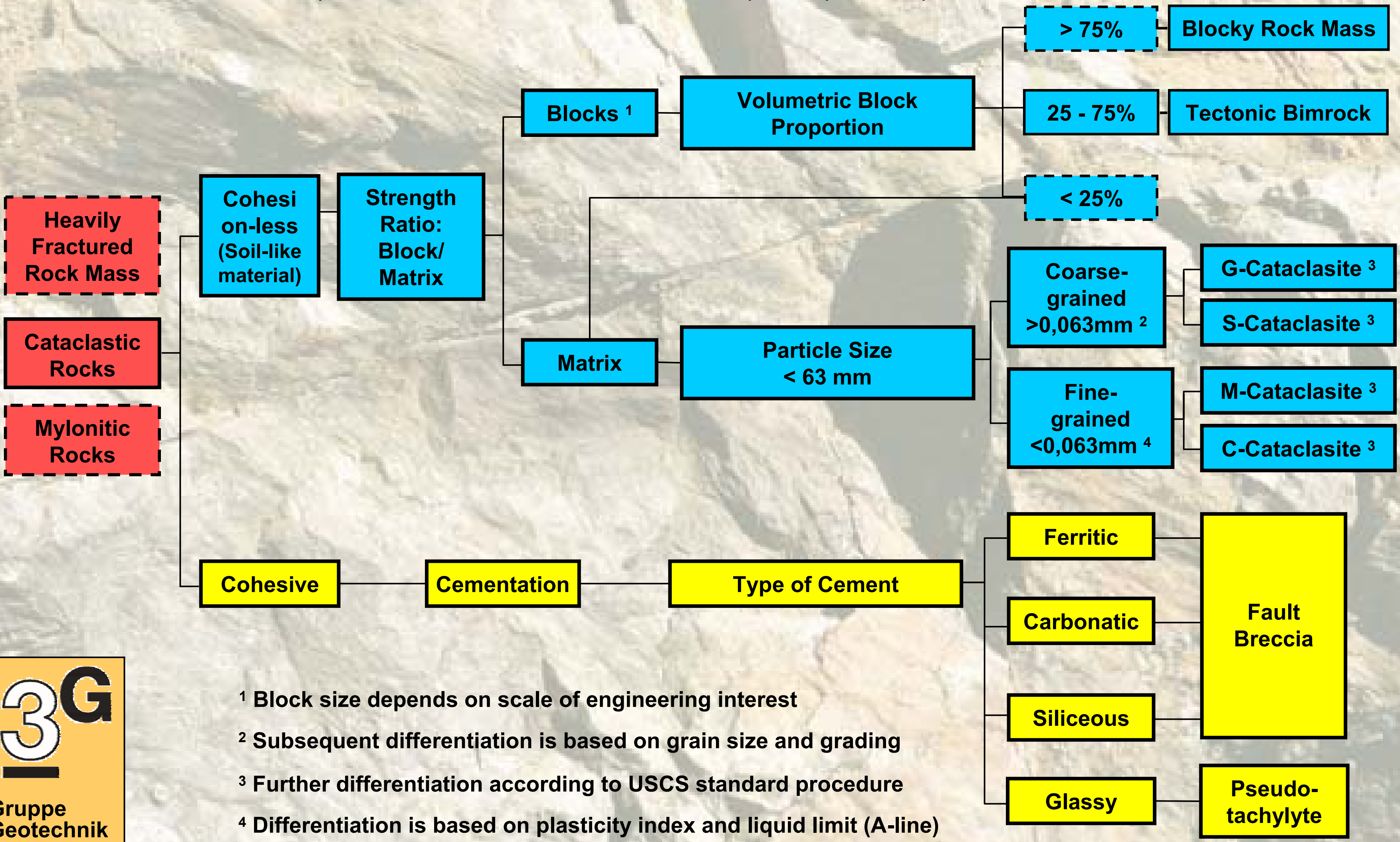


Systematic Transformations of Clay Minerals in Fault Zones
(G. Riedmüller 1976)

Classification

Engineering Geological Classification of Fault Rocks

(Riedmüller et al., Felsbau 19 (2001) No. 4)



Heavily Fractured Rock Mass

Cataclastic Rocks

Mylonitic Rocks

- **Cohesion-less (Soil-like material)**
  - **Strength Ratio: Block/ Matrix**
    - **Blocks [1]**
      - **Volumetric Block Proportion**
        - **> 75%** – **Blocky Rock Mass**
        - **25 - 75%** – **Tectonic Bimrock**
        - **< 25%**
    - **Matrix**
      - **Particle Size < 63 mm**
        - **Coarse-grained >0,063mm [2]**
          - **G-Cataclasite [3]**
          - **S-Cataclasite [3]**
        - **Fine-grained <0,063mm [4]**
          - **M-Cataclasite [3]**
          - **C-Cataclasite [3]**
- **Cohesive**
  - **Cementation**
    - **Type of Cement**
      - **Ferritic**
      - **Carbonatic**
      - **Siliceous**
      - **Glassy**

Fault Breccia

Pseudo-tachylyte

[1] Block size depends on scale of engineering interest

[2] Subsequent differentiation is based on grain size and grading

[3] Further differentiation according to USCS standard procedure

[4] Differentiation is based on plasticity index and liquid limit (A-line)

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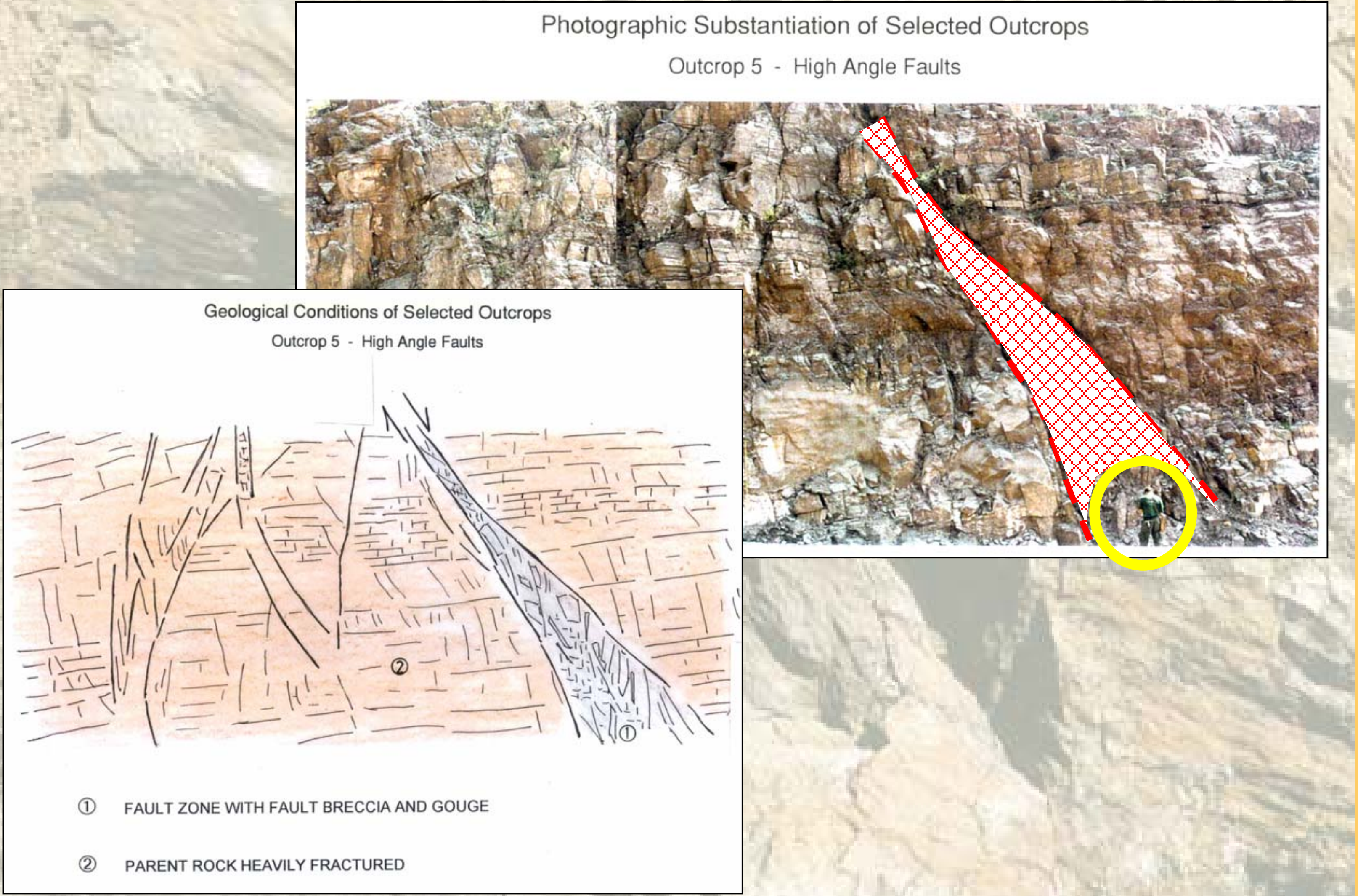
General Procedure

- **Desk Studies**
  - Satellite Images, Aerial Photographs, Maps etc.
- **Geological Field Survey**
  - Morphological Features
  - Outcrop Studies
    - Rock Mass Characterization
    - Paleostress Analysis
- **Subsurface Investigation**
  - Trenches, Trial Pits
  - Core Drilling
  - Borehole in-situ tests
  - Geophysical Survey
- **Laboratory Analyses**
  - Mineralogical Analyses
  - Mechanical Analyses

Outcrop Studies



Photographic Substantiation of Selected Outcrops

Outcrop 5 - High Angle Faults

Geological Conditions of Selected Outcrops

Outcrop 5 - High Angle Faults

① FAULT ZONE WITH FAULT BRECCIA AND GOUGE

② PARENT ROCK HEAVILY FRACTURED

Hydro Power Project Xiaolangdi

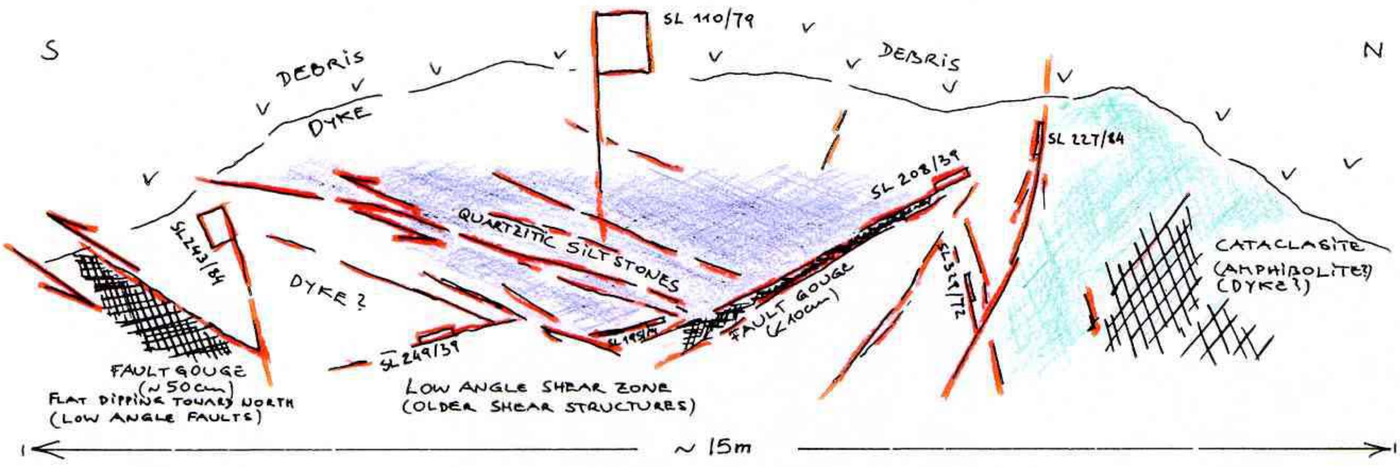
Outcrop Studies

Paleostress Analysis

- **Fault Slip Data**
  - P/T Method
  - Method of Right Dihedra
- **Extension Joints**
  - Plumose Structure

Outcrop Studies

Thrust Displaced by Strike – Slip Faults



Low angle faults (SL 293/34, 290/42, 302/37, 331/42, 208/39, 249/39) displaced by conjugated faults
(SL 227/84, 329/72, 91/87, 243/84, 226/86)

Bolu Tunnel, Turkey

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Strategies

Objective of Investigation

OWNER'S INTEREST:

- **Construction schedule**
- **Construction costs**

- **Definition of uncertainties**
- **Geotechnical risk assessment**
- **Identification of environmental problems**

Strategies

Common understanding

High standards and quality for a site investigation lead to an economical and technical successful construction

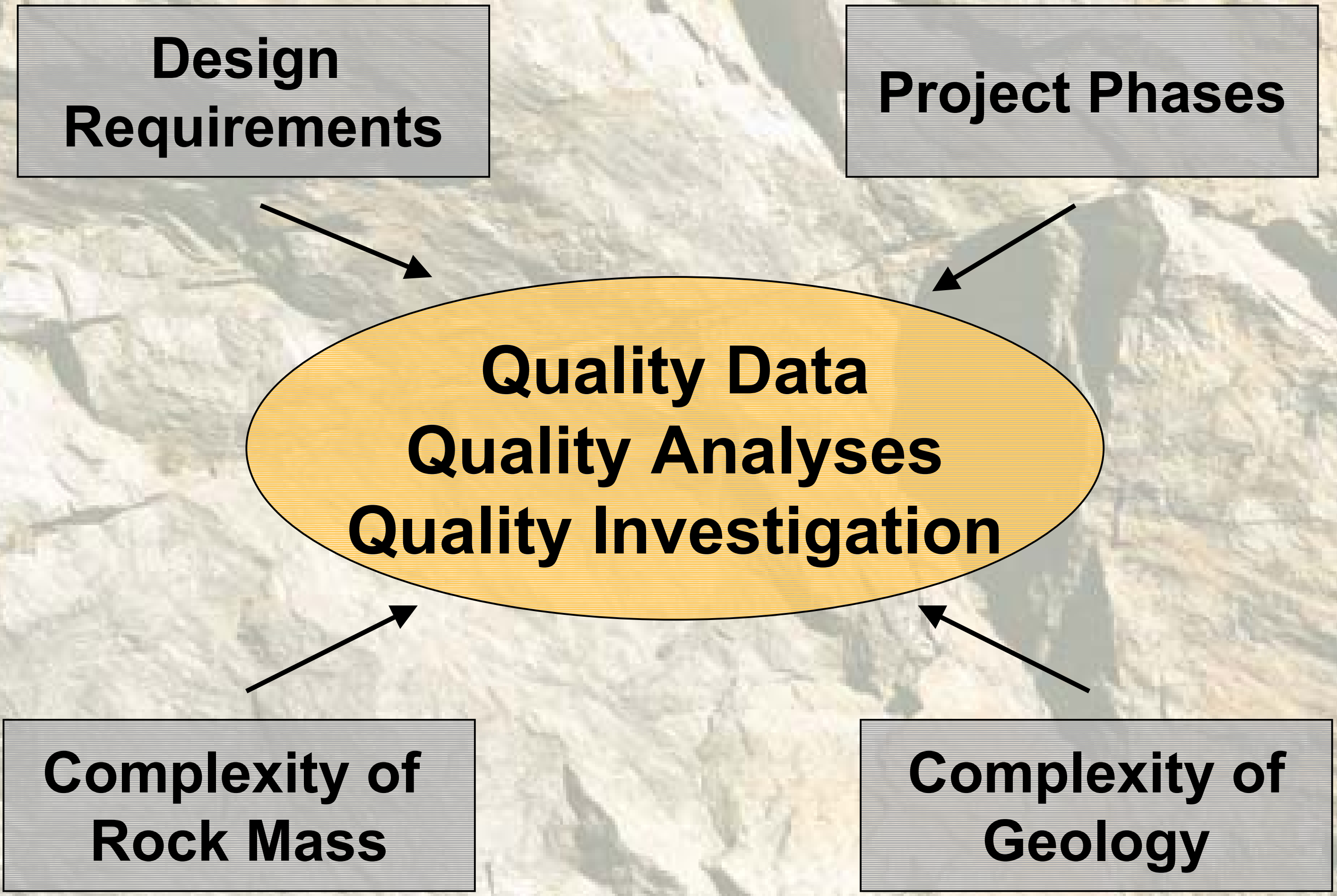
Strategies

Quality

QUALITY *is a relative attribute and depends upon the specific circumstance. In the sense of a technical sound and economic investigation quality is determined to be either adequate or inadequate.*

What is an acceptable quality investigation in one situation can be an inadequate and unacceptable investigation in another.

Strategies



Design Requirements

Project Phases

Quality Data
Quality Analyses
Quality Investigation

Complexity of Rock Mass

Complexity of Geology

Strategies

Quality Data Collection
Quality Data Analysis

- geotechnically relevant
- statistically representative
- legally defensible

Strategies

Quality Data Collection
(with adequate quality control and quality assessment)

- Office Data Collection
- Field Survey
- Subsurface Exploration
- In Situ Testing
- Laboratory Testing

Strategies

Quality Data Analysis
(with adequate quality control and quality assessment)

- Statistical Evaluation
- Assessment of Probabilistic Confidence
- Geologic Modelling
- Kinematic Modelling
- Mechanical Modelling

Strategies

Quality Site Investigation

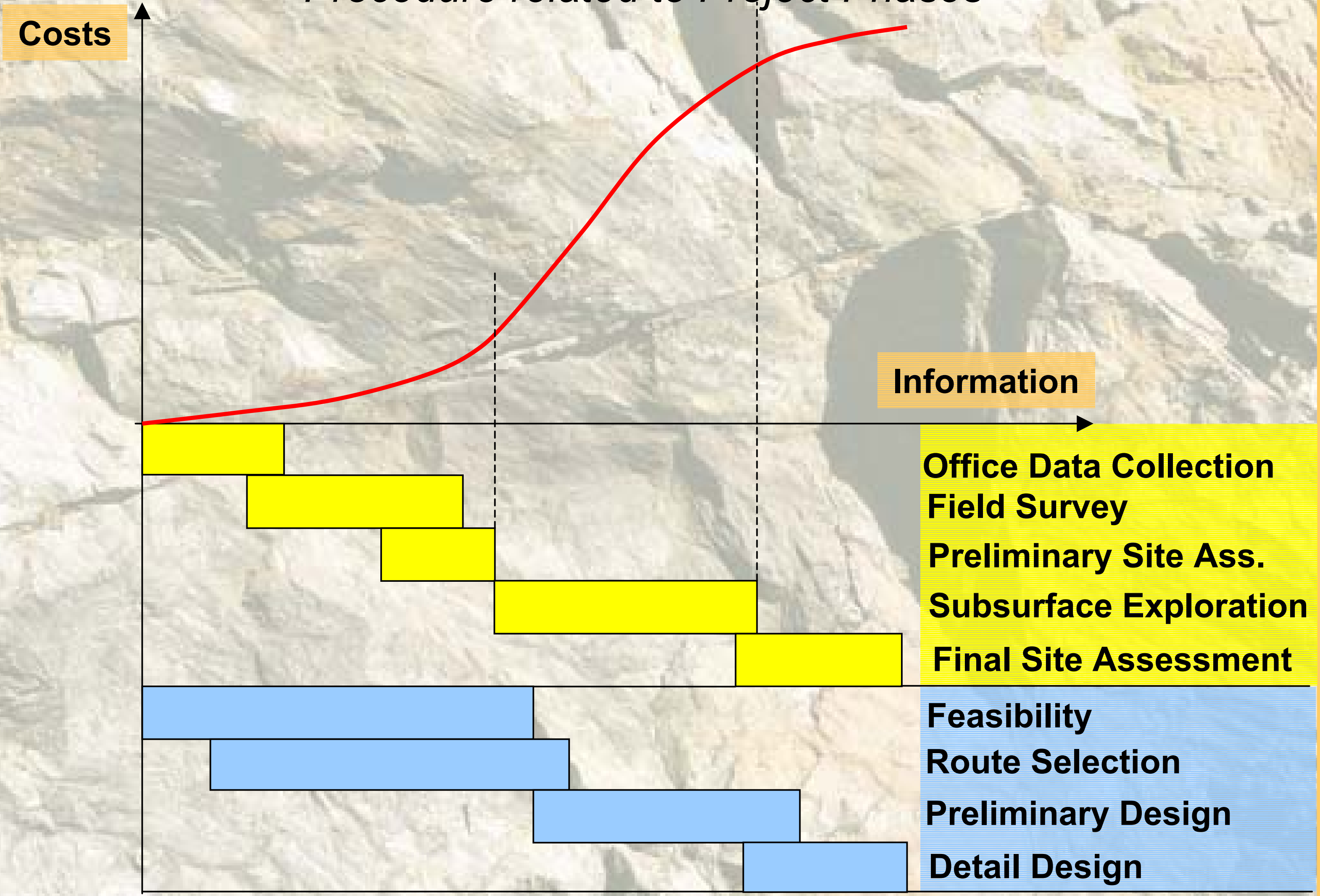
A QUALITY INVESTIGATION needs more than just QUALITY DATA and QUALITY ANALYSES.

It requires:

1. **Specific sequence of investigative procedures**
2. **Design phase and rock mass specific investigations**
3. **Input from experienced professionals**

Strategies

Cost - Benefit Relation of Investigation Procedure related to Project Phases



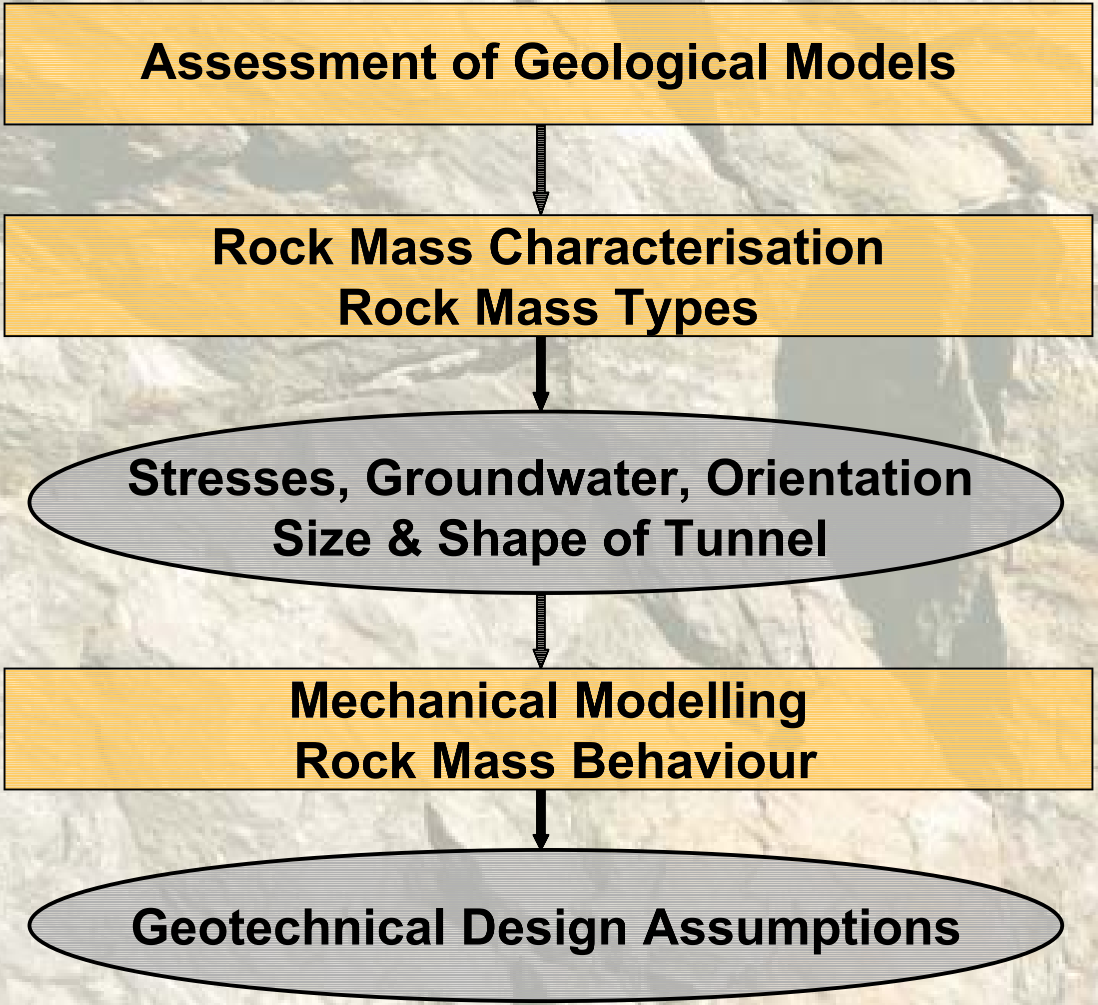
Strategies

Project Phases - Geotechnical Objectives

Pre-Feasibility Feasibility	Conceptual Design Route Selection	Preliminary Design	Detail Design Tender	Final Design Construction
Corridor Assessment ■ **Comparison of Routes** ■ **First Cost Estimate**	**Basic Assessment of Rock Mass Behaviour, Support Systems and Construction Methods** ■ **Assessment of Routes** ■ **Cost Estimate**	**Assessment of Rock Mass Behaviour, Support Systems and Construction Methods** ■ **Environmental Impact Assessment** ■ **Cost Estimate**	**Detail Construction Design** ■ **Bill of Quantities** ■ **Contractual Set-Up** ■ **Final Cost Estimate**	**Final Determination of Support and Construction Methods** ■ **Update of Construction Schedule and Costs**

Strategies

Analytical Procedure in Each Design Phase



Assessment of Geological Models

Rock Mass Characterisation
Rock Mass Types

Stresses, Groundwater, Orientation
Size & Shape of Tunnel

Mechanical Modelling
Rock Mass Behaviour

Geotechnical Design Assumptions

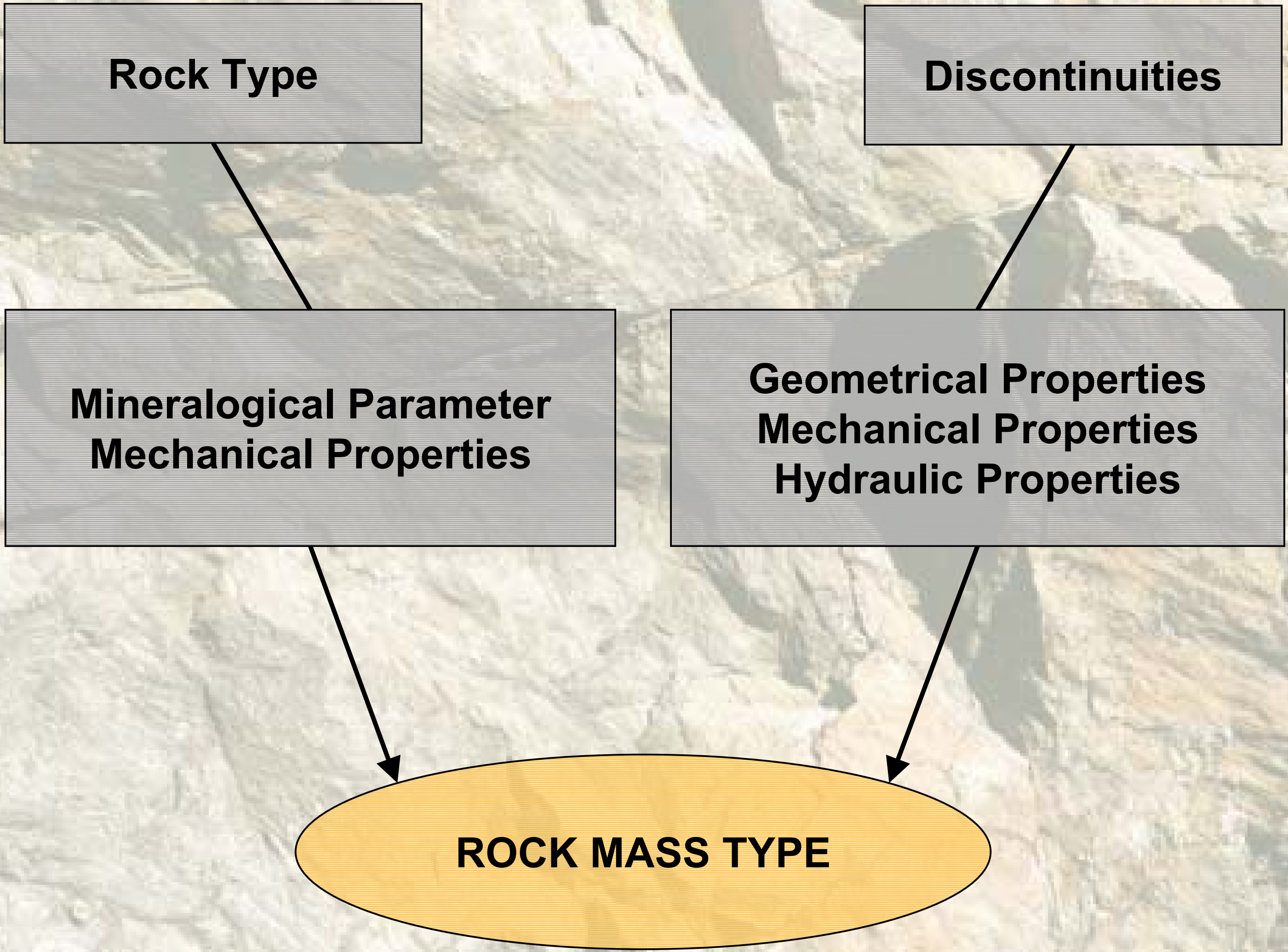
Strategies

Assessment of Geological Models

Conceptual **Geological Models** include three-dimensional interpretations of the distribution and orientation of structures and rock types.
The models are presented as geological maps, vertical and horizontal sections and, most recently,
as 3D-models

Strategies

Rock Mass Characterisation
Rock Mass Types



Rock Type

Discontinuities

Mineralogical Parameter
Mechanical Properties

Geometrical Properties
Mechanical Properties
Hydraulic Properties

ROCK MASS TYPE

Strategies

Definition of Rock Mass Types

Rock Mass Types are defined by

“KEY PARAMETERS“

Strategies

Key Parameters

Key Parameters depend on

- Rock Type
- Project Phase
- Design Requirements

Strategies

Rock Type → Key Parameters

Phyllite

- Anisotropy
- Shear parameters and stiffness of foliation planes
- Content of sheet silicates and clay minerals

Strategies

Rock Type → Key Parameters

Granite

- Grain size
- Texture
- UCS
- Joint sets (orientation,number)
- Persistence, spacing

Strategies

Basic Rock Types	Key Parameters																				
	Intact Rock Properties														Discontinuities						
	1	2	3	4	5	6	7	8	9	10	11	12	13	14	15	16	17	18	19	20	21
Volcanic Rocks				o	x	x						x	x		x	x		o	x	o	
Plutonic Rocks		x	x	x		o						x			x	x		o	x	o	
Fine-Grained Clastic Rocks (massive)			x				x	x	x		x	o			o	o					
Fine-Grained Clastic Rocks (bedded)	x		x				x	x	x		x			x			x			o	x
Coarse-Grained Clastic Rocks (massive)		o	x	o	o			o			x	x	x		o	o		o	o		
Coarse-Grained Clastic Rocks (bedded)	x	o	x		o			o			x	x	x	x			x				x
Carbon. Rocks		x								x		x			x	x		o	x	o	
Sulfatic Rocks		x							x	x		o									
Metam. Rocks (massive)		x	x	x		o						x			x	x		o	x		
Metam. Rocks (foliated)	x	x	x	x		o						x		x						x	x
Brittle Fault Rocks		o				o	x	x	x		x	x	x								

LEGEND

x	Significant Parameter
o	Less Important Parameter

(1)	Anisotropy
(2)	Mineral Composition
(3)	Grain Size
(4)	Texture
(5)	Porosity
(6)	Secondary Alteration
(7)	Clay Mineral Composition
(8)	Clay Content
(9)	Swelling Properties
(10)	Solution Phenomena
(11)	Cementation
(12)	Strength Properties
(13)	Ratio Matrix/Components
(14)	Orientation of Dominant Set
(15)	No. and Orientation of Sets
(16)	Fracture Frequency
(17)	Roughness
(18)	Persistence
(19)	Aperture
(20)	Infilling
(21)	Shear Strength

Investigation

Rock Type Specific Key Parameters

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Faulted Rock Mass

- **Block / Matrix Ratio**

- **Matrix Properties**
  - Particle Size Distribution
  - Clay Mineral Composition
  - Swelling Properties
  - Shear Strength

- **Block Properties**
  - Lithology
  - Size
  - Shape
  - Strength

- **Discontinuities**
  - Type (shear, extension fractures etc.)
  - Orientation
  - Fracture Degree
  - Relative Movements on Slickensides

Key Parameters

Investigation

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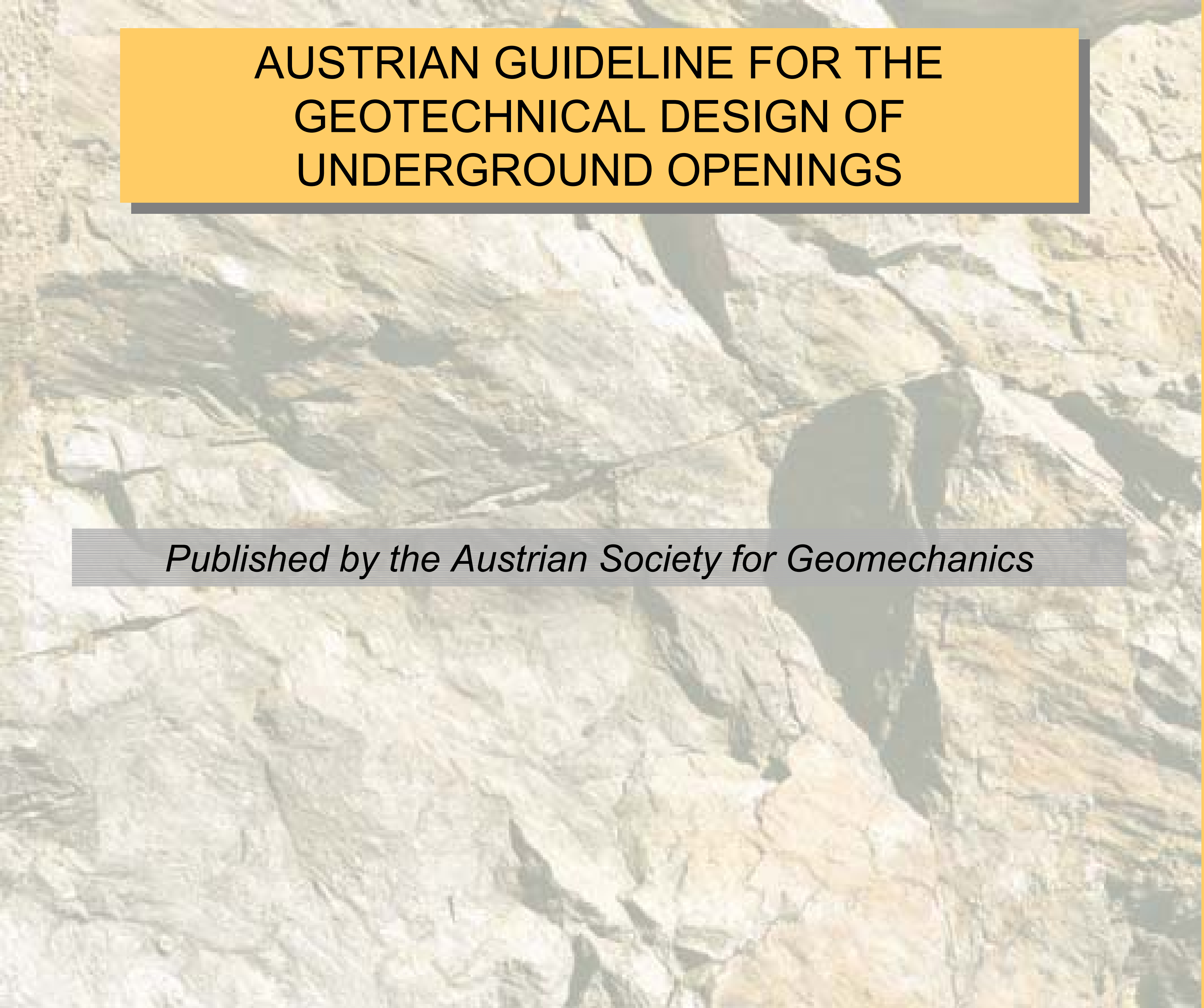

AUSTRIAN GUIDELINE FOR THE GEOTECHNICAL DESIGN OF UNDERGROUND OPENINGS

Published by the Austrian Society for Geomechanics

Guideline

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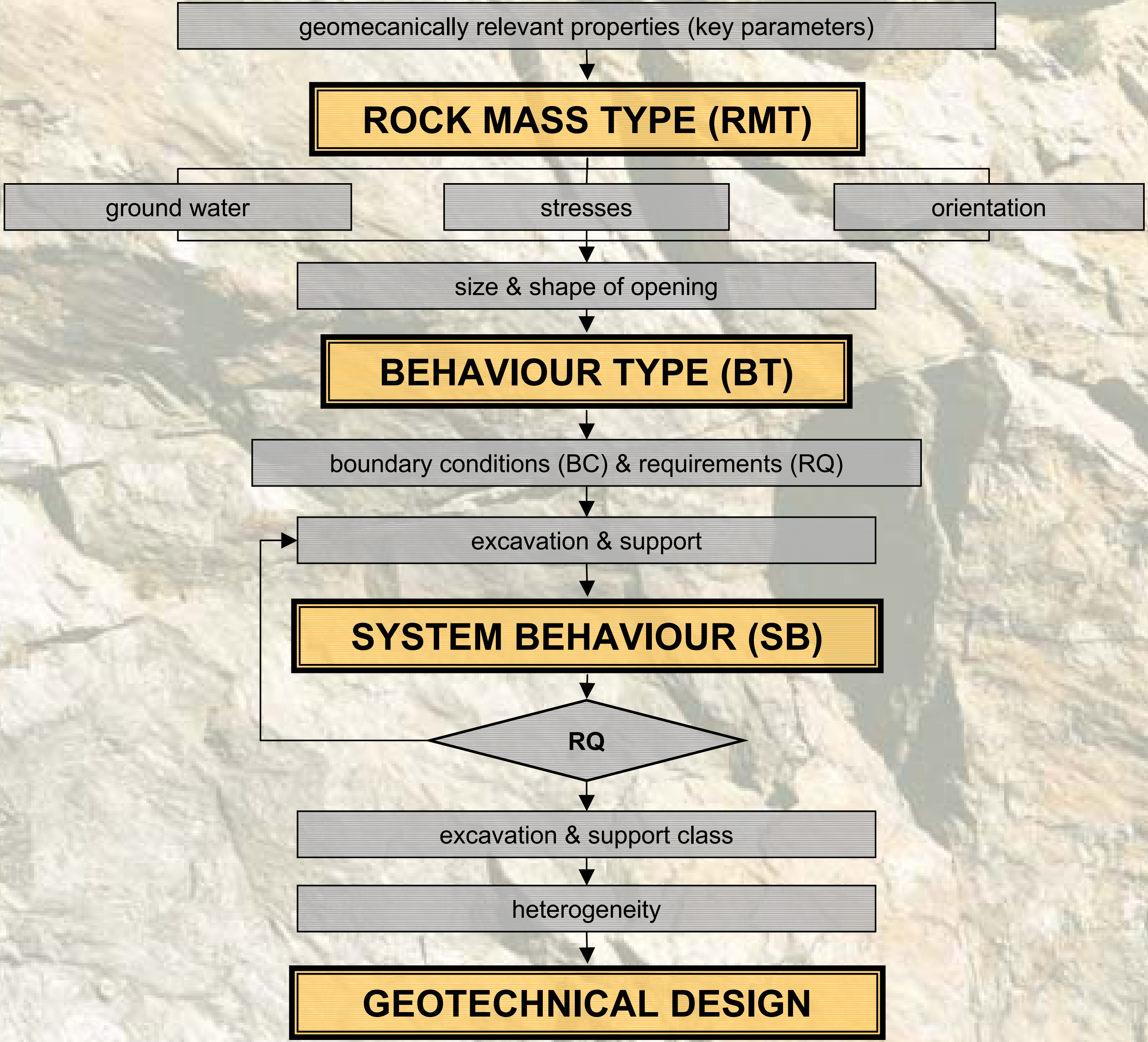
OBJECTIVE

- Transparent, consistent procedure for the design and construction of tunnels
- Design phases, rock mass types and influencing factors have to be considered
- Decisions during construction have to be based on objective and systematic collection, evaluation and interpretation of quality data

Guideline



geomecanically relevant properties (key parameters)

ROCK MASS TYPE (RMT)

ground water

stresses

orientation

size & shape of opening

BEHAVIOUR TYPE (BT)

boundary conditions (BC) & requirements (RQ)

excavation & support

SYSTEM BEHAVIOUR (SB)

RQ

excavation & support class

heterogeneity

GEOTECHNICAL DESIGN

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KEY PARAMETERS

Basic Rock Types	Key Parameters																				
	Intact Rock Properties														Discontinuities						
	1	2	3	4	5	6	7	8	9	10	11	12	13	14	15	16	17	18	19	20	21
Volcanic Rocks				o	x	x						x	x		x	x		o	x	o	
Plutonic Rocks		x	x	x		o						x			x	x		o	x	o	
Fine-Grained Clastic Rocks (massive)			x				x	x	x		x	o			o	o					
Fine-Grained Clastic Rocks (bedded)	x		x				x	x	x		x			x			x			o	x
Coarse-Grained Clastic Rocks (massive)		o	x	o	o			o			x	x	x		o	o		o	o		
Coarse-Grained Clastic Rocks (bedded)	x	o	x		o			o			x	x	x	x			x				x
Carbon. Rocks		x								x		x			x	x		o	x	o	
Sulfatic Rocks		x							x	x		o									
Metam. Rocks (massive)		x	x	x		o						x			x	x		o	x		
Metam. Rocks (foliated)	x	x	x	x		o						x		x						x	x
Brittle Fault Rocks		o				o	x	x	x		x	x	x								

LEGEND

x Significant Parameter

o Less Important Parameter

(1) Anisotropy
(2) Mineral Composition
(3) Grain Size
(4) Texture
(5) Porosity
(6) Secondary Alteration
(7) Clay Mineral Composition
(8) Clay Content
(9) Swelling Properties
(10) Solution Phenomena
(11) Cementation
(12) Strength Properties
(13) Ratio Matrix/Components
(14) Orientation of Dominant Set
(15) No. and Orientation of Sets
(16) Fracture Frequency
(17) Roughness
(18) Persistence
(19) Aperture
(20) Infilling
(21) Shear Strength

Guideline

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BASIC BEHAVIOUR TYPES

Basic Behavior Type		Description
1	Stable	Stable rock mass with small local gravity induced falling or sliding of blocks
2	Stable with the potential of discontinuity controlled block fall	Deep reaching discontinuity controlled, gravity induced falling and sliding of blocks, occasional local shear failure
3	Shallow shear failure	Shallow stress controlled shear failures in combination with discontinuity and gravity controlled failure of the rock mass
4	Deep seated shear failure	Deep seated, stress induced shear failures and large deformations
5	Rock burst	Sudden and violent failure of the rock mass, caused by highly stressed rock and the rapid release of accumulated strain energy
6	Buckling failure	Buckling of rocks with a narrowly spaced discontinuity set, frequently associated with shear failure
7	Shear failure under low confining pressure	Potential for excessive overbreak and progressive shear failure with the development of dead loads, caused mainly by a deficiency of side pressure
8	Raveling ground	Flow of cohesionless dry or moist material
9	Flowing ground	Flow of material with high water content
10	Swelling	Time dependent volume increase of the rock mass, caused by physical- chemical reactions of rock and water in combination with stress relief, leading to inward movement of the tunnel perimeter
11	Rock mass with frequently changing deformation characteristics	Rapid variations of stresses and deformations, caused by block-in matrix situation of a tectonic melange (brittle fault)

Guideline

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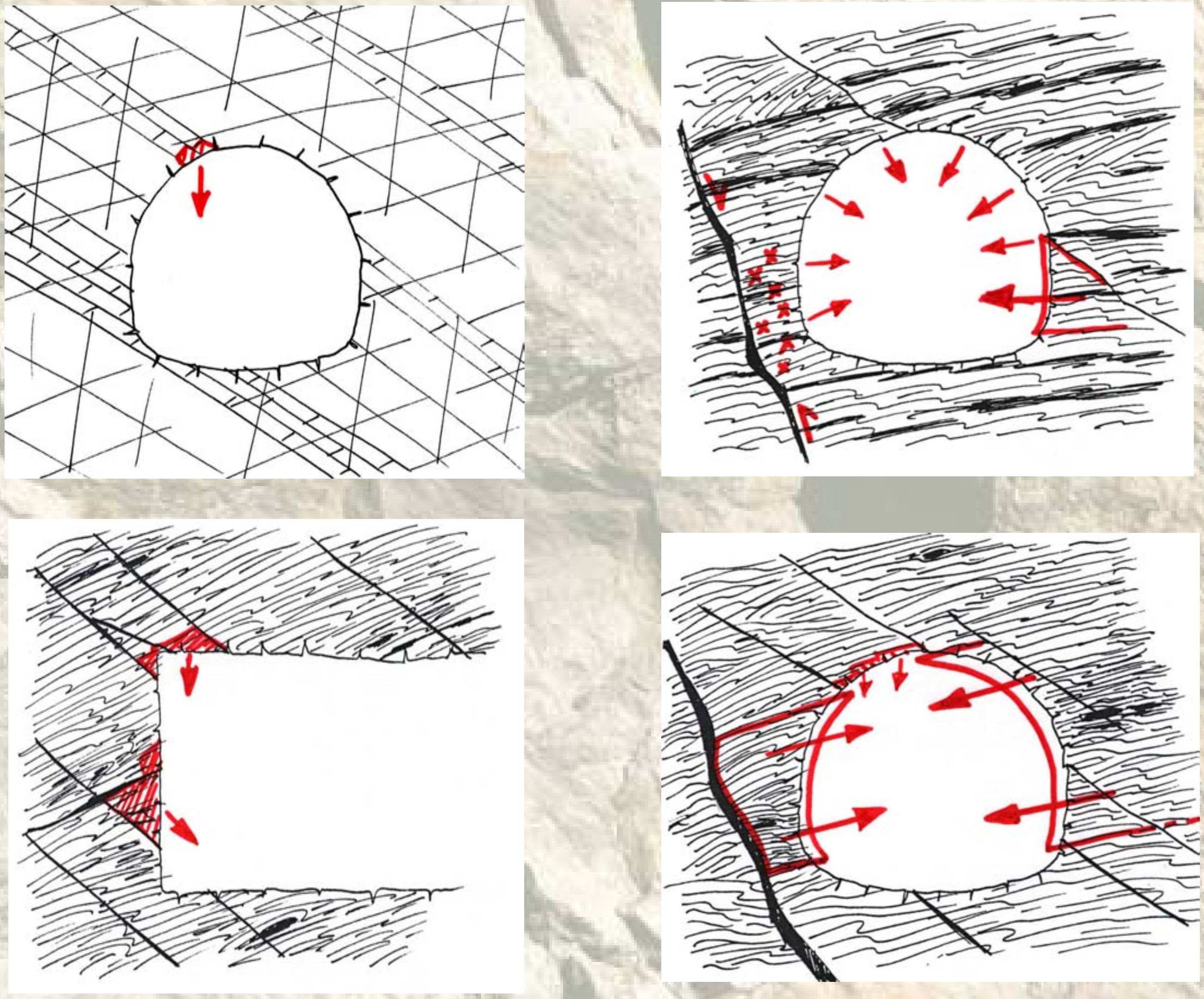
BEHAVIOUR TYPES (examples)



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TRANSFER OF GEOLOGICAL MODELS INTO GEOTECHNICAL DESIGN

GEOLOGICAL LONGITUDINAL SECTION

↓

ROCK MASS TYPES

stepwise assigned (e.g. 20 m intervals)

↓

ANALYTICAL CALCULATIONS

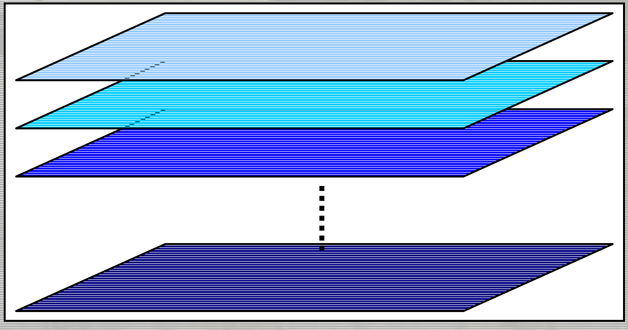
for each 20 m step

Input: influencing factors, geotechnical properties

Output: displacements, depths of broken zones, etc.

DETERMINATION OF BEHAVIOUR TYPES

OUTPUT OF ANALYTICAL CALCULATIONS

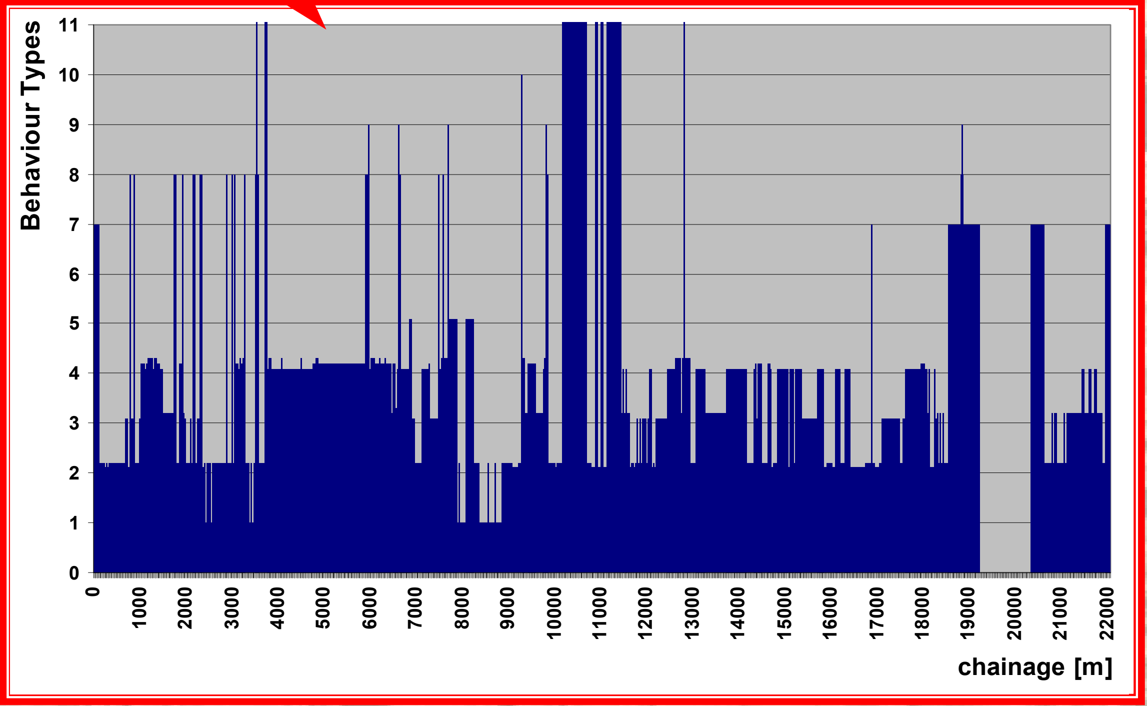


eleven parameter groups for the determination of the basic **BEHAVIOUR TYPES**

BEHAVIOUR TYPE
determined for each 20 m step

DETERMINATION OF BEHAVIOUR TYPES

chainage from	to	Rock Mass Type	Behaviour Type	Displacement Category	Support Pressure	System Behaviour	Excavation Category	Support Class
0	20	G10	7	1	0,7	c	4	b
20	40	G10	7	1	0,	c	4	b
40	60	G						
60	80	G						
80	100	G						
100	120	G						
120	140	G						
140	160	G						
160	180	G						
180	200	G						
200	220	G						
220	240	G						
240	260	G						
260	280	G						
280	300	G						
300	320	G						



Distribution of **BEHAVIOUR TYPES** along the tunnel alignment

Guideline

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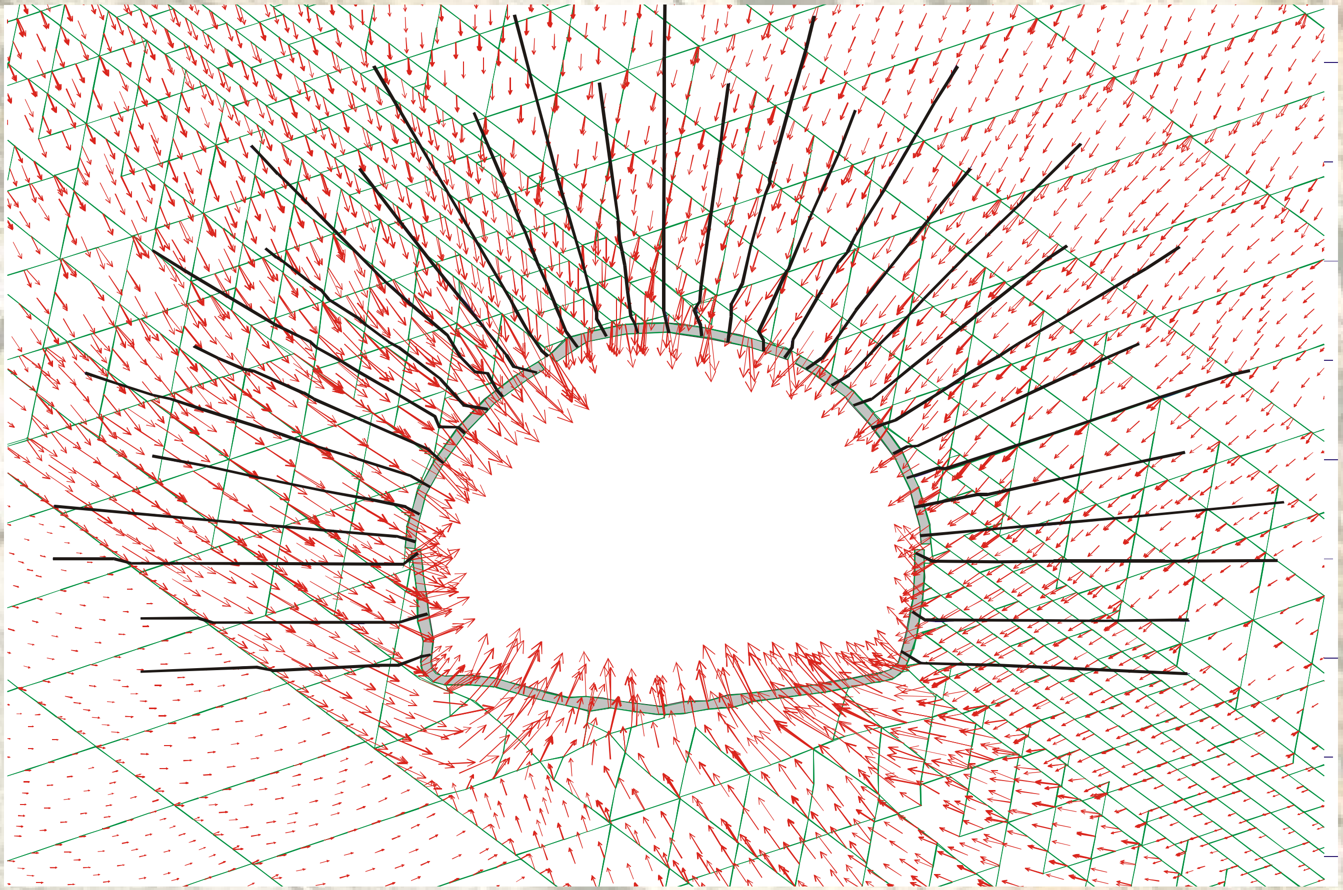
DETERMINATION SYSTEM BEHAVIOUR

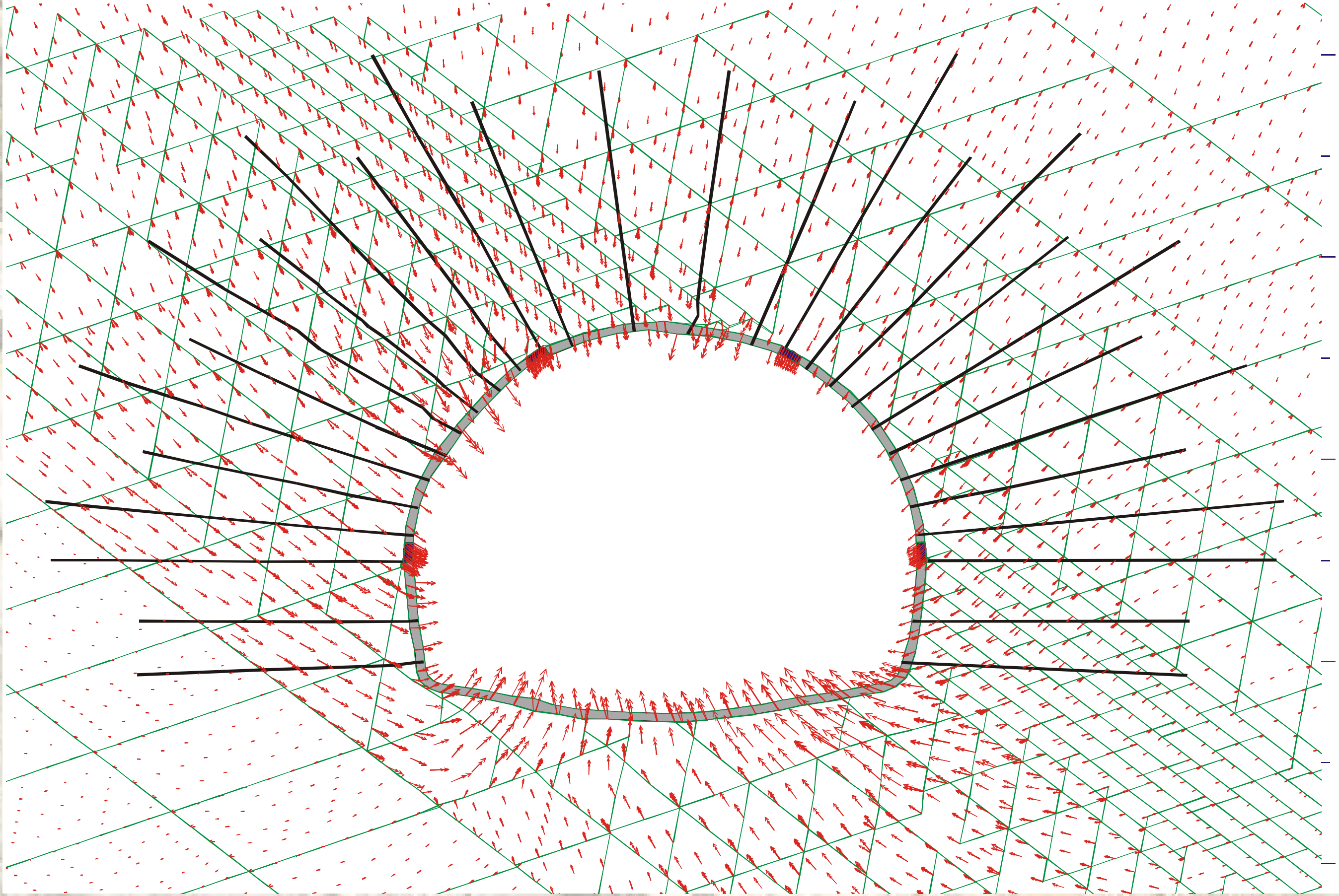
Heavily broken primary lining



Galgenberg Tunnel, Austria

DETERMINATION SYSTEM BEHAVIOUR

Substantial improvement by installing LSC elements



Galgenberg Tunnel, Austria

PROCEDURE DURING CONSTRUCTION

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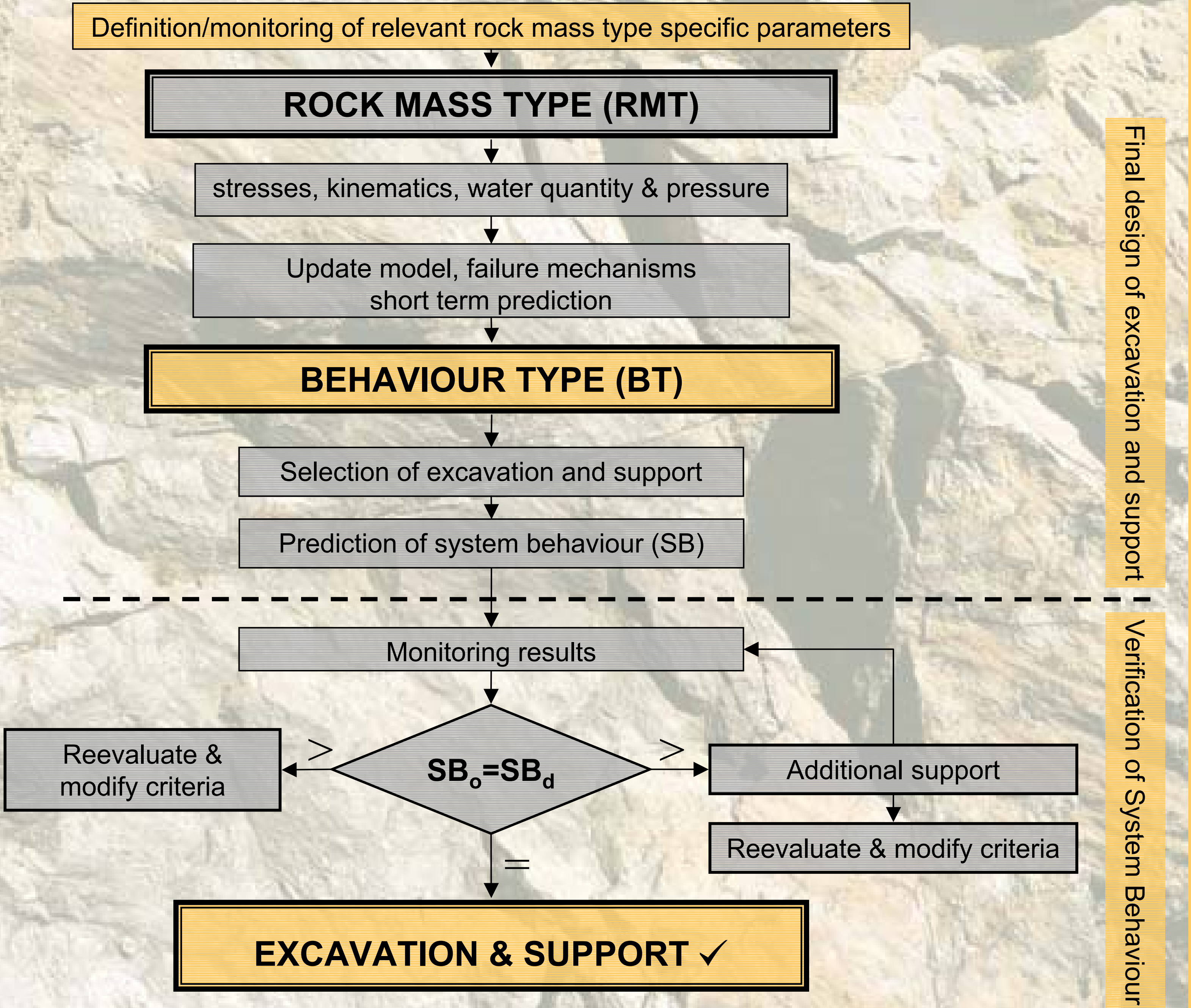

Definition/monitoring of relevant rock mass type specific parameters

ROCK MASS TYPE (RMT)

stresses, kinematics, water quantity & pressure

Update model, failure mechanisms
short term prediction

BEHAVIOUR TYPE (BT)

Selection of excavation and support

Prediction of system behaviour (SB)

Final design of excavation and support

Monitoring results

Reevaluate &
modify criteria

>

$SB_o=SB_d$

>

Additional support

Reevaluate & modify criteria

=

EXCAVATION & SUPPORT ✓

Verification of System Behaviour

Guideline

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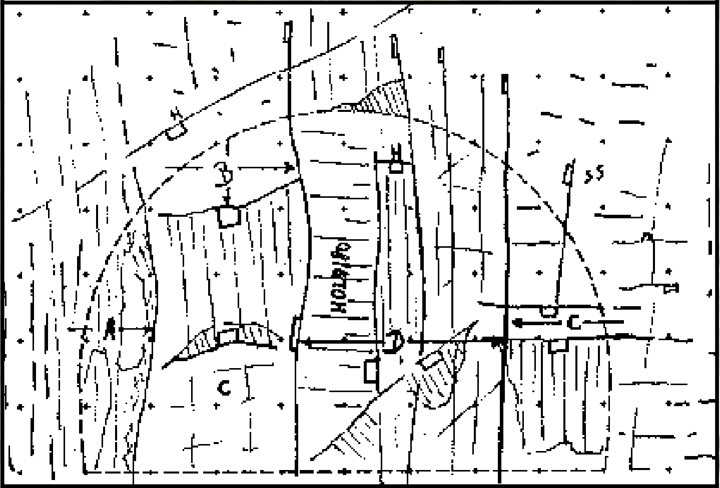
EXAMPLE CONSTRUCTION



area	lithology	bedding thickn. a	b	c	deg. of fract. low	med.	high	apert. +/-	R. M. Type
A	MS		X			X		+	9
B	LD	X				X		+	2
C	LD	X				X		+	2
D	LD		X			X		+	3

area	interlocked yes	no	water inflow no	< 5	> 5	Behav. Type local
A		X	X			4
B	X		X			2
C		X	X			3
D		X	X			4

dominating regions

A,C

Displacement category (cm)

[✓ <5] 5-10 >10

Behavior Type 2

rock mass with potential for systematical and voluminous overbreak, no stress induced failures

Support & Excavation Concept

round length: 1.3 m
support type: ST 3

Guideline

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Case Studies

Conceptual (Route Selection)and Feasibility Study

Mae Kuang Inflow Augmentation Project

Case Studies

Conceptual (Route Selection)and Feasibility Study

Project Data and Tasks

Chiang Mai flood protection project. Deviation of water from the Mae Ngut reservoir through TBM tunnels

- No.1 Tunnel (length: 32.6 km, diameter 4.60 m)
- No.3 Tunnel (length: 25.0 km, diameter 4.60 m)
- No.6 Tunnel (length: 28.8 km, diameter 4.60 m)
- Main Tunnel (length: 21.7 km, diameter 5.0 m)

Geological-geotechnical field studies and consulting services, supervision of site investigation, cost estimate and comparison

Geology

Paleozoic and Mesozoic shale,sandstone,limestone and Triassic granitic intrusions were subjected to intense thrusting. Tertiary tectonic events generated pull-apart-basins filled with gravels and sands

Mae Kuang Inflow Augmentation Project

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Case Studies

Mae Kuang Inflow Augmentation Project

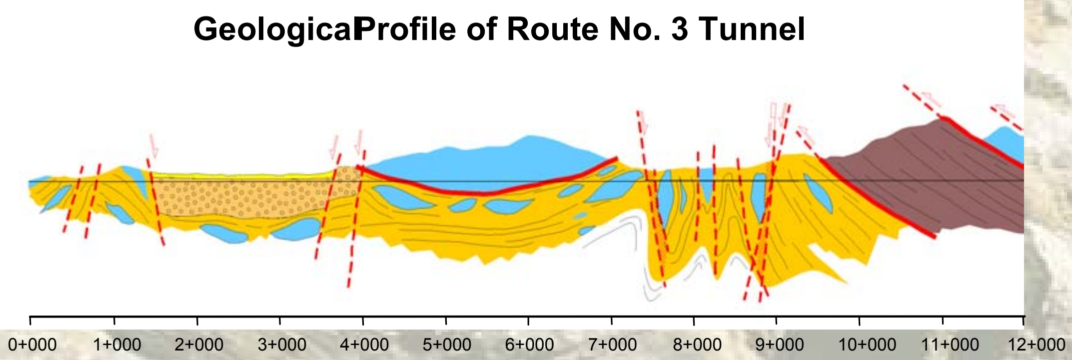
Rock Mass Type

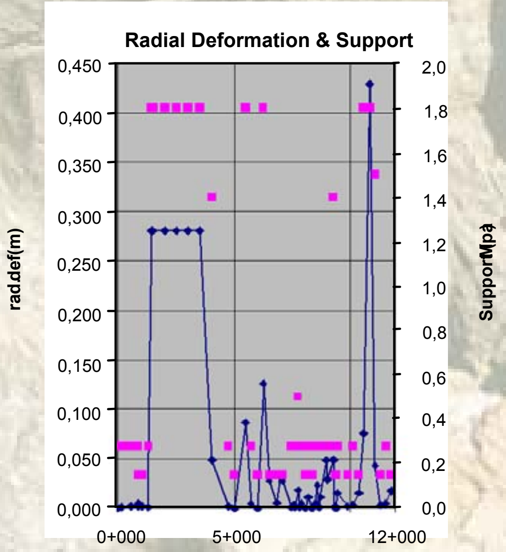
- Rock Type
- UCS
- mi
- GSI

Parameters for Analytical Calculation

Case Studies

Mae Kuang Inflow Augmentation Project

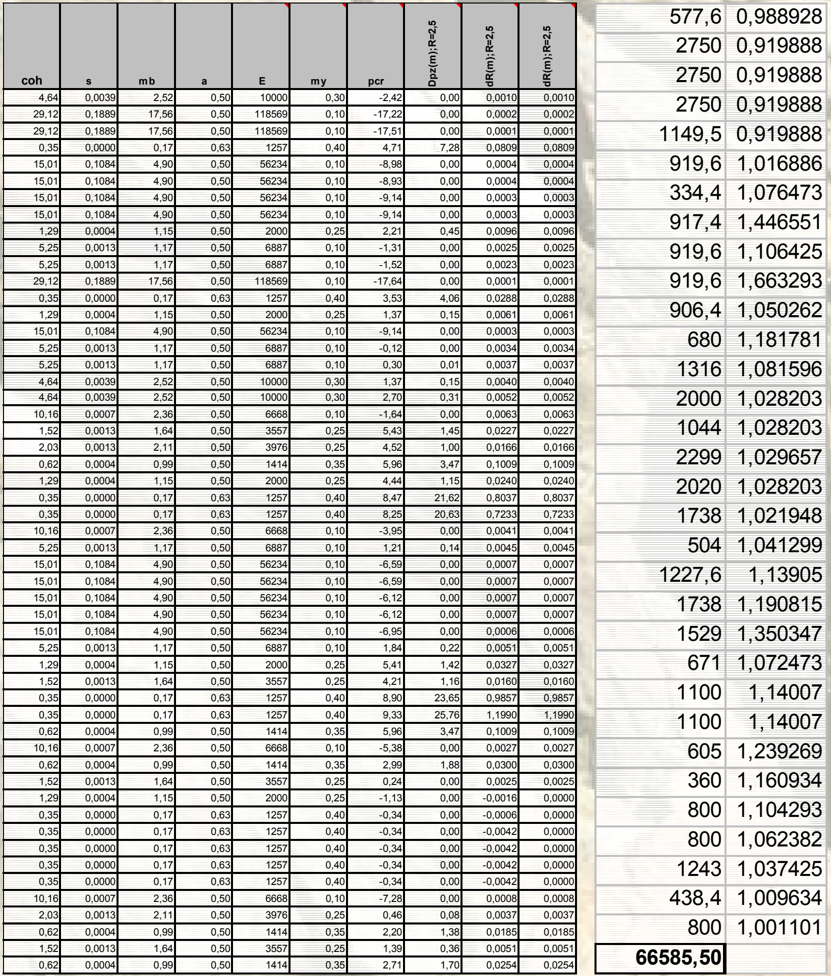

Geological Profile of Route No. 3 Tunnel


Radial Deformation & Support

Results of Analytical Calculation

Case Studies

Mae Kuang Inflow Augmentation Project



coh	s	mb	a	E	my	pcr	Dpz(m);R=2,5	dR(m);R=2,5	dR(m);R=2,5
4,64	0,0039	2,52	0,50	10000	0,30	-2,42	0,00	0,0010	0,0010
29,12	0,1889	17,56	0,50	118569	0,10	-17,22	0,00	0,0002	0,0002
29,12	0,1889	17,56	0,50	118569	0,10	-17,51	0,00	0,0001	0,0001
0,35	0,0000	0,17	0,63	1257	0,40	4,71	7,28	0,0809	0,0809
15,01	0,1084	4,90	0,50	56234	0,10	-8,98	0,00	0,0004	0,0004
15,01	0,1084	4,90	0,50	56234	0,10	-8,93	0,00	0,0004	0,0004
15,01	0,1084	4,90	0,50	56234	0,10	-9,14	0,00	0,0003	0,0003
15,01	0,1084	4,90	0,50	56234	0,10	-9,14	0,00	0,0003	0,0003
1,29	0,0004	1,15	0,50	2000	0,25	2,21	0,45	0,0096	0,0096
5,25	0,0013	1,17	0,50	6887	0,10	-1,31	0,00	0,0025	0,0025
5,25	0,0013	1,17	0,50	6887	0,10	-1,52	0,00	0,0023	0,0023
29,12	0,1889	17,56	0,50	118569	0,10	-17,64	0,00	0,0001	0,0001
0,35	0,0000	0,17	0,63	1257	0,40	3,53	4,06	0,0288	0,0288
1,29	0,0004	1,15	0,50	2000	0,25	1,37	0,15	0,0061	0,0061
15,01	0,1084	4,90	0,50	56234	0,10	-9,14	0,00	0,0003	0,0003
5,25	0,0013	1,17	0,50	6887	0,10	-0,12	0,00	0,0034	0,0034
5,25	0,0013	1,17	0,50	6887	0,10	0,30	0,01	0,0037	0,0037
4,64	0,0039	2,52	0,50	10000	0,30	1,37	0,15	0,0040	0,0040
4,64	0,0039	2,52	0,50	10000	0,30	2,70	0,31	0,0052	0,0052
10,16	0,0007	2,36	0,50	6668	0,10	-1,64	0,00	0,0063	0,0063
1,52	0,0013	1,64	0,50	3557	0,25	5,43	1,45	0,0227	0,0227
2,03	0,0013	2,11	0,50	3976	0,25	4,52	1,00	0,0166	0,0166
0,62	0,0004	0,99	0,50	1414	0,35	5,96	3,47	0,1009	0,1009
1,29	0,0004	1,15	0,50	2000	0,25	4,44	1,15	0,0240	0,0240
0,35	0,0000	0,17	0,63	1257	0,40	8,47	21,62	0,8037	0,8037
0,35	0,0000	0,17	0,63	1257	0,40	8,25	20,63	0,7233	0,7233
10,16	0,0007	2,36	0,50	6668	0,10	-3,95	0,00	0,0041	0,0041
5,25	0,0013	1,17	0,50	6887	0,10	1,21	0,14	0,0045	0,0045
15,01	0,1084	4,90	0,50	56234	0,10	-6,59	0,00	0,0007	0,0007
15,01	0,1084	4,90	0,50	56234	0,10	-6,59	0,00	0,0007	0,0007
15,01	0,1084	4,90	0,50	56234	0,10	-6,12	0,00	0,0007	0,0007
15,01	0,1084	4,90	0,50	56234	0,10	-6,12	0,00	0,0007	0,0007
15,01	0,1084	4,90	0,50	56234	0,10	-6,95	0,00	0,0006	0,0006
5,25	0,0013	1,17	0,50	6887	0,10	1,84	0,22	0,0051	0,0051
1,29	0,0004	1,15	0,50	2000	0,25	5,41	1,42	0,0327	0,0327
1,52	0,0013	1,64	0,50	3557	0,25	4,21	1,16	0,0160	0,0160
0,35	0,0000	0,17	0,63	1257	0,40	8,90	23,65	0,9857	0,9857
0,35	0,0000	0,17	0,63	1257	0,40	9,33	25,76	1,1990	1,1990
0,62	0,0004	0,99	0,50	1414	0,35	5,96	3,47	0,1009	0,1009
10,16	0,0007	2,36	0,50	6668	0,10	-5,38	0,00	0,0027	0,0027
0,62	0,0004	0,99	0,50	1414	0,35	2,99	1,88	0,0300	0,0300
1,52	0,0013	1,64	0,50	3557	0,25	0,24	0,00	0,0025	0,0025
1,29	0,0004	1,15	0,50	2000	0,25	-1,13	0,00	-0,0016	0,0000
0,35	0,0000	0,17	0,63	1257	0,40	-0,34	0,00	-0,0006	0,0000
0,35	0,0000	0,17	0,63	1257	0,40	-0,34	0,00	-0,0042	0,0000
0,35	0,0000	0,17	0,63	1257	0,40	-0,34	0,00	-0,0042	0,0000
0,35	0,0000	0,17	0,63	1257	0,40	-0,34	0,00	-0,0042	0,0000
0,35	0,0000	0,17	0,63	1257	0,40	-0,34	0,00	-0,0042	0,0000
10,16	0,0007	2,36	0,50	6668	0,10	-7,28	0,00	0,0008	0,0008
2,03	0,0013	2,11	0,50	3976	0,25	0,46	0,08	0,0037	0,0037
0,62	0,0004	0,99	0,50	1414	0,35	2,20	1,38	0,0185	0,0185
1,52	0,0013	1,64	0,50	3557	0,25	1,39	0,36	0,0051	0,0051
0,62	0,0004	0,99	0,50	1414	0,35	2,71	1,70	0,0254	0,0254

577,6	0,988928
2750	0,919888
2750	0,919888
2750	0,919888
1149,5	0,919888
919,6	1,016886
334,4	1,076473
917,4	1,446551
919,6	1,106425
919,6	1,663293
906,4	1,050262
680	1,181781
1316	1,081596
2000	1,028203
1044	1,028203
2299	1,029657
2020	1,028203
1738	1,021948
504	1,041299
1227,6	1,13905
1738	1,190815
1529	1,350347
671	1,072473
1100	1,14007
1100	1,14007
605	1,239269
360	1,160934
800	1,104293
800	1,062382
1243	1,037425
438,4	1,009634
800	1,001101
66585,50	

66585,50

Geotechnical Rating for No.3 Tunnel

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Case Studies

Mae Kuang Inflow Augmentation Project

Mae Kuang Project, 2nd Mission Report

Geotechnical Ratings:

Tunnel No.1:	**51,757**
Tunnel No.3:	**66,585**
Tunnel No.6:	**59,926**
Main Tunnel:	**32,866**

Construction costs of No. 1 Tunnel are 10% less than No.3 Tunnel

Route Selection Study

Investigation

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Case Studies

Project Data
Core piece of a new high capacity railway line which will link Styria with Carinthia. Length 32,8 km. Maximum overburden 1200 m

Tasks
Site investigation for the feasibility study and the preliminary design. Geotechnical assessment of the route corridor, route selection. Environmental impact assessment

Geology
Polymetamorphic basement consisting of gneiss, amphibolite, mica schist and marble. Development of complex fault systems, in particular at the boundaries to Tertiary basins

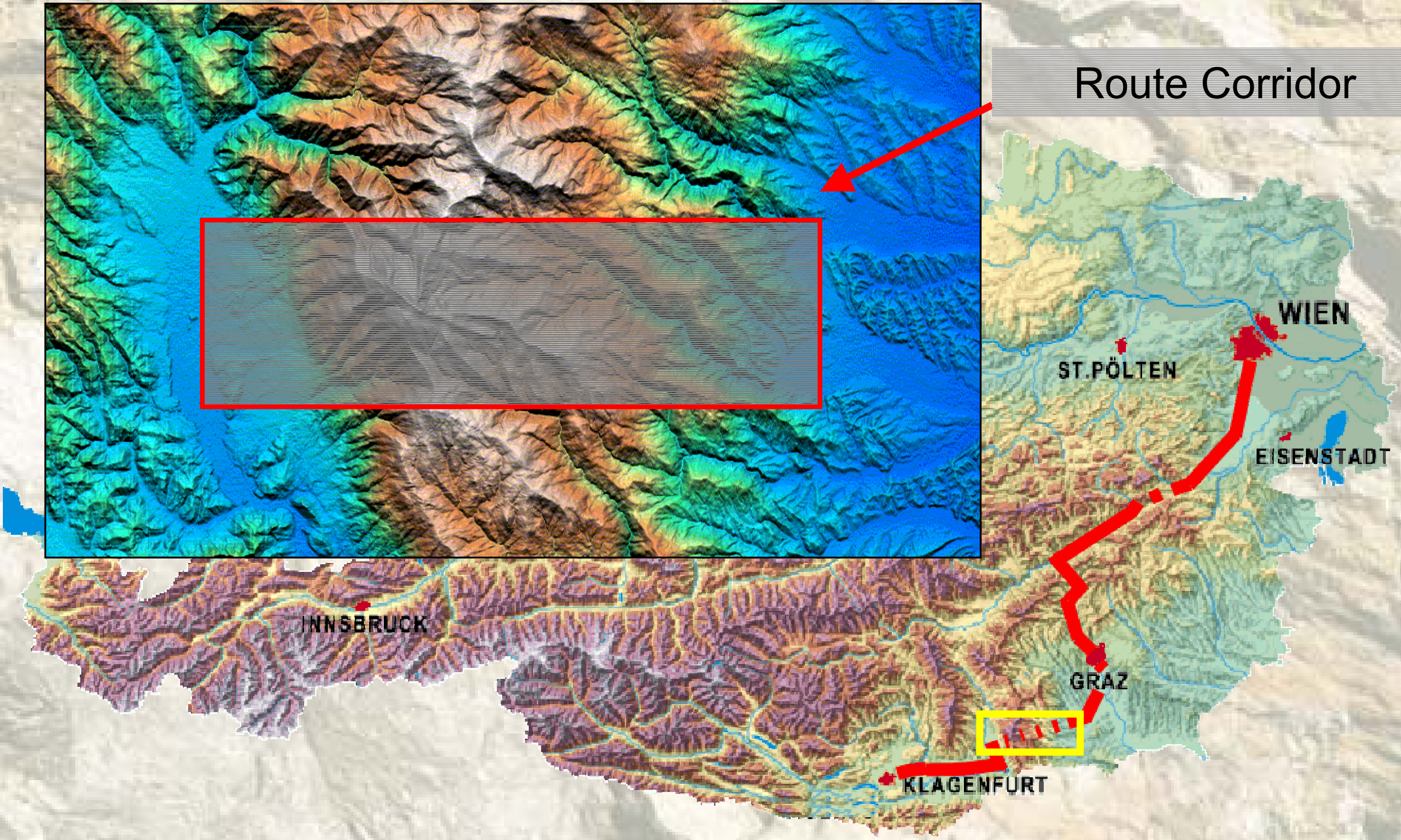
Case Studies

Preliminary Corridor Assessment

Koralm Tunnel, Austria

Case Studies

Location

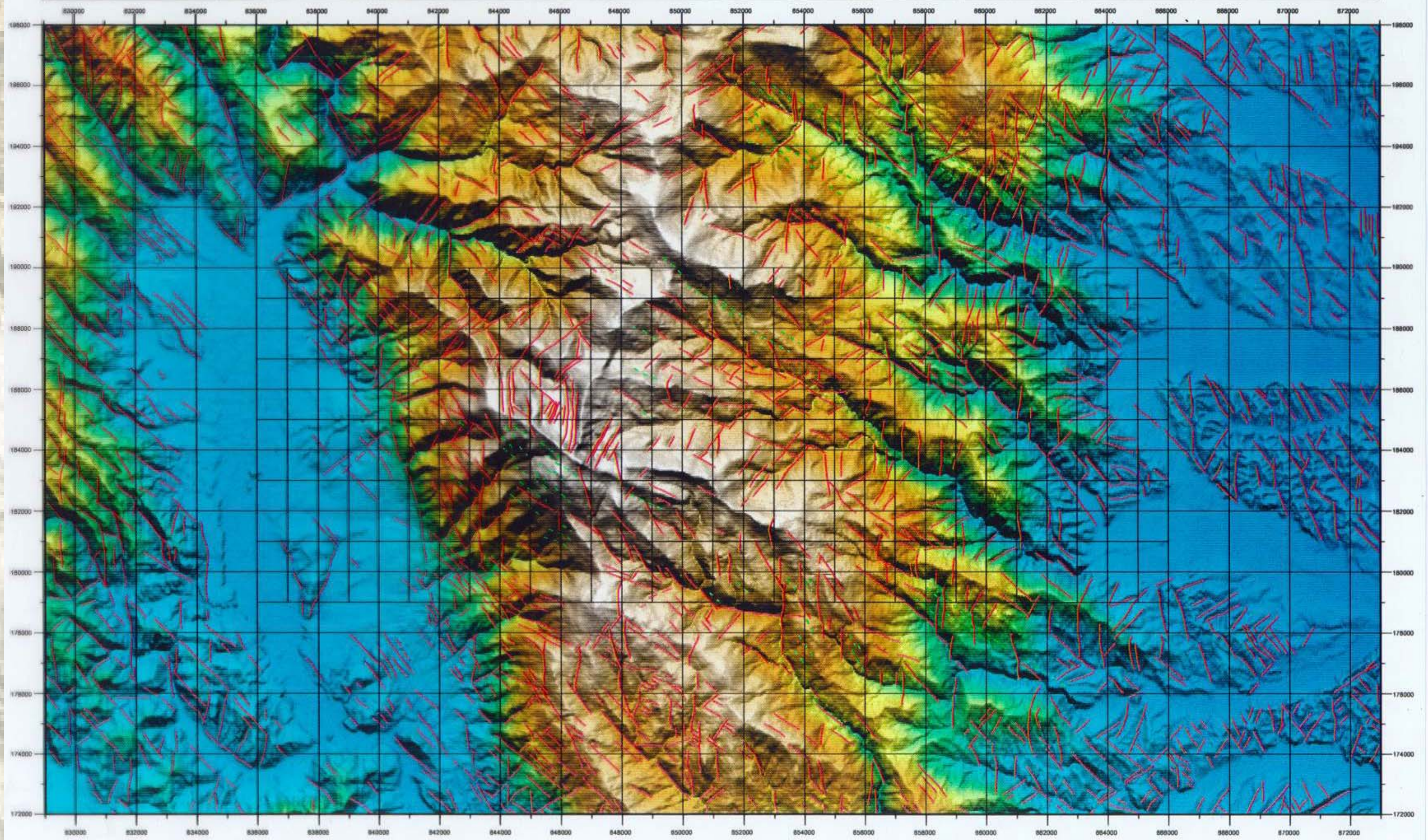


Koralm Tunnel, Austria

Case Studies

Corridor Assessment

Shaded digital elevation model overlain by fault pattern



Koralm Tunnel, Austria

Investigation

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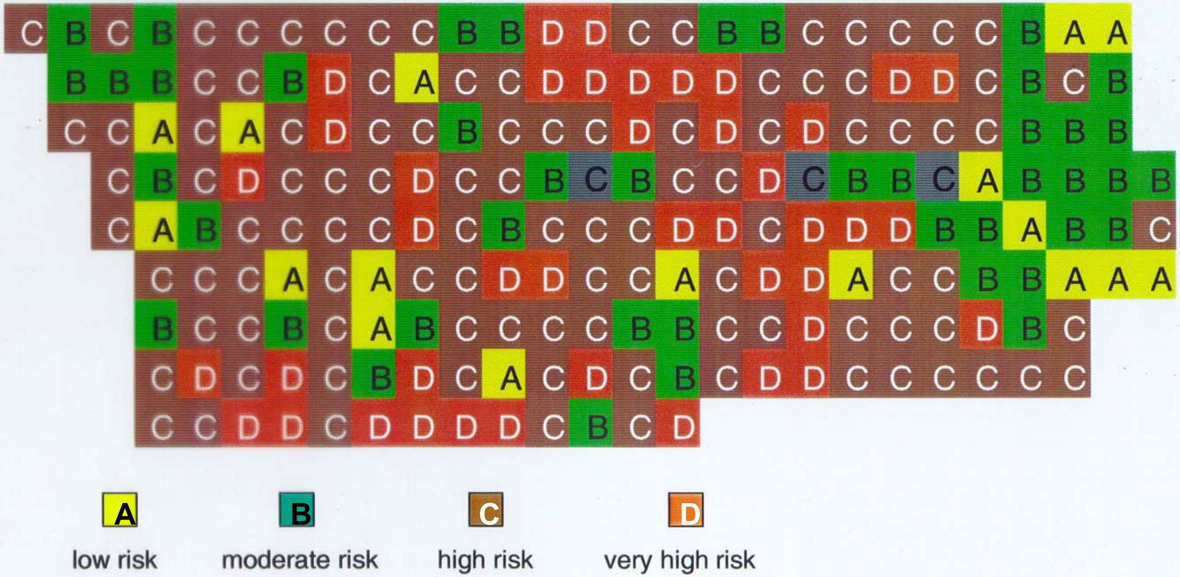
Case Studies

Corridor Assessment

$$Rating = \frac{\sum_{i=1}^{3} a_i}{b \cdot c} \cdot 10^4$$

a_1 = overburden
a_2 = lithology
a_3 = orientation of schistosity
b = faults
c = groundwater



C	B	C	B	C	C	C	C	C	C	B	B	D	D	C	C	B	B	C	C	C	C	C	B	A	A	
	B	B	B	C	C	B	D	C	A	C	C	D	D	D	D	D	C	C	C	D	D	C	B	C	B	
	C	C	A	C	A	C	D	C	C	B	C	C	C	D	C	D	C	D	C	C	C	C	B	B	B	
		C	B	C	D	C	C	C	D	C	C	B	C	B	C	C	D	C	B	B	C	A	B	B	B	B
		C	A	B	C	C	C	C	D	C	B	C	C	C	D	D	C	D	D	D	B	B	A	B	B	C
			C	C	C	A	C	A	C	C	D	D	C	C	A	C	D	D	A	C	C	B	B	A	A	A
			B	C	C	B	C	A	B	C	C	C	C	B	B	C	C	D	C	C	C	D	B	C		
			C	D	C	D	C	B	D	C	A	C	D	C	B	C	D	D	C	C	C	C	C	C		
			C	C	D	D	C	D	D	D	D	C	B	C	D											

A low risk
B moderate risk
C high risk
D very high risk

Koralm Tunnel, Austria

Case Studies

Quantitative Route Selection

- Horizontal section at tunnel level
- Grid: 500 x 500 m
- Defining key parameters
- Assigning key parameters to grid
- Determination and calculation
- Information reliability
- Information layers (GIS)

Koralm Tunnel, Austria

Investigation

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Case Studies

Quantitative Route Selection

Input Data

Mechanical data:

Intact rock

UCS, m_i, E, ν, σ_t

Anisotropic behaviour

Abrasivity

Joints **ϕ, ϕ_{rest}**

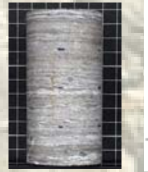
Geological data:

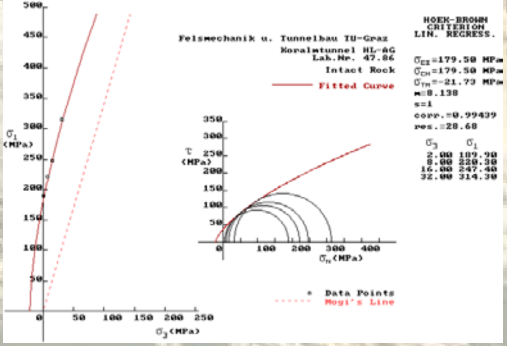
Overburden

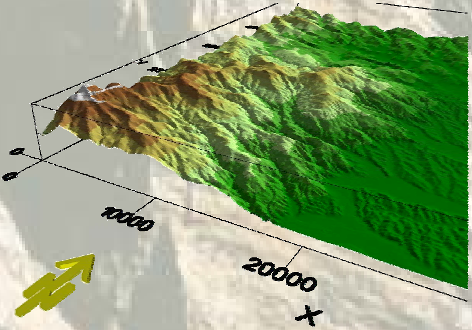
Orientation of joint sets

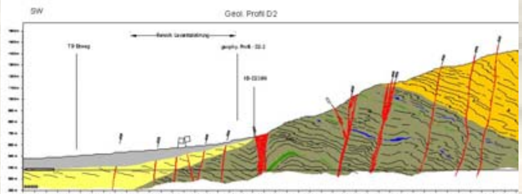
Faults

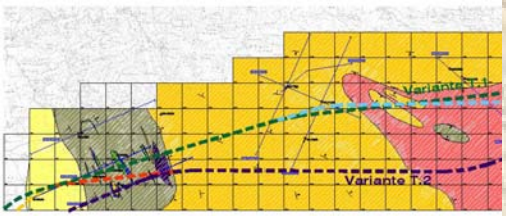
Distribution of lithological units











Koralm Tunnel, Austria

Investigation

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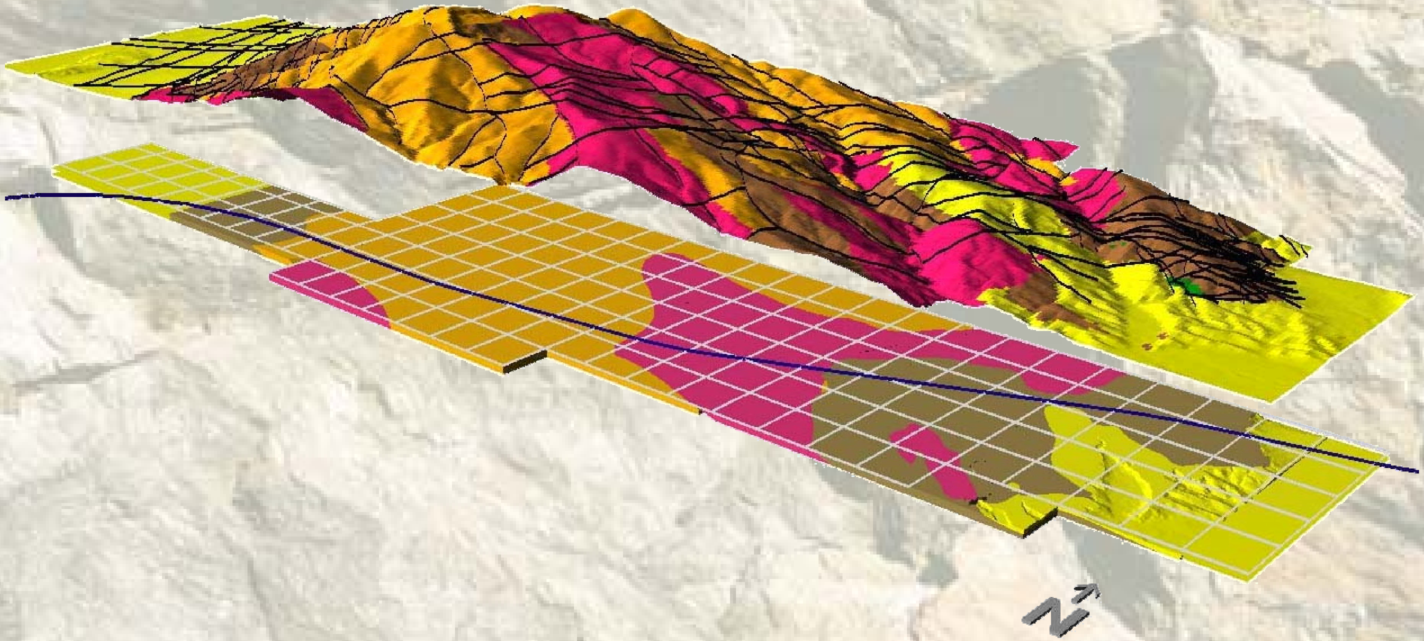
Case Studies

Quantitative Route Selection

Input: Geological Architecture



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Investigation

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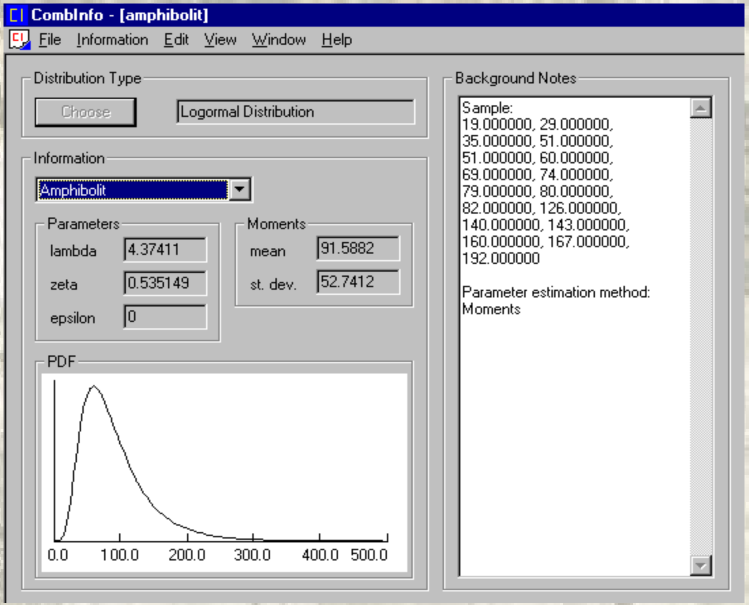
Case Studies

Quantitative Route Selection

Input: Mechanical Data

Laboratory data



CombInfo - [amphibolit]

Distribution Type: Logormal Distribution

Information: Amphibolit

Parameters

lambda	4.37411
zeta	0.535149
epsilon	0

Moments

mean	91.5882
st. dev.	52.7412

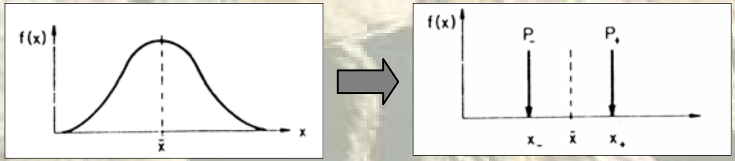
Background Notes

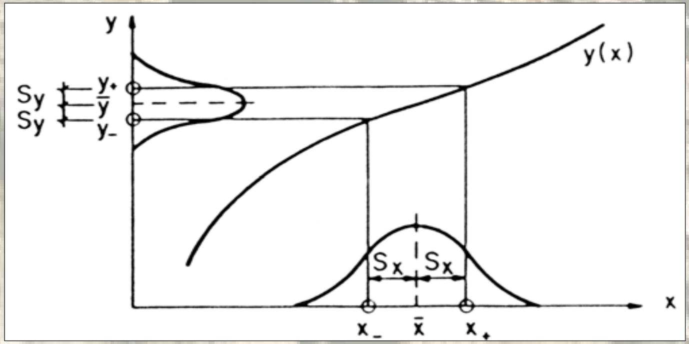
Sample:
19.000000, 29.000000,
35.000000, 51.000000,
51.000000, 60.000000,
69.000000, 74.000000,
79.000000, 80.000000,
82.000000, 126.000000,
140.000000, 143.000000,
160.000000, 167.000000,
192.000000

Parameter estimation method:
Moments

Probability Analysis

(Point Estimation Method, Rosenblueth)





Functions with several variables

Integration formulas

Permutations from n+1 to $2n^2+1$

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Investigation

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Case Studies

Quantitative Route Selection

Input: Fault Geometry

Geometrical conditions

$$L_{fault} = 3 * \left(\frac{D}{\tan \alpha} + \frac{1}{\sin \alpha} \right)$$

Probability of intersecting a fault

$$P(f) = \frac{L_{fault} * \sin \alpha}{500}$$

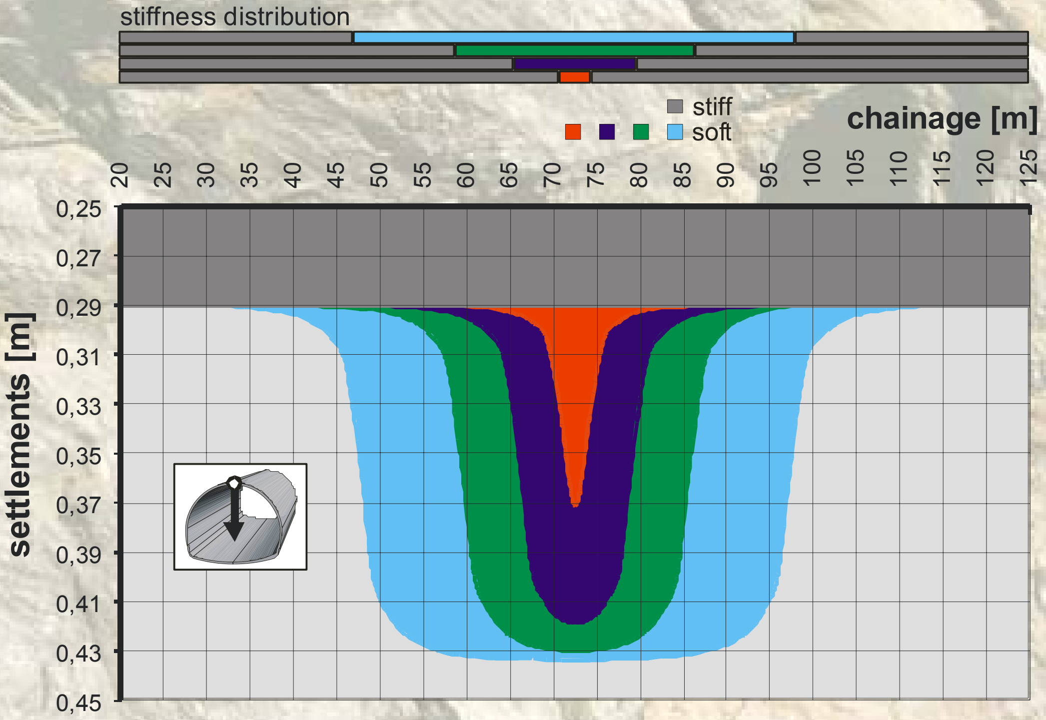
Koralm Tunnel, Austria

Case Studies

Quantitative Route Selection

Calculation of Settlements (E. Hoek)

Undisturbed (stiff) and Faulted Rock Mass (soft)



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Investigation

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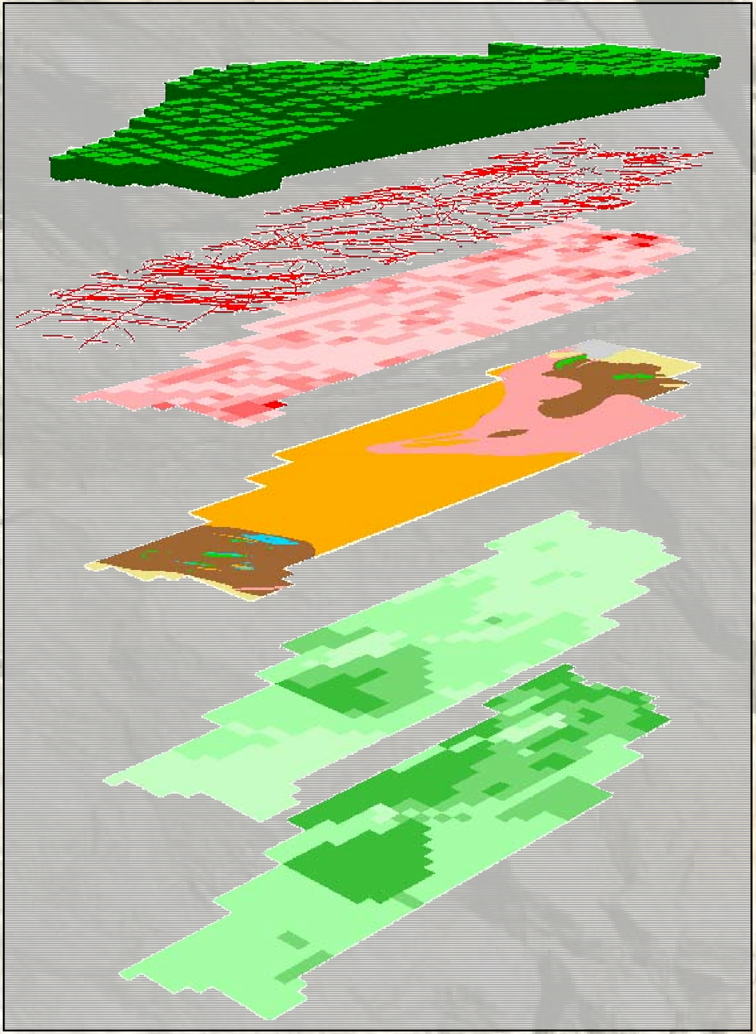
Case Studies

Quantitative Route Selection

Input Layers for GIS Based Analysis of Radial Deformation



← **Overburden**

← **Faults**

← **Fault Influenced Excavation Length**

← **Lithology**

← **Rock Mass Strength**

⇩ ⇩

← **Radial Deformation**

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Investigation

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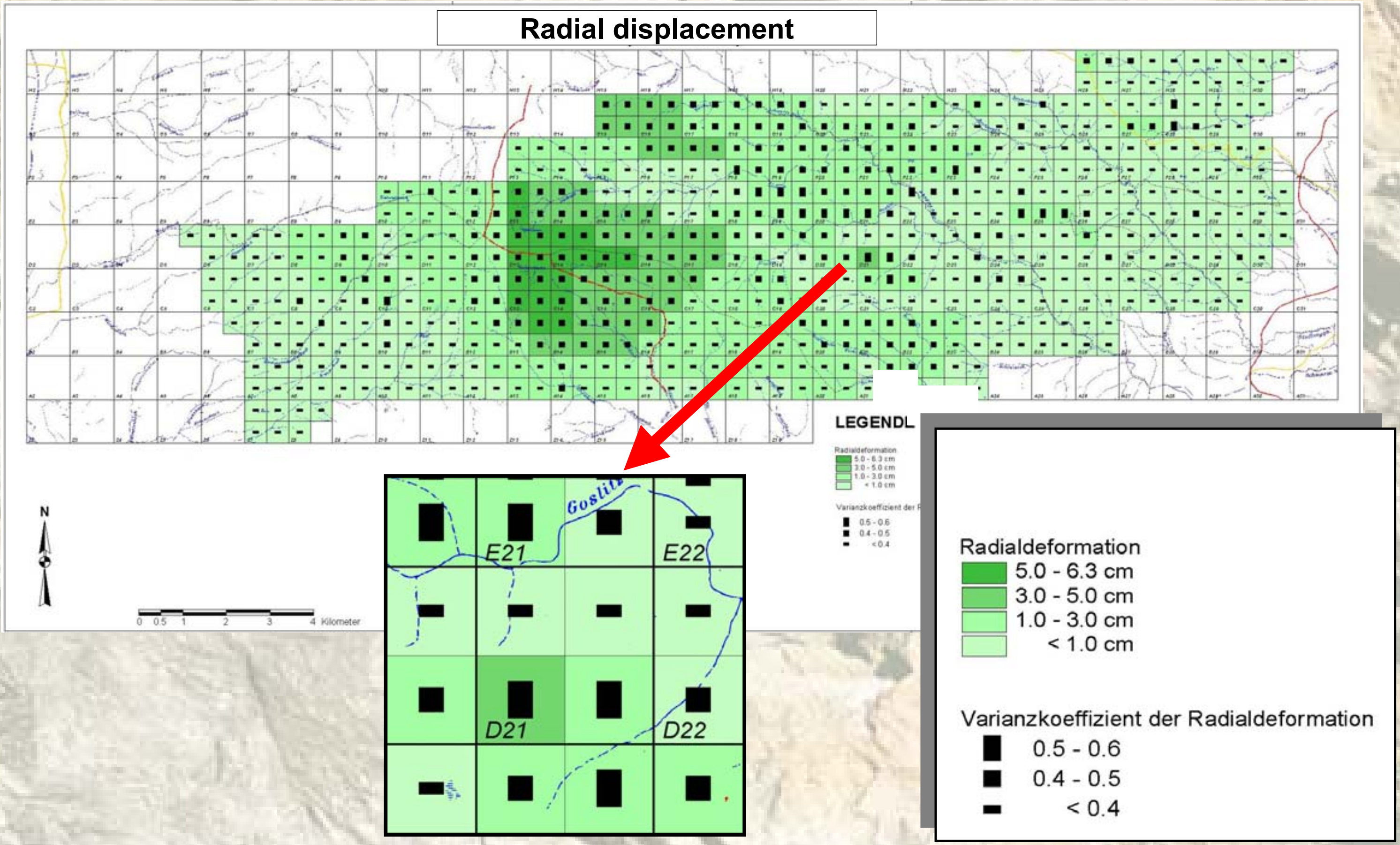
Case Studies

Quantitative Route Selection

Result Layer: Radial Deformation

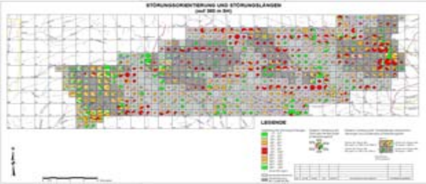


Koralm Tunnel, Austria

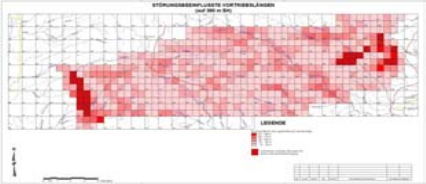
Case Studies

Quantitative Route Selection

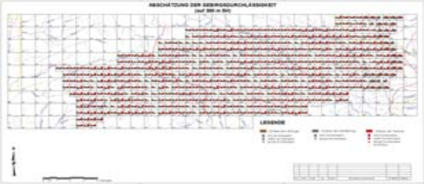
Input Layers



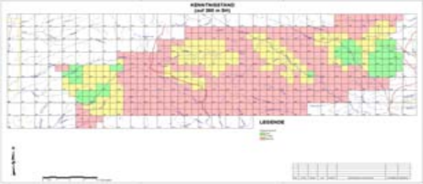
Faults, orientation, total lengths



Faults, excavation lengths

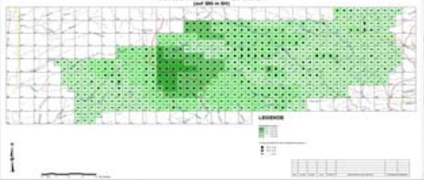


Permeability

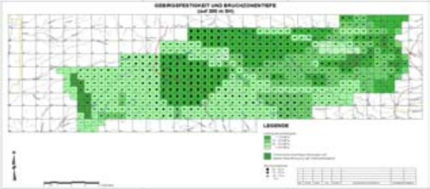


Information reliability

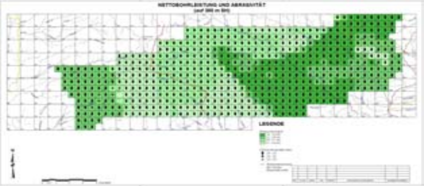
Result Layers



Depths of broken zone



Radial displacement



Penetration rate
(TBM and rock mass data)

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Investigation

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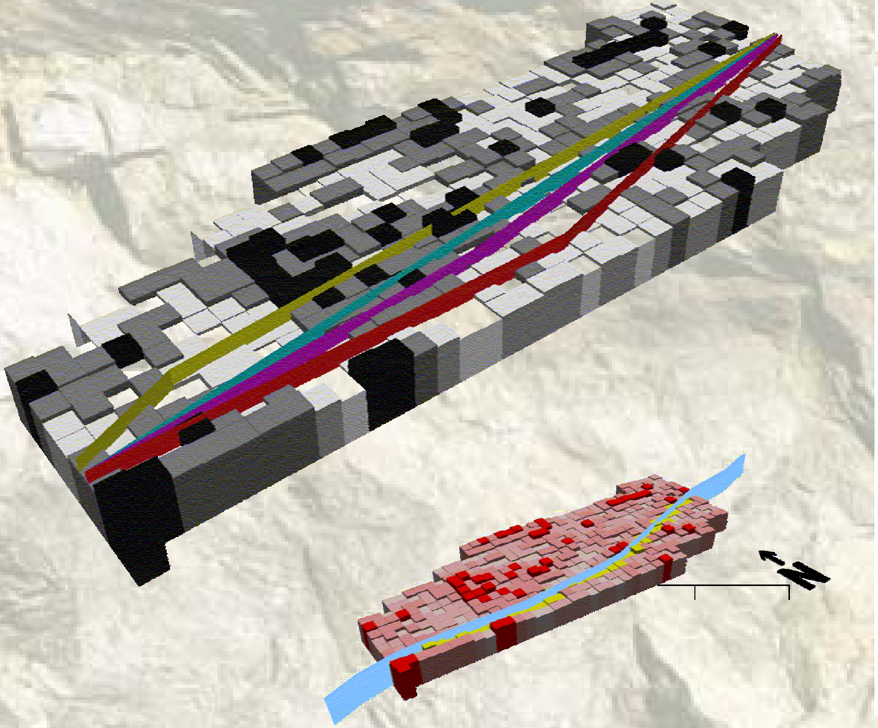
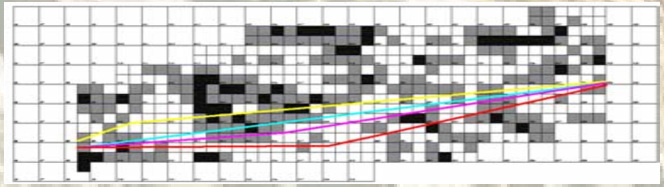
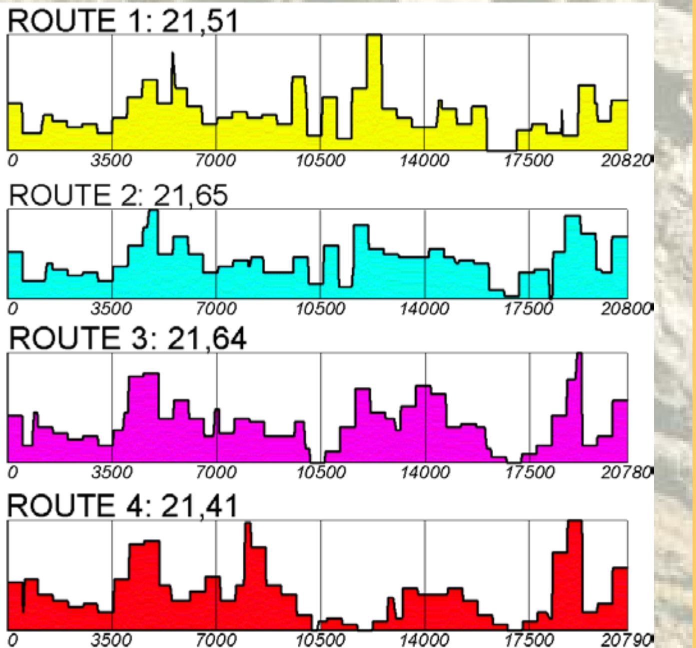
Case Studies

Quantitative Route Selection

Results







Koralm Tunnel, Austria

Investigation

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Case Studies

Preliminary Design

Geological 3D-Modelling

Objectives:

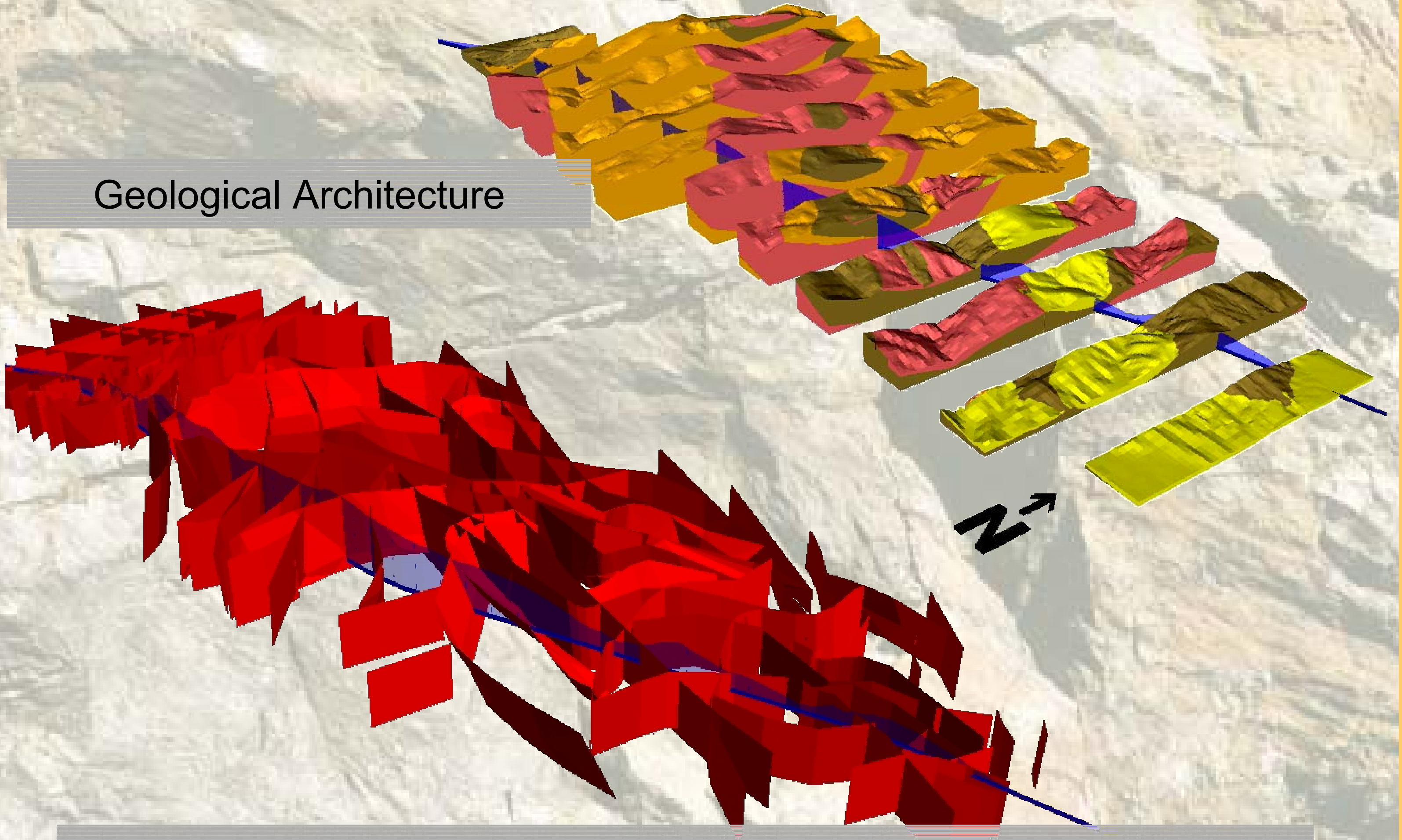
- Reliability of Geological Architecture
- Assessment of Groundwater Models
- Assessment of Tunnel-Groundwater Interactions
- Estimate of In-Situ Rock Temperatures
- Optimization of Further Site Investigations

Koralm Tunnel, Austria

Case Studies

Preliminary Design

Geological Architecture

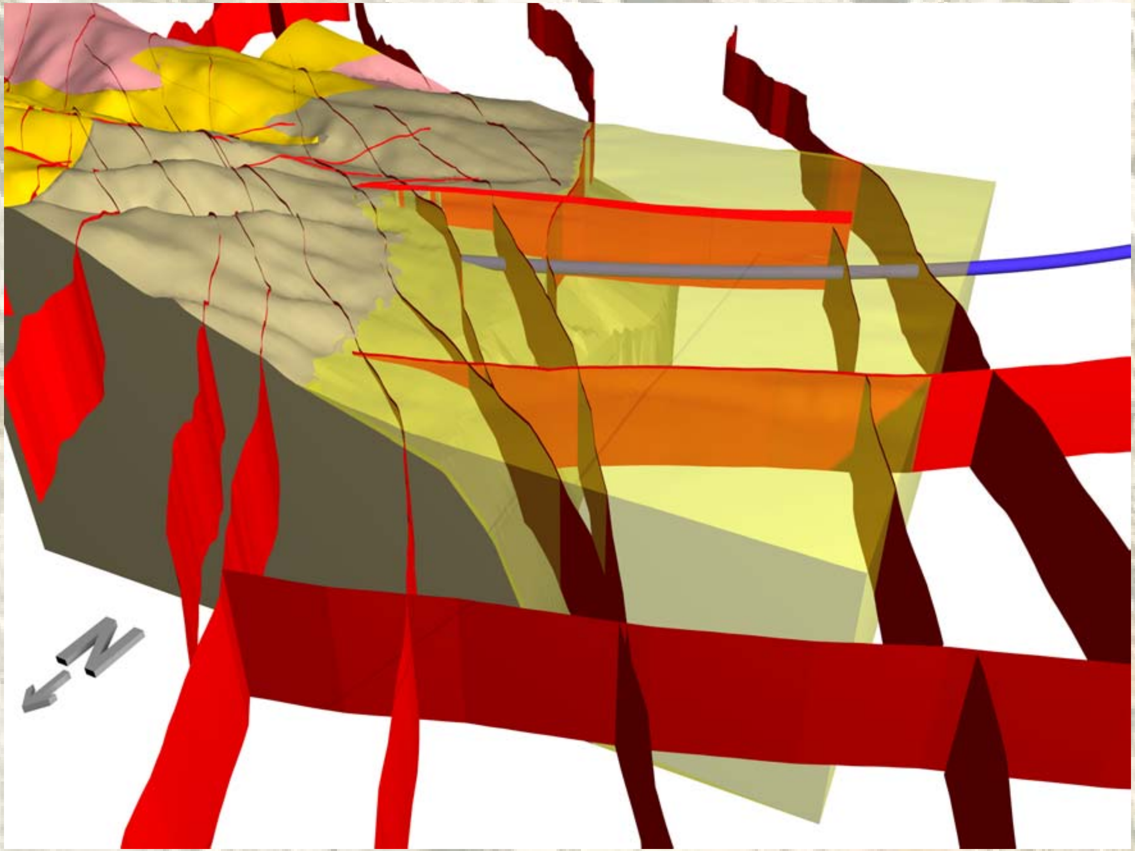


Koralm Tunnel, Austria

Case Studies

Preliminary Design

Geological 3D-Modelling



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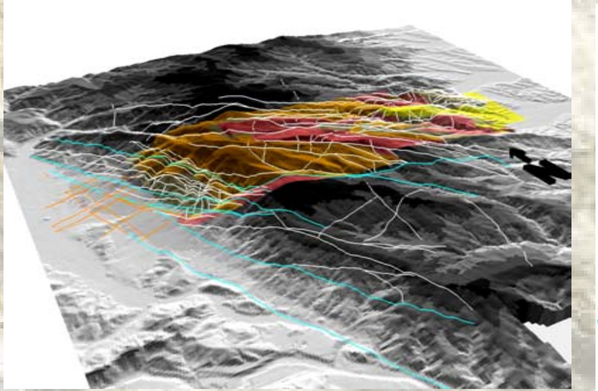
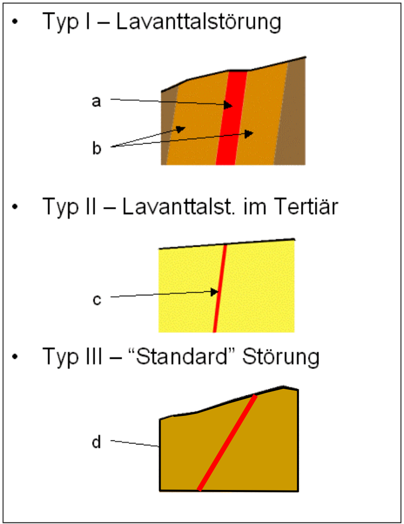
Case Studies

Investigation

Preliminary Design





- Typ I – Lavanttalstörung
- Typ II – Lavanttalst. im Tertiär
- Typ III – "Standard" Störung

Hydraulic Fault Zone Definitions (modified after Caine et al. 1996)

Typ I, Major Strike-Slip Fault in Crystalline Basement

Well-developed Fault Core (predominantly M- and C- cataclasites) with low permeability) surrounded by high permeable Fracture Zone (G- and S-cataclasite) and Blocky Rock Mass

Typ II Major Strike-Slip Fault in Tertiary Clastic Sediments

Fault Core poorly developed. No Fracture Zones

Typ III Normal Fault in Crystalline Basement

Fault Core poorly developed. Well-developed Fracture Zone associated with high permeable fracture network

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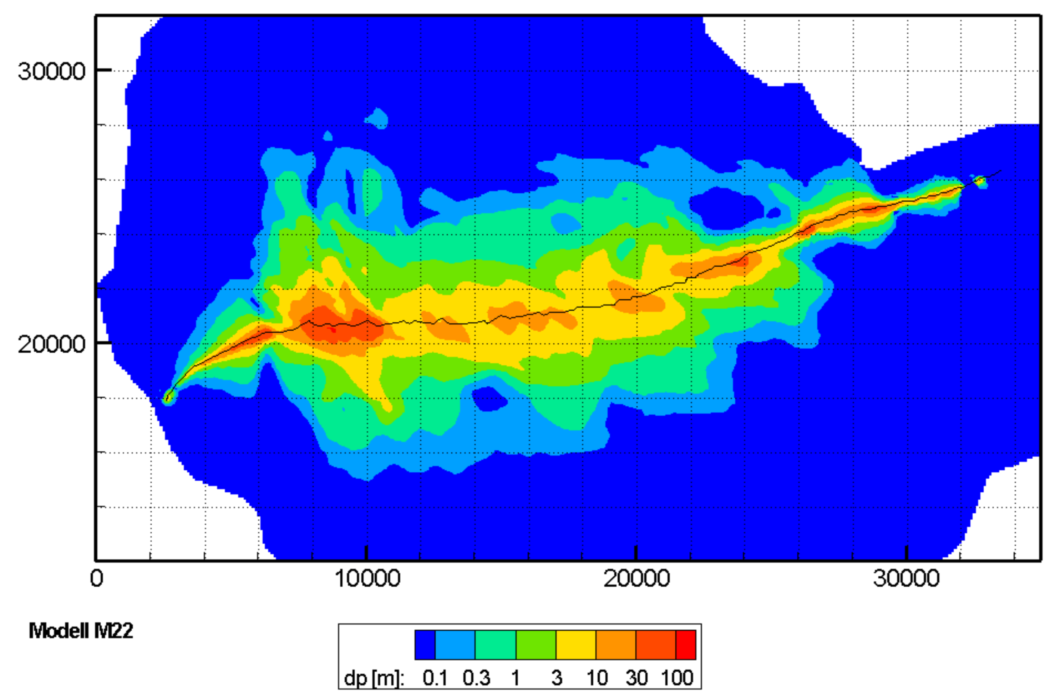
Case Studies

Preliminary Design

Hydraulic Model, maximum possible lowering of the groundwater table



Conservative Model (1D Hydraulic Flow)

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Investigation

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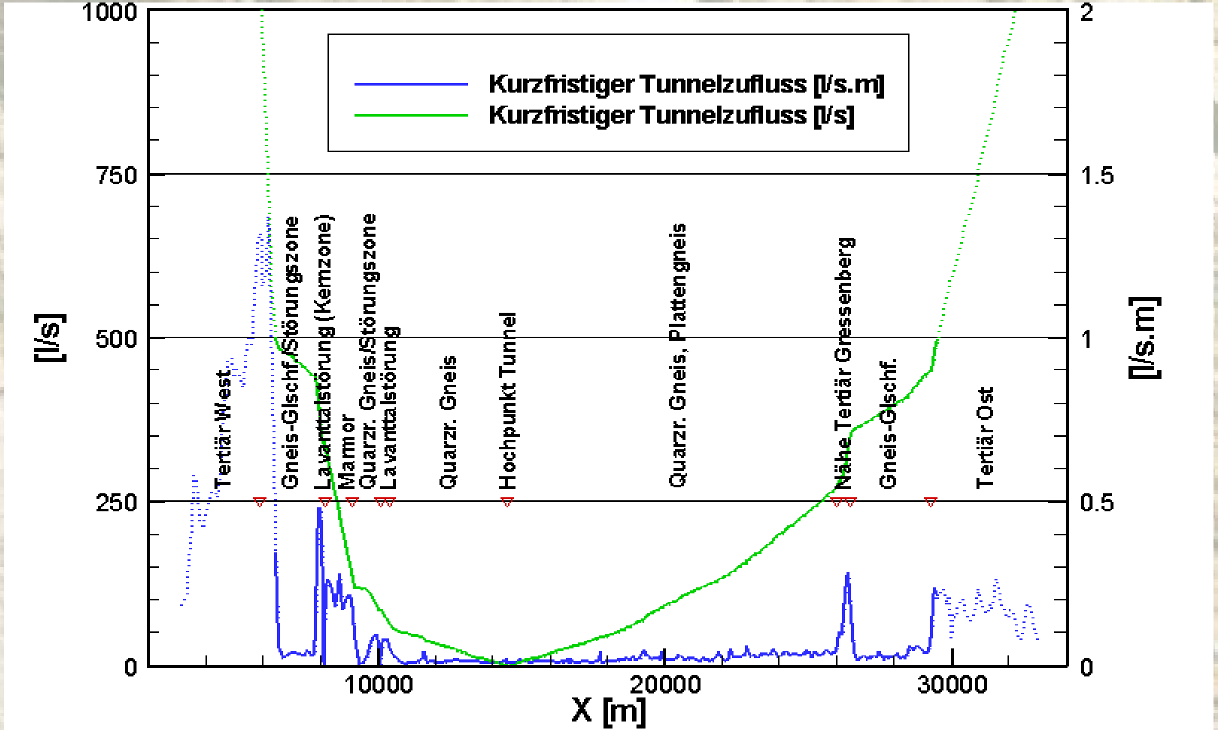
Case Studies

Preliminary Design

Predicted Short-Term Inflows During Tunnel Excavation



Boundary Conditions: (1) Groundwater at Surface (2) Recharge unlimited

Koralm Tunnel, Austria

Case Studies

Assessment of Geotechnical Risk

Input

Geological model

- Geological architecture
- Lithology
- Discontinuities
- Fault zones
- Groundwater

Rock mass characterization

- Key parameters
- Influencing factors

Investigation

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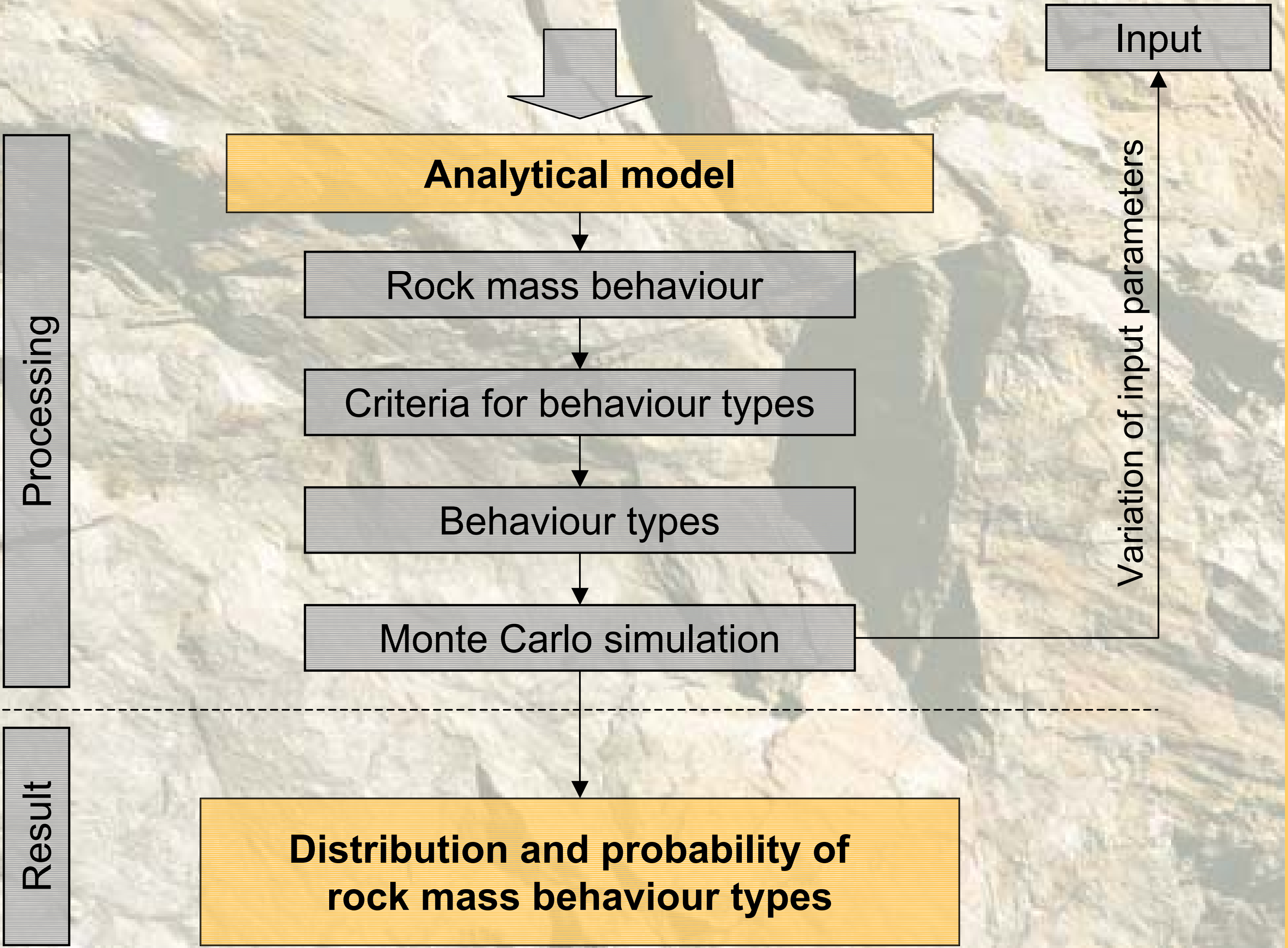
Case Studies

Assessment of Geotechnical Risk



Input

Analytical model

Rock mass behaviour

Criteria for behaviour types

Behaviour types

Monte Carlo simulation

Variation of input parameters

Processing

Result

Distribution and probability of rock mass behaviour types

Case Studies

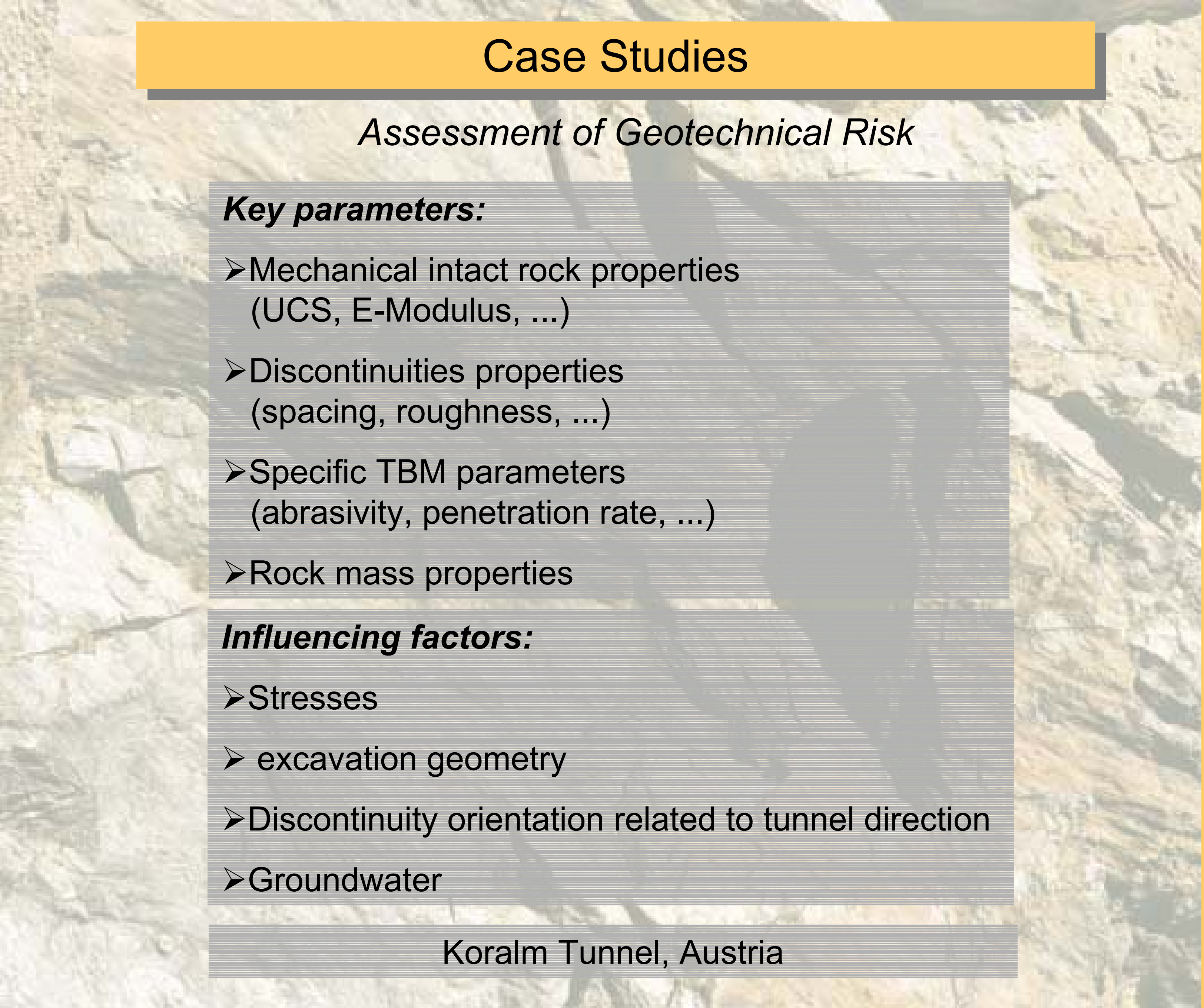
Assessment of Geotechnical Risk

Key parameters:

- Mechanical intact rock properties
  (UCS, E-Modulus, ...)
- Discontinuities properties
  (spacing, roughness, ...)
- Specific TBM parameters
  (abrasivity, penetration rate, ...)
- Rock mass properties

Influencing factors:

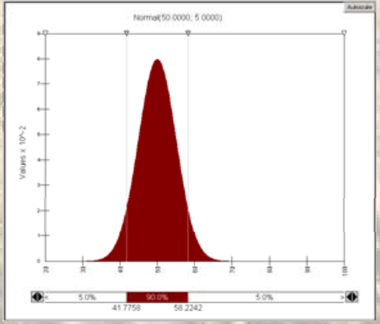
- Stresses
- excavation geometry
- Discontinuity orientation related to tunnel direction
- Groundwater



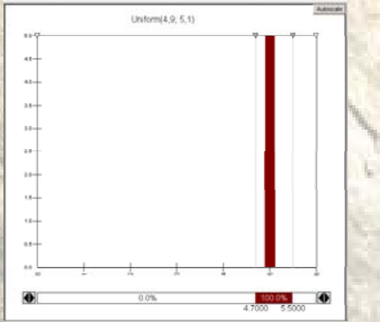
Koralm Tunnel, Austria

Case Studies

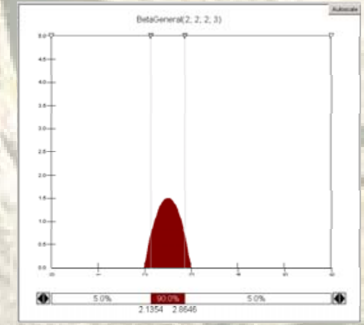
Assessment of Geotechnical Risk



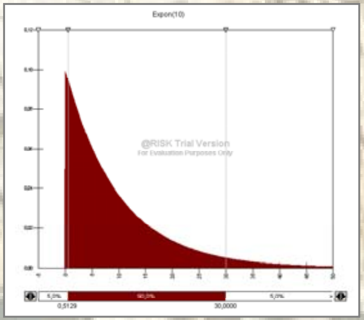
UCS



Tunnel diameter

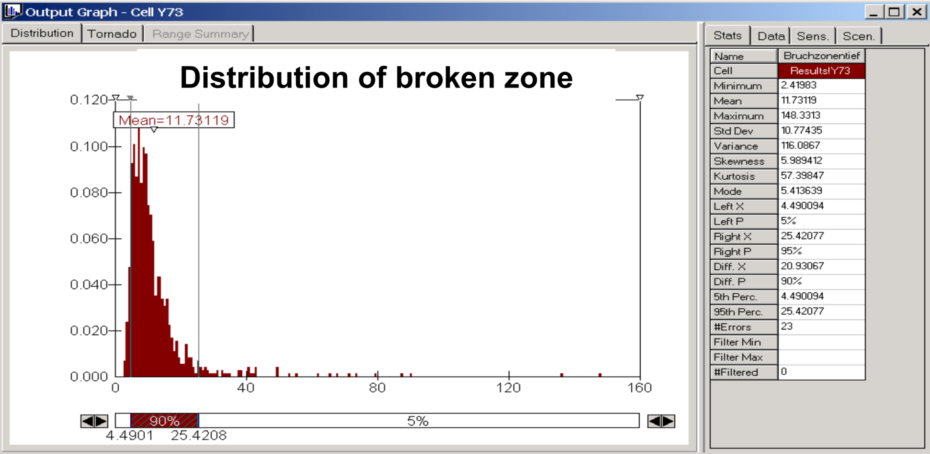


Principal stresses



Spacing

Input



Distribution of broken zone

Mean=11.73119

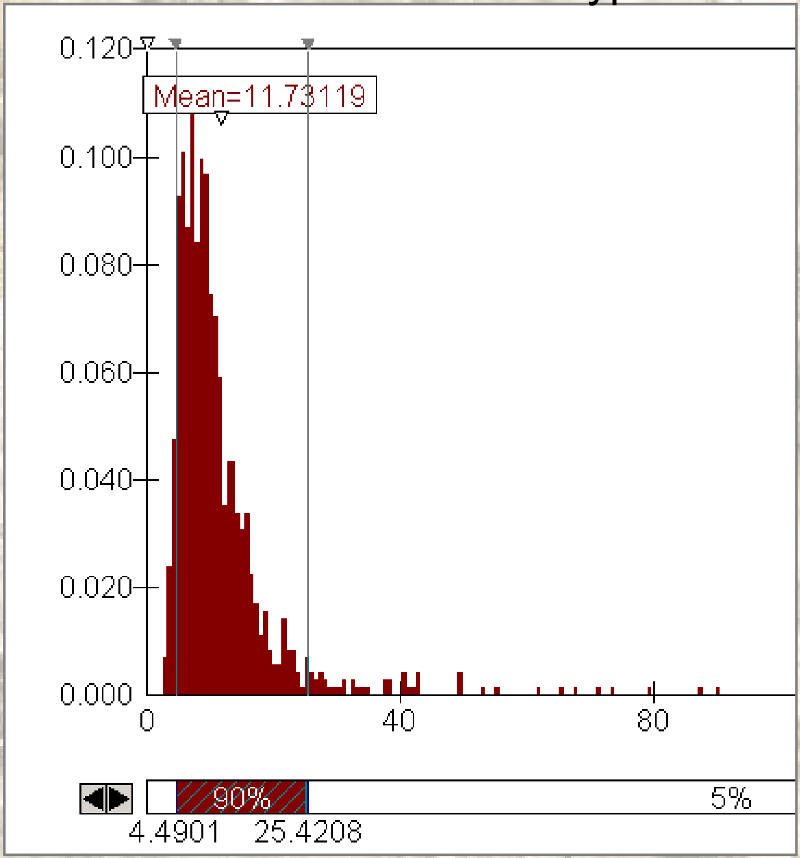
Name	Bruchzonentief
Cell	Results!Y73
Minimum	2.41983
Mean	11.73119
Maximum	148.3313
Std Dev	10.77435
Variance	116.0867
Skewness	5.989412
Kurtosis	57.39847
Mode	5.413639
Left X	4.490094
Left P	5%
Right X	25.42077
Right P	95%
Diff. X	20.93067
Diff. P	90%
5th Perc.	4.490094
95th Perc.	25.42077
#Errors	23
Filter Min	
Filter Max	
#Filtered	0

Koralm Tunnel, Austria

Case Studies

Assessment of Geotechnical Risk

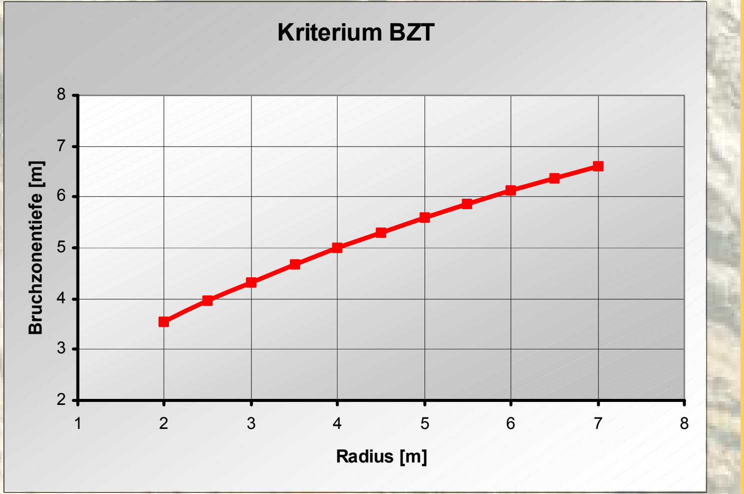
Criteria for the determination of rock mass behaviour types



Criteria

$$DBZ = f(R)$$

$$DBZ > D \times \left(\frac{2{,}5}{R^{0{,}5}} \times 0.5_{(inp)} \right)$$



Koralm Tunnel, Austria

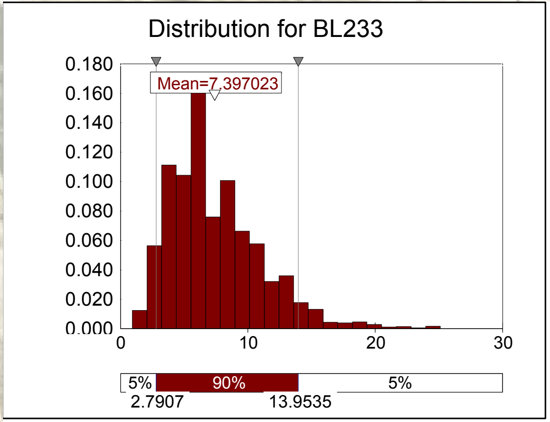
Investigation

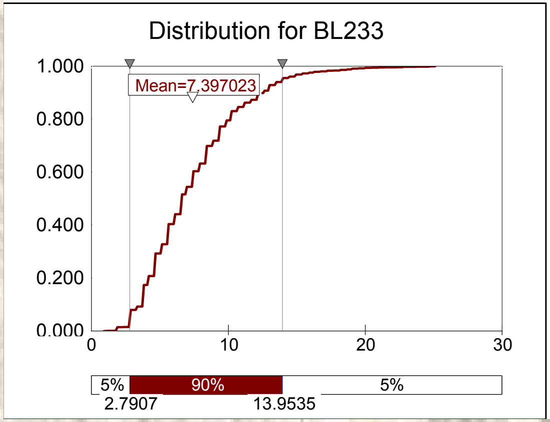
Gruppe Geotechnik Graz ZT GMBH

Case Studies

Assessment of Geotechnical Risk

Distribution of a behaviour type calculated for a tunnel section


Distribution for BL233


Distribution for BL233

Summary Information	
Workbook Name	T-Pilotstollen-Risikoanaly
Number of Simulations	1
Number of Iterations	5000
Number of Inputs	175
Number of Outputs	38
Sampling Type	Latin Hypercube
Simulation Start Time	01.05.2002 14:34
Simulation Stop Time	01.05.2002 14:39
Simulation Duration	00:05:11
Random Seed	1808478211

Summary Statistics			
Statistic	Value	%tile	Value
Minimum	0,930232584	5%	2,790697575
Maximum	25,1162796	10%	3,720930338
Mean	7,39702322	15%	3,720930338
Std Dev	3,647360066	20%	4,1860466
Variance	13,30323545	25%	4,651162624
Skewness	1,148729854	30%	5,116279125
Kurtosis	4,876067642	35%	5,581395149
Median	6,511627674	40%	5,581395149
Mode	4,651162624	45%	6,511627674
Left X	2,790697575	50%	6,511627674
Left P	5%	55%	7,441860676
Right X	13,95348835	60%	7,441860676
Right P	95%	65%	8,372093201
Diff X	11,16279078	70%	8,837209702
Diff P	90%	75%	9,302325249
#Errors	0	80%	10,23255825
Filter Min		85%	11,1627903
Filter Max		90%	12,5581398
#Filtered	0	95%	13,95348835

Koralm Tunnel, Austria

Case Studies

Assessment of Geotechnical Risk

Distribution and probability of rock mass behaviour types

calc. segment

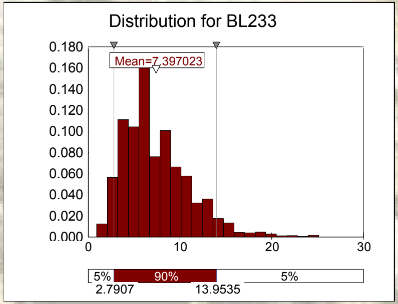
Assignment of excavation and support to behaviour types

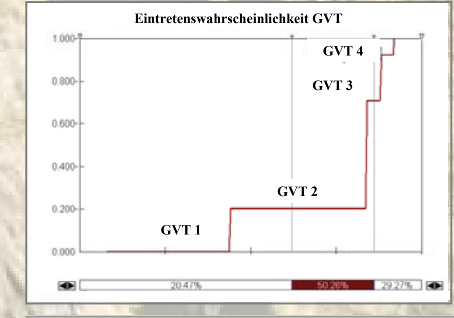
Assessment of time and costs

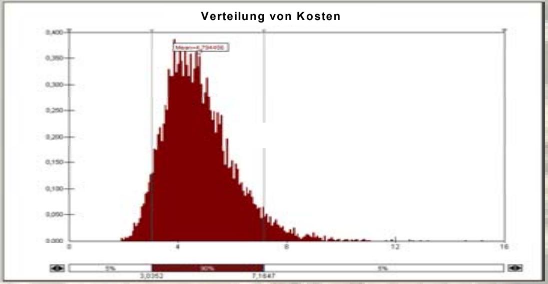
Tunnel

Distribution of time and costs

Time and costs







Koralm Tunnel, Austria

Investigation

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Case Studies

Preliminary Design

Project Data
Part of the Egnatia Motorway which will connect the towns Igoumenitsa at the Adriatic Sea and Thessaloniki at the Agean Sea. Double tube two lane tunnel.
Length 2100 m, maximum overburden 230 m

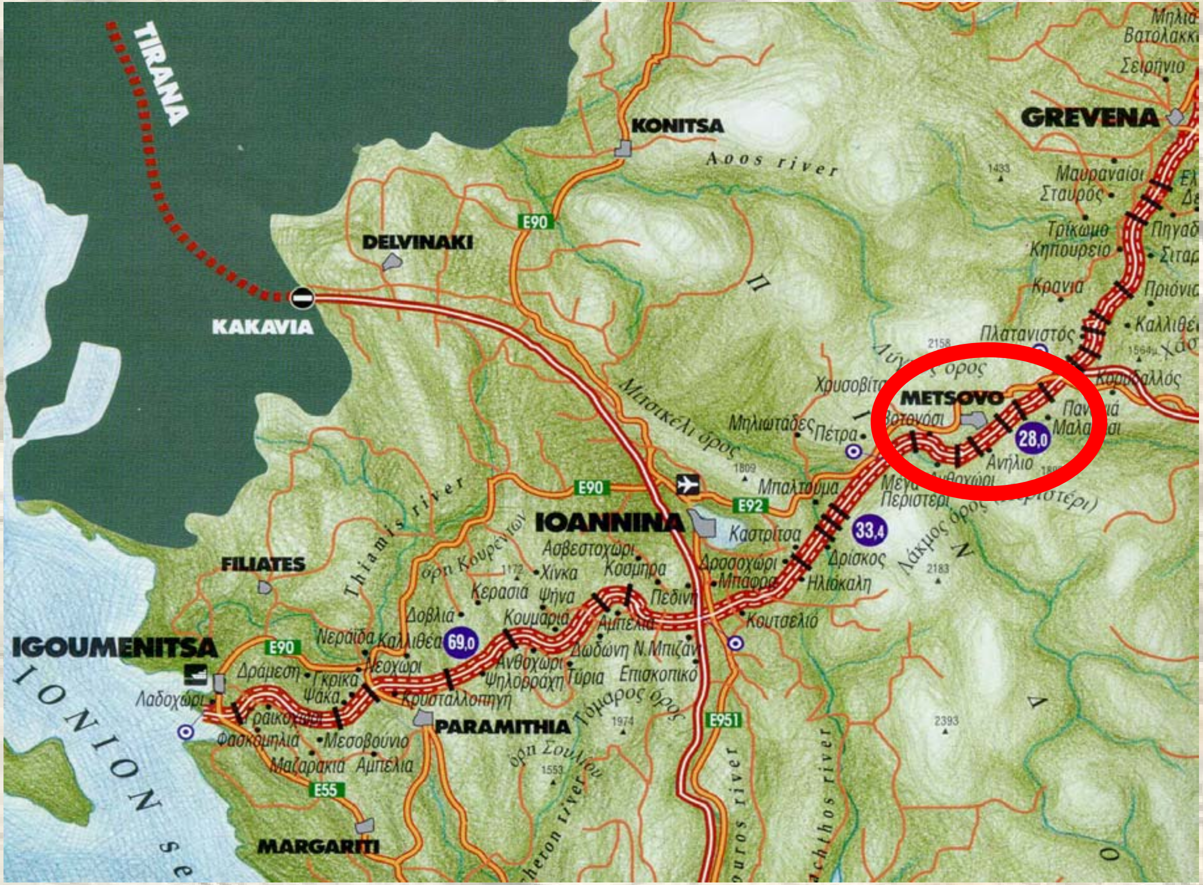
Tasks
Geological alignment mapping. Assessment of rock mass behaviour and support for the preliminary and detail design.
Consulting service during construction

Geology
Complex fold-thrust belt in Tertiary flysch sequences.
Development of thick tectonic melanges with clayey gouges

Egnatia Motorway, Anilio Tunnel (Greece)

Case Studies

Location

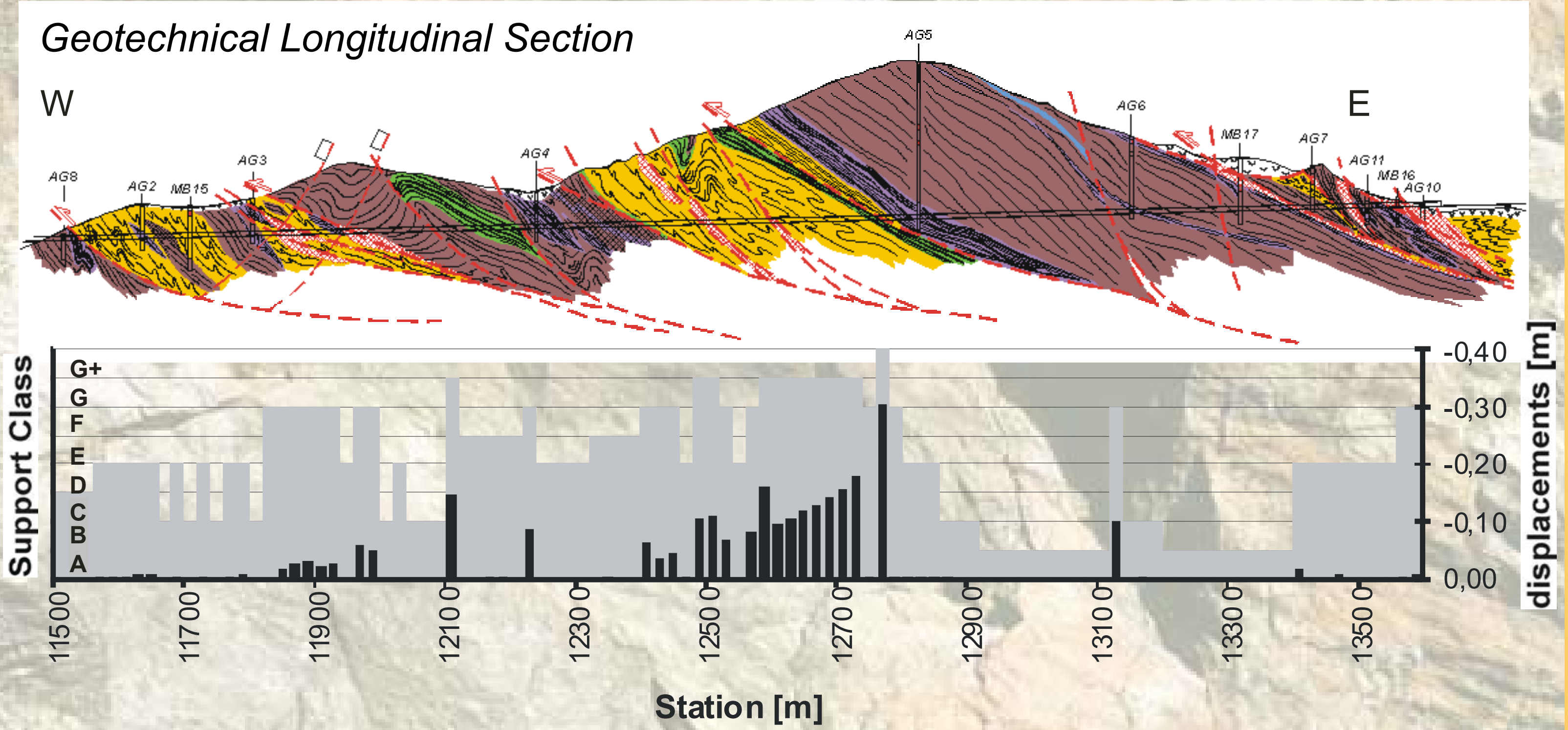


Egnatia Motorway, Anilio Tunnel (Greece)

Case Studies

Investigation

Preliminary Design



Geotechnical Longitudinal Section

Egnatia Motorway, Anilio Tunnel (Greece)

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Case Studies

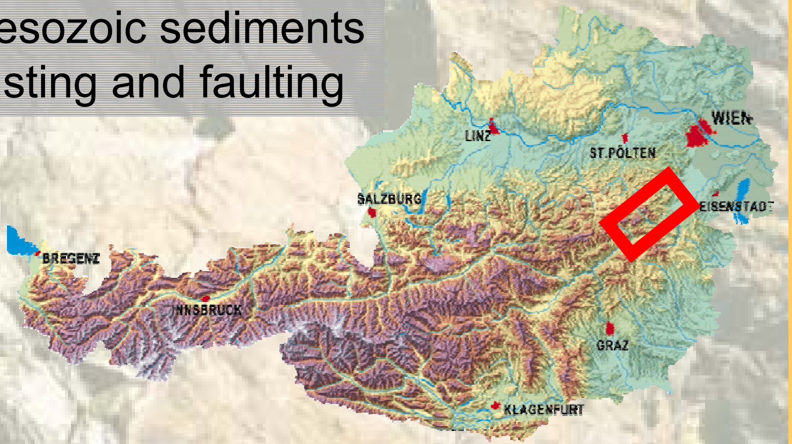
Detail Design

Project Data
Core piece of Austrian‘s high speed railway project.
Length 22 km, maximum overburden 900 m

Tasks
Geological-geotechnical site investigations from the feasibility study to the detail design. Geotechnical risk assessment for TBM excavation.
Investigation of alternative systems (double track tube with emergency tunnel versus two single track tubes).

Geology
Polymetamorphic basement rocks and low-grade metamorphic Paleozoic as well as Mesozoic sediments were subjected to intense Alpine thrusting and faulting

Semmering Base Tunnel, Austria



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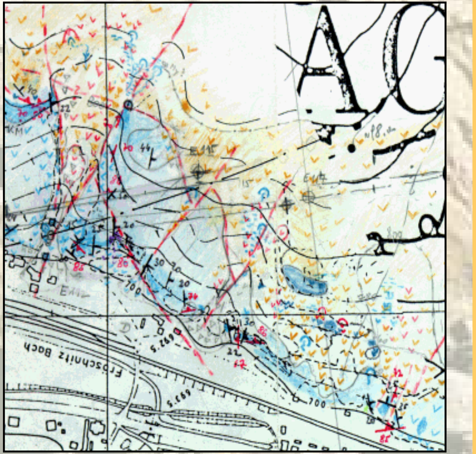
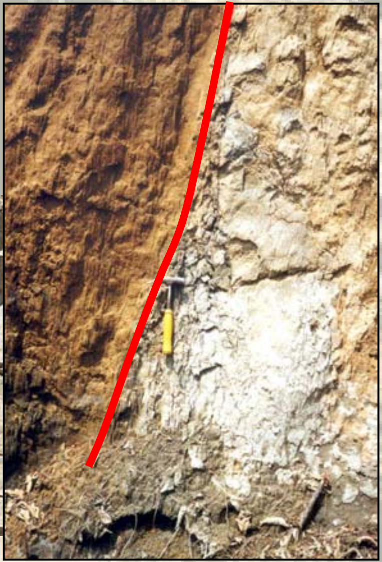
Case Studies

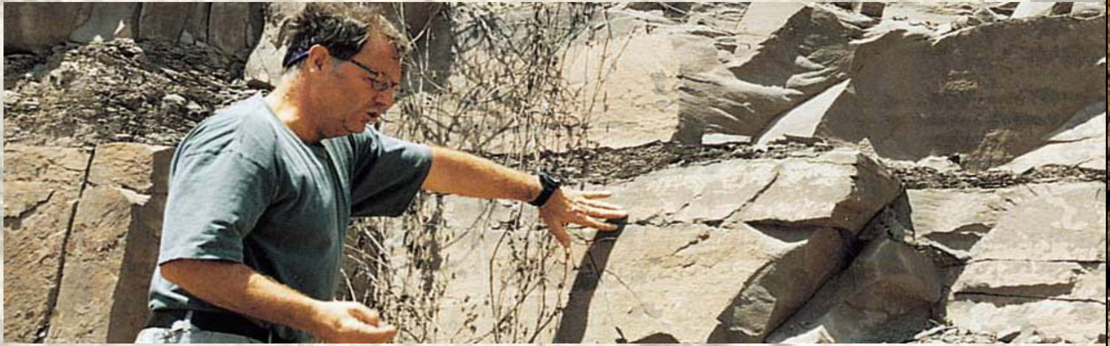
Site Investigation

Engineering geological mapping

- Identification of relevant morphological features
- Outcrop Studies
- Identification and characterisation of fault zones
- Assessment of seeps and springs





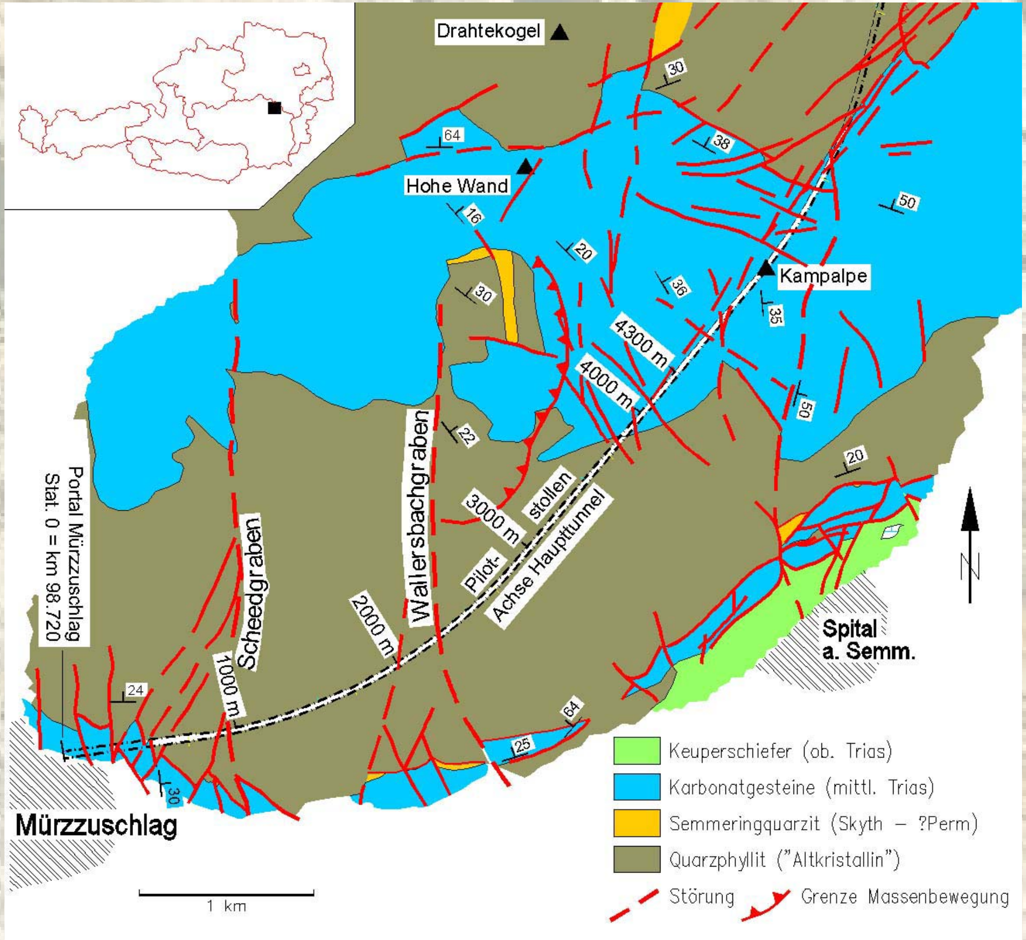


Semmering Base Tunnel, Austria

Gruppe Geotechnik Graz ZT GMBH

Case Studies

Site Investigation



Semmering Base Tunnel, Austria

Case Studies

Site Investigation

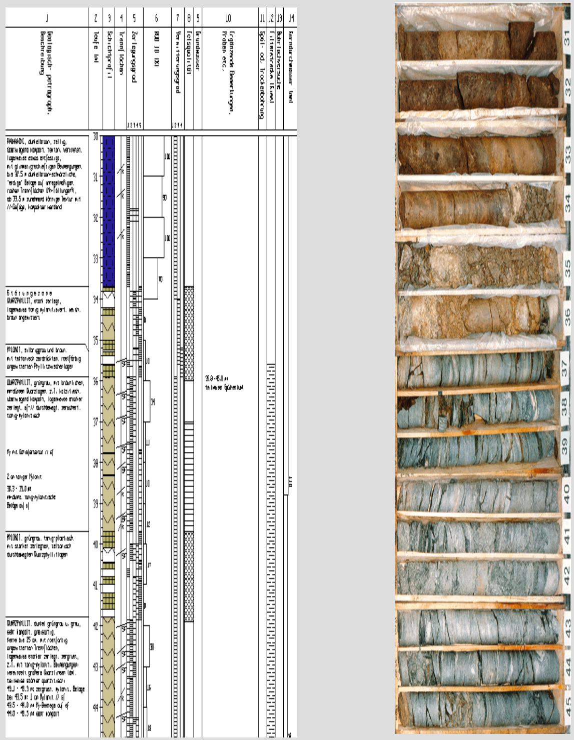
Subsurface Investigations

- Exploratory drilling
- Geophysical surveys
- Borehole in situ testing
- Pilot tunnel

Laboratory testing

- Mineralogical analyses
- Mechanical analyses

DRILL CORE LOGGING

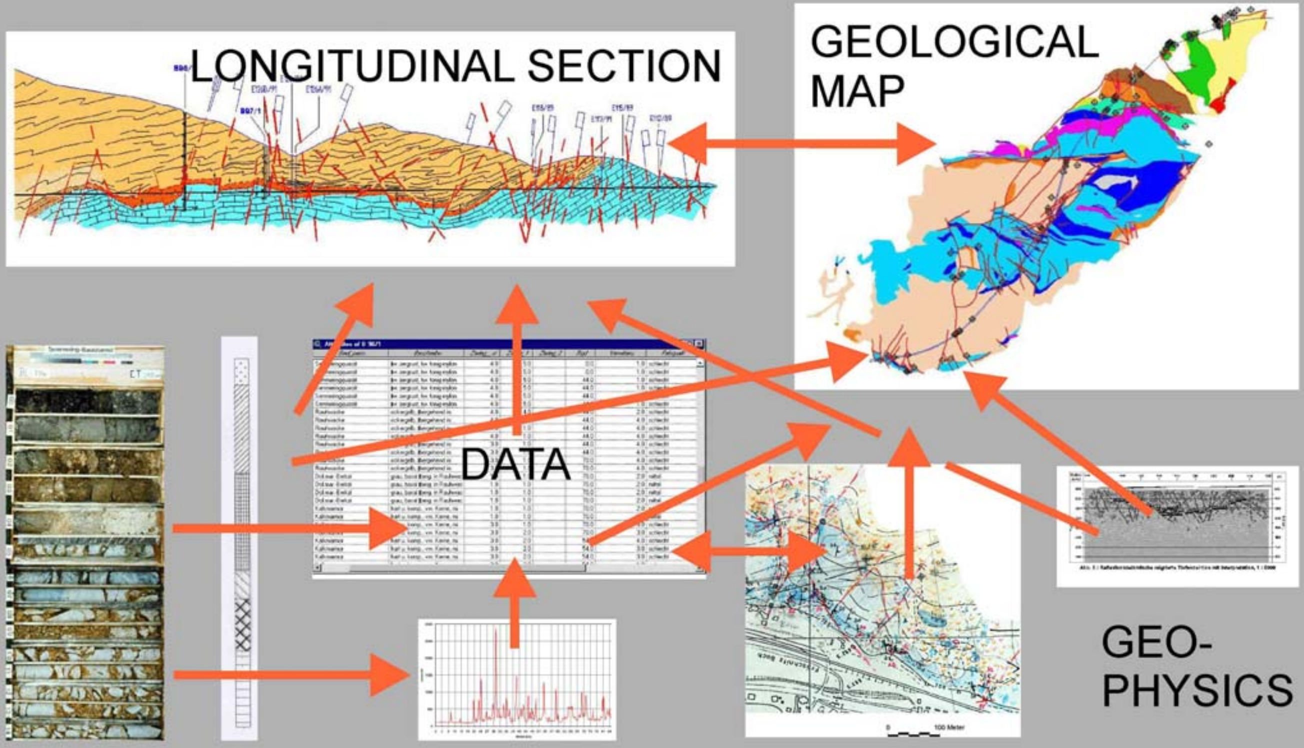


Semmering Base Tunnel, Austria

Case Studies

Site Investigation

GIS based data management



LONGITUDINAL SECTION

GEOLOGICAL MAP

DATA

DRILL CORES

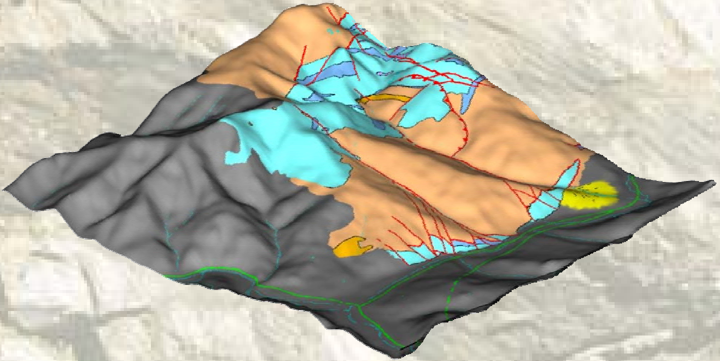
LABORATORY

DETAIL MAPPING

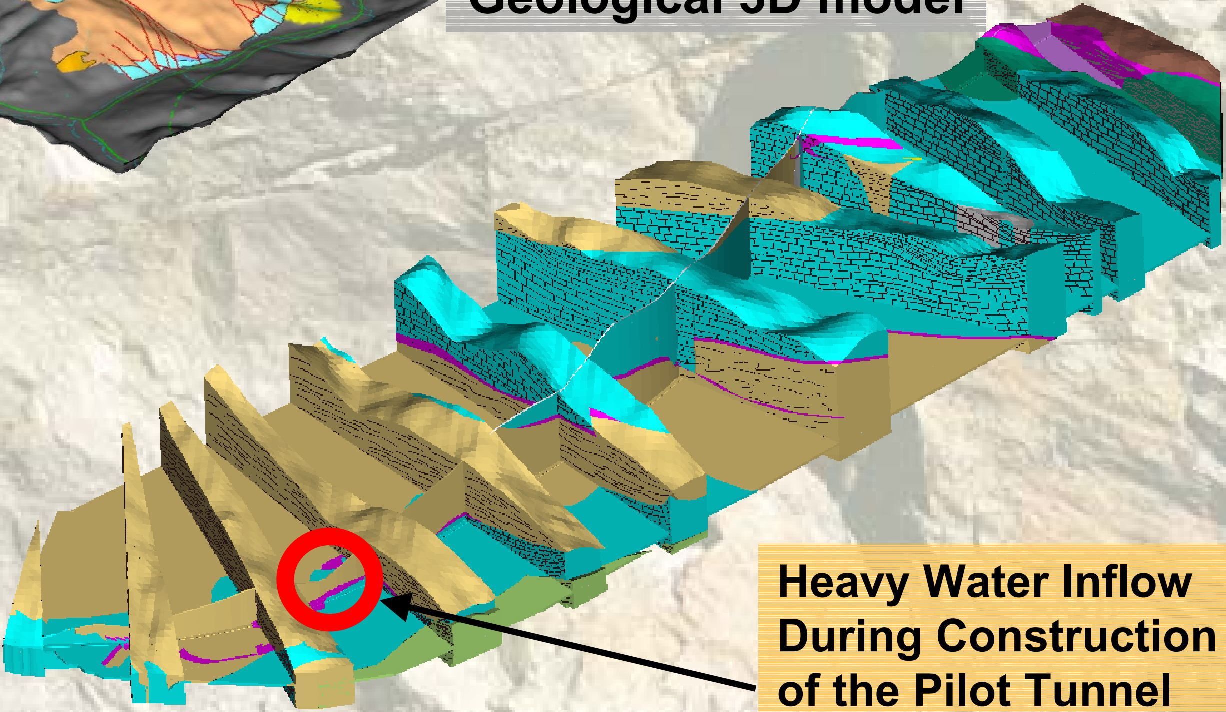
GEO-PHYSICS

Case Studies

Site Investigation



Geological 3D model



Heavy Water Inflow During Construction of the Pilot Tunnel

Semmering Base Tunnel, Austria

Investigation

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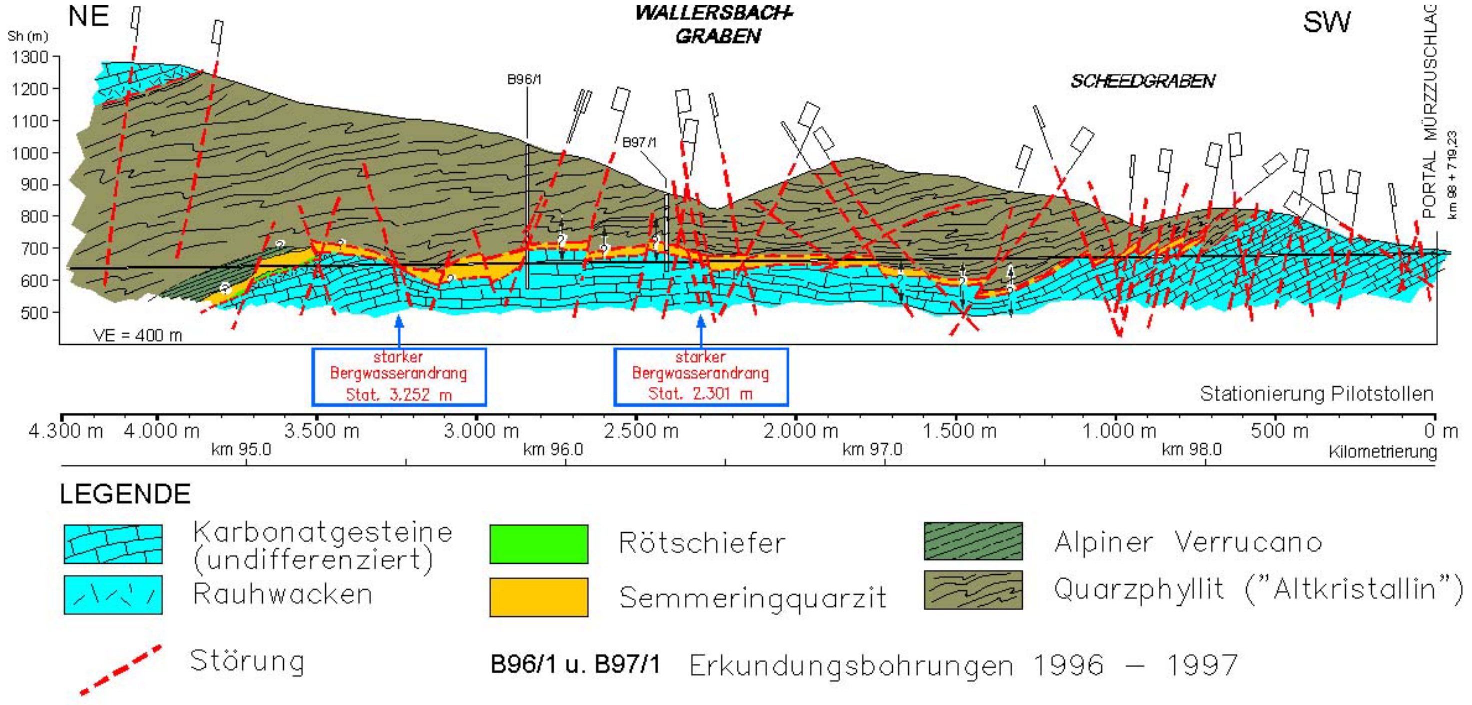
Case Studies

Site Investigation

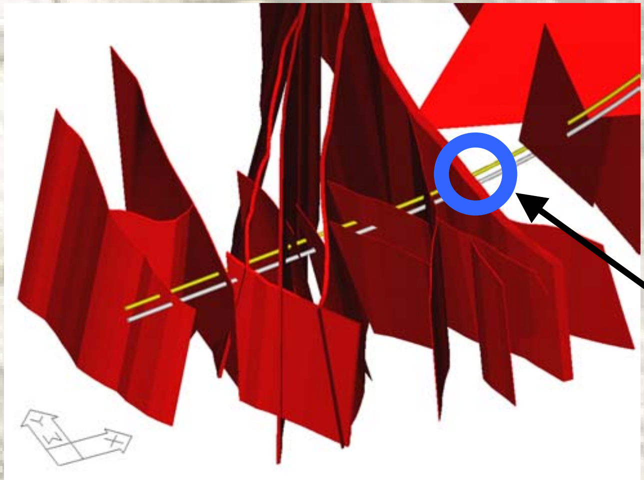
Pilot tunnel, water inflow (350 l/s) at station 2301 m



Semmering Base Tunnel, Austria

Case Studies

Site Investigation

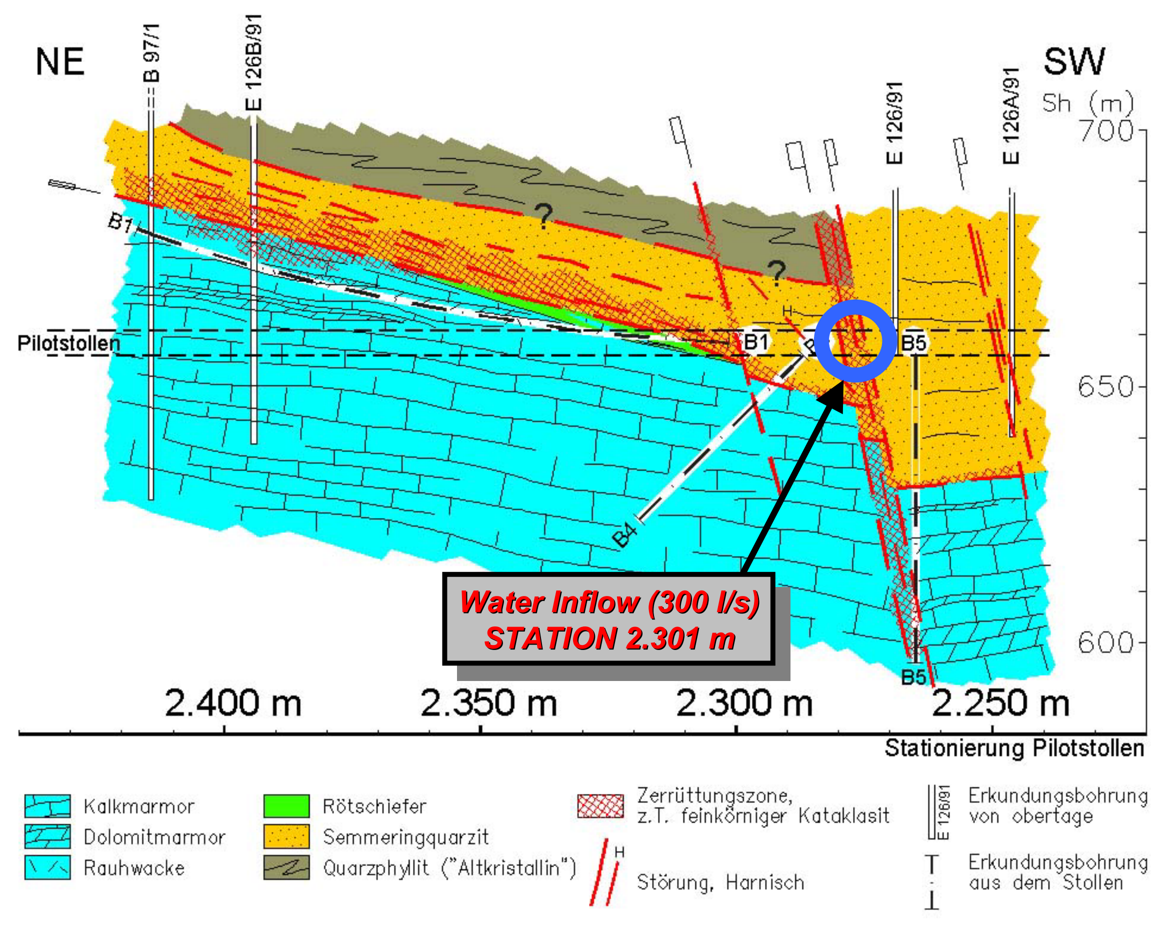


Water Inflow
STATION 2.301 m

Semmering Base Tunnel, Austria

Case Studies

Site Investigation

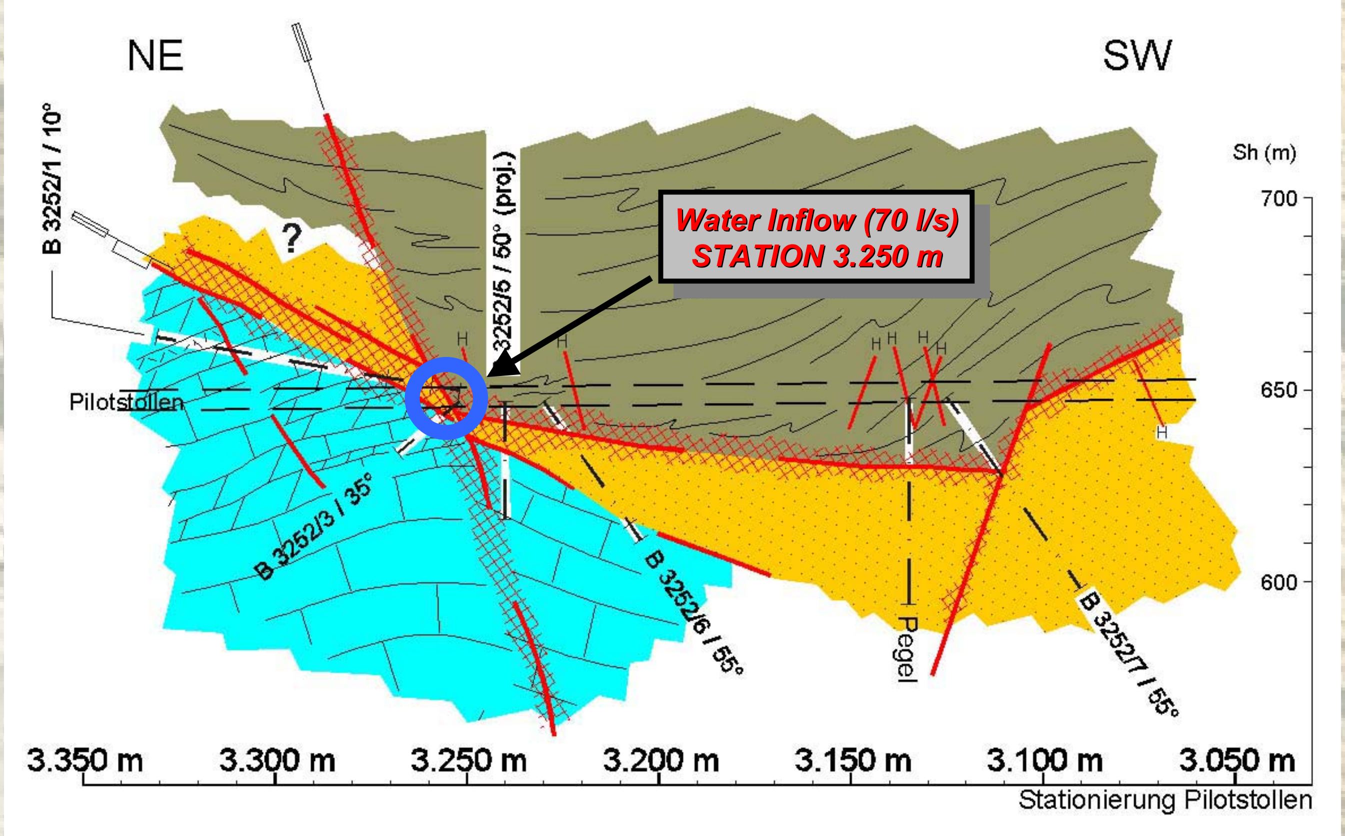


Water Inflow (300 l/s)
STATION 2.301 m

Semmering Base Tunnel, Austria

Case Studies

Site Investigation



Water Inflow (70 l/s)
STATION 3.250 m

Semmering Base Tunnel, Austria

Investigation

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Case Studies

Investigation

Rock Mass Characterisation

Key Parameters

Rock Mass Type 1	
Lithology	Limestone / Dolomite
Foliation / Anisotropy	massive
Block size	> 20 cm
Joint properties	mainly rough
Persistence	low
Aperture	closed
Intact Rock	
Parameter	average / standard deviation / number of samples
UCS [MPa]	102,6 / 29,0 / 26
m_i Hoek Constant [ ]	13,4 / 6,2 / 20
c [MPa]	24,2 / 8,2 / 20
φ [°]	40,7 / 4,9 / 20
E [GPa]	68,3 / 17,6 / 23
ν [ ]	0,19 / 0,05 / 23
Cerchar Abrasivity Index	1,4 / 0,4 / 18
Rock Mass	
Parameter	average / standard deviation
GSI	70 / 10
UCS [MPa]	33,2 / 12,1
c [MPa]	8,0 / 2,8
φ [°]	37,7 / 4,7
E [GPa]	35,0 / 19,4
Joint properties	
Parameter	estimated values
Friction angle [°]	35-45
Residual friction angle [°]	30-40

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Case Studies

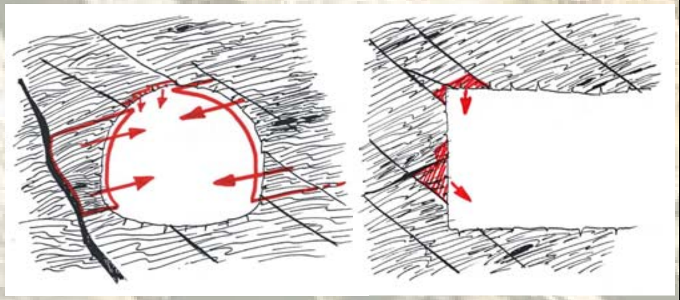
Definition of Rock Mass Behaviour Types

Rock Mass Type 15

Rock type	Phyllite		
Foliation	< 6 cm		
Block Size	< 20 cm		
Joint condition	coated with clay		
Persistence	dominating low		
Aperture	Dominating closed		
Intact Rock Properties	μ	σ	No. of tests
UCS [MPa]	28,2	13,6	19
m_i [-]	14,5	6,0	6
c [MPa]	10,8	3,1	6
φ [°]	31,7	1,5	6
E [GPa]	26,7	19,1	18
ν [-]	0,43	0,18	5
CAI [-]	2,5 bis 3		
Joint Properties	μ	σ	Anz.Vers.
Friction angle [°]	33,7	6,3	15
Res. Friction angle [°]	28,5	5,6	23
Rock Mass Properties	μ	σ	
GSI [-]	40	5	
UCS [MPa]	3,9	2,0	
c [MPa]	1,1	0,5	
φ [°]	31,3	3,6	
E [GPa]	3,0	1,0	

▨ ... shaded => estimated values

Type of Rock Mass Behaviour 4/1



Symbolische Darstellung für Phyllit

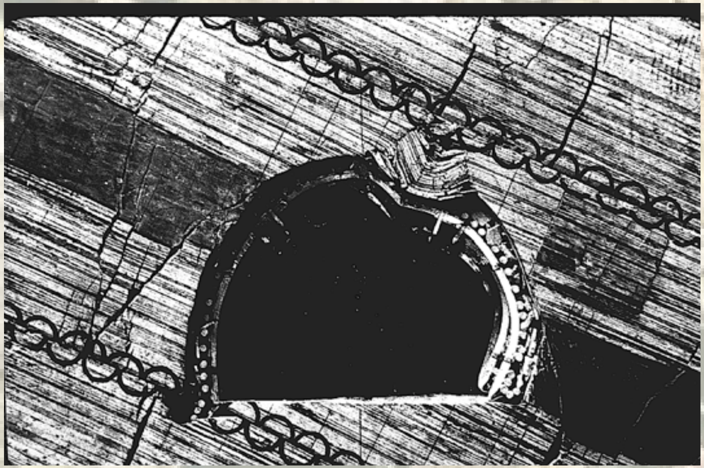
Rock Mass Type	RMT15
Orientation of main discontinuity set	Foliation, dipping moderately to flatly towards direction of drive
Stress Conditions	stress level equals rock mass strength
Groundwater	Dry, occasionally dripping
Rock Mass Behaviour (excavatability, failure mechanism)	Potential for overbreak. Highly anisotropic rock mass. Block failures controlled by shearing along foliation planes. Favourable face stability for foliation dipping into the face. Potential of small, local block sliding caused by unfavourably oriented discontinuities. Slickensides with high persistence may generate deep reaching shear failures.
Radial Deformation	Several centimetres, controlled by discontinuities.

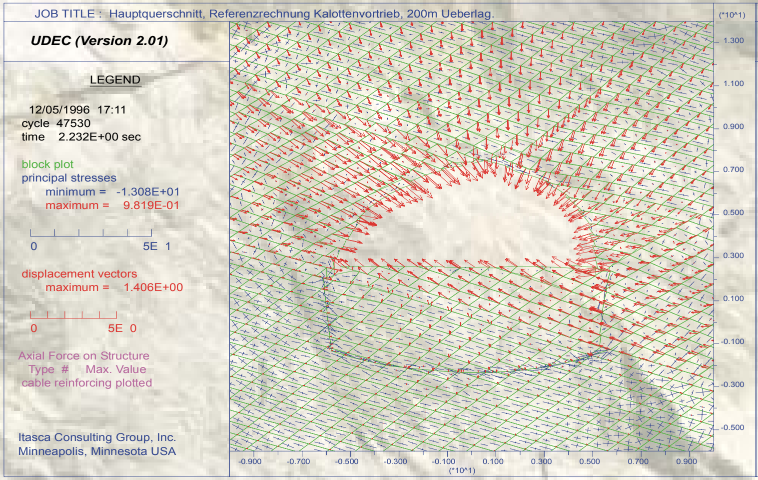
Semmering Base Tunnel, Austria

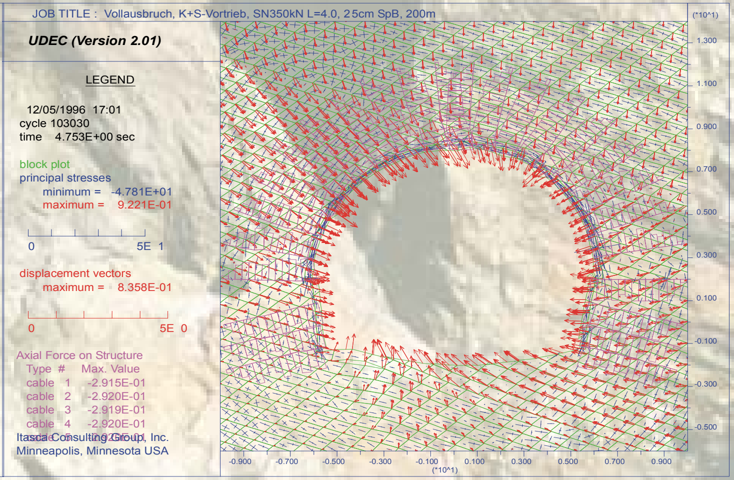
Case Studies

Calculation of Failure Mechanisms (Phyllite)

Failure mechanisms



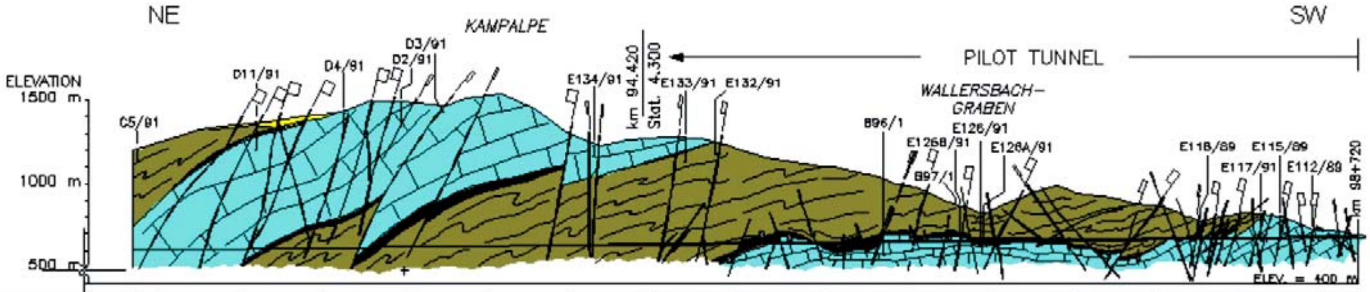


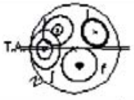
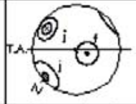
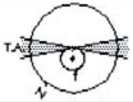
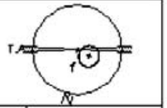


Semmering Base Tunnel, Austria

Case Studies

Geotechnical Longitudinal Section



CHAINAGE		km 92.0	km 93.0	km 94.0		km 95.0				km 96.0			km 97.0		km 98.0
TECTONIC UNIT		LOWER AUSTROALPINE UNIT													
		Permotriassic	"Altkristallin"			Permotriassic							"Altkristallin"		Permotriasssic
STRUCTURAL DOMAINS		6		5		4				3			2		1
DISCONTINUITY STRUCTURE j – MAJOR JOINTS f – FOLIATION															
GEOTECHNICAL SECTION		13	12	11b	11a	10	9	8	7	6	5	4	3	2	1
ROCK MASS TYPES	DOMINATING	1, 2, 3, 4, 5, 6	12	12	12	8 9	1	12	9 10	1 2	9 10	9	12	3, 12	1tf, 2
	OCCASIONAL	7, 9, 10, 11	4, 5, 6, 7, 9, 10, 14	14	14	10 11	1tf, 2, 4, 9	14	8	1tf 3, 4	8	8, 10, 12, 14	14	4, 9, 10, 14	1, 2tf, 3, 3tf, 14
TYPES OF ROCK MASS BEHAVIOR	DOMINATING	2/1, 2/2, 3/1, 3/3	3/2, 4/2	3/2, 4/2	4/2	2/2 3/1	1	4/1 4/2	2/2 7/1	1 2/1	2/2 7/1	2/2	4/1 4/2	2/2, 4/1	2/1, 2/2
	OCCASIONAL	1, 4/2, 5, 7/1, 7/2, 9/1	3/3, 4/3, 7/1, 7/2	4/3	4/3	7/1 9/1	2/1, 2/2, 3/1, 7/1	3/1 4/3	2/1 3/1	2/2 3/1	2/1 3/1	2/1, 3/1, 4/2, 4/3, 7/1	3/1 4/3	3/1, 4/2, 4/3, 7/1	1, 3/1, 6, 7/1

▨ MARBLE, RAUHWACKE

▨ QUARTZPHYLLITE

■ QUARTZITE

╱ FAULT

FOLIATION

B96/1 BOREHOLE

Semmering Base Tunnel, Austria

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Case Studies

Geotechnical Hazard Assessment

Project Data

Upgrading of the Seyhan river for energy production. Located in the Toros mountains north of Adana.

- Weir at the confluence of Yenice and Göksu river
- Headrace tunnel (length 9km, diameter 9,0m
- Power house

Tasks

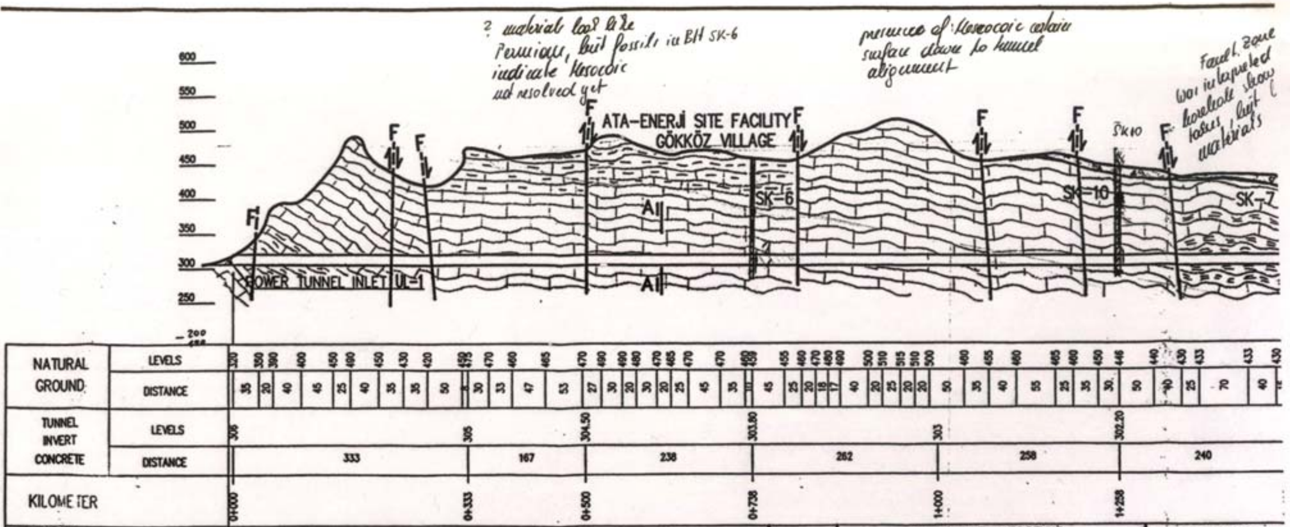
Geotechnical hazard assessment and optimization of design prior to construction

Hepp Kavsak, Turkey

Case Studies

Geotechnical Hazard Assessment

Geotechnical Longitudinal Section of the Tender Design



LITHOLOGY		LIMESTONE – CLAYEY LIMESTONE, PALEOZOIC (PERMIAN)		LIMESTONE, MESOZOIC		LIMESTONE, MA
GROUND WATER CONDITIONS		SEEPAGE FROM FAULT ZONES AND FRACTURES		INFLOW FROM FAULT ZONES		WATER SEEP
ROCK MECHANICS PROPERTIES		UNIAXIAL COMPRESSIVE STRENGTH (UCS): 92,80,60 Mpa		UCS: 52 – 40 Mpa		UCS:0–20 M
STRUCTURAL PROPERTIES		LAYERED,INCLINED TO THE VALLEY FAULTED,JOINTED CARSTIC	FAULTED	LAYERED, FAULTED,FRACTURED		FAULT ZONE
METHOD OF EXCAVATION		CONVENTIONAL		CONVENTIONAL		CONVENTIONA
ROCK CLASS	RMR	59 – 67 FAIR – GOOD ROCK (III)	14-24		40-47 FAIR	14-24 VERY POOR
	Q	5.83 – 10 FAIR – FAIR TO GOOD ROCK	0.06-0.15	1.83 – 3.3 POOR ROCK	1.3 – 2.72	0.06–0.15 VERY POO
	TERZAGHI	4 ROCK LOAD Hp=0.25B – 0.35(B+Ht)	6	Hp=0.25B – 0.35(B+Ht)	5	6 HP= 1.1 (B+
PRPOSED SUPPORT REQUIREMENT		SYSTEMATIC BOLTS 4m LONG, SPACED 1.0 – 1.5 m WITH WIRE MESH AND SHOTCRETE	•	SYSTEMATIC BOLTS 4m LONG, SPACED 1.0 – 1.5 m WITH WIRE MESH AND SHOTCRETE		SYSTEMATIC BOLTS 4 SPACED 1.0 – 1.5 WIRE MESH AND SH

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Case Studies

Geotechnical Hazard Assessment

Hepp Kavsak, Turkey

Case Studies

Geotechnical Hazard Assessment

Hepp Kavsak, Turkey

Case Studies

Geotechnical Hazard Assessment

Hepp Kavsak, Turkey

Case Studies

Geotechnical Hazard Assessment

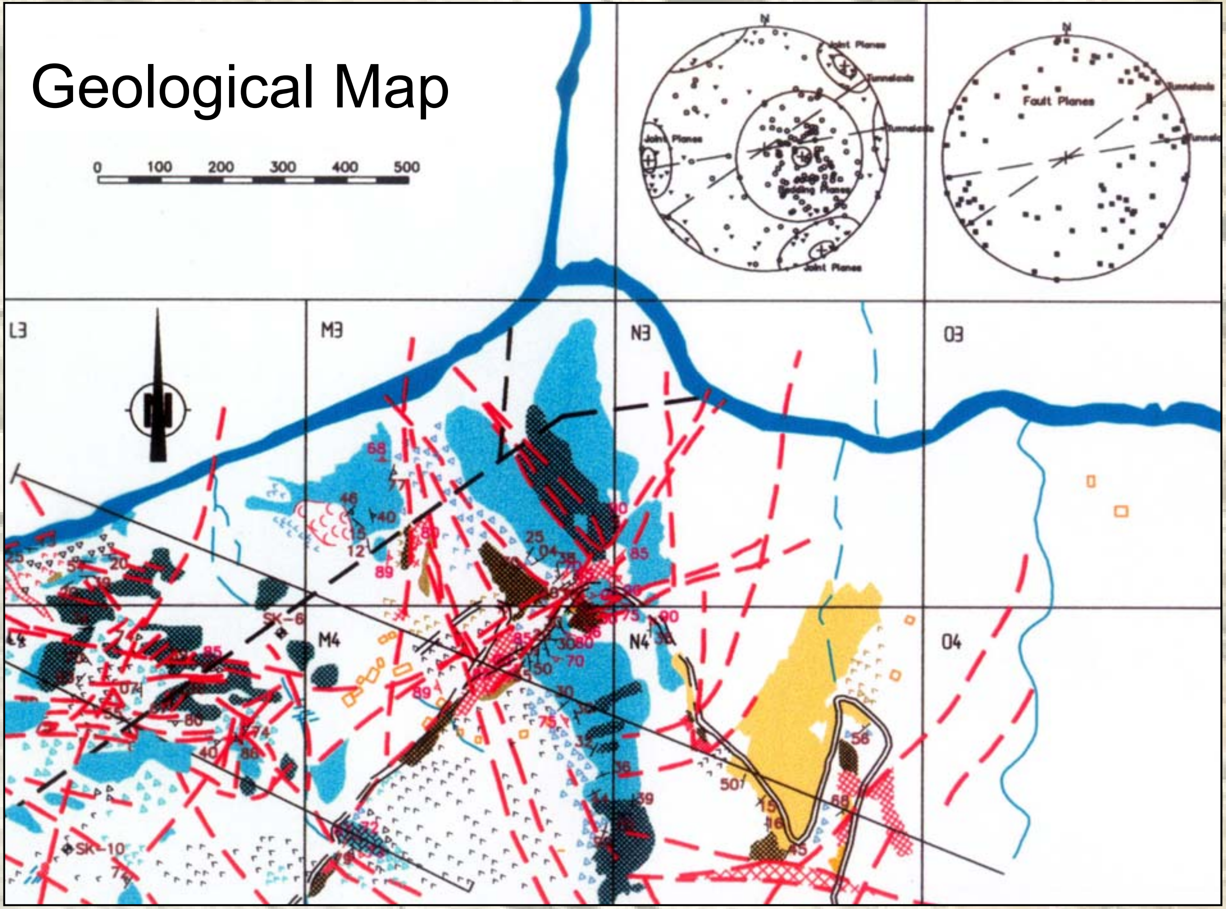
Hepp Kavsak, Turkey

Investigation

Gruppe
Geotechnik
Graz ZT GMBH

Case Studies

Geotechnical Hazard Assessment



Hepp Kavsak, Turkey

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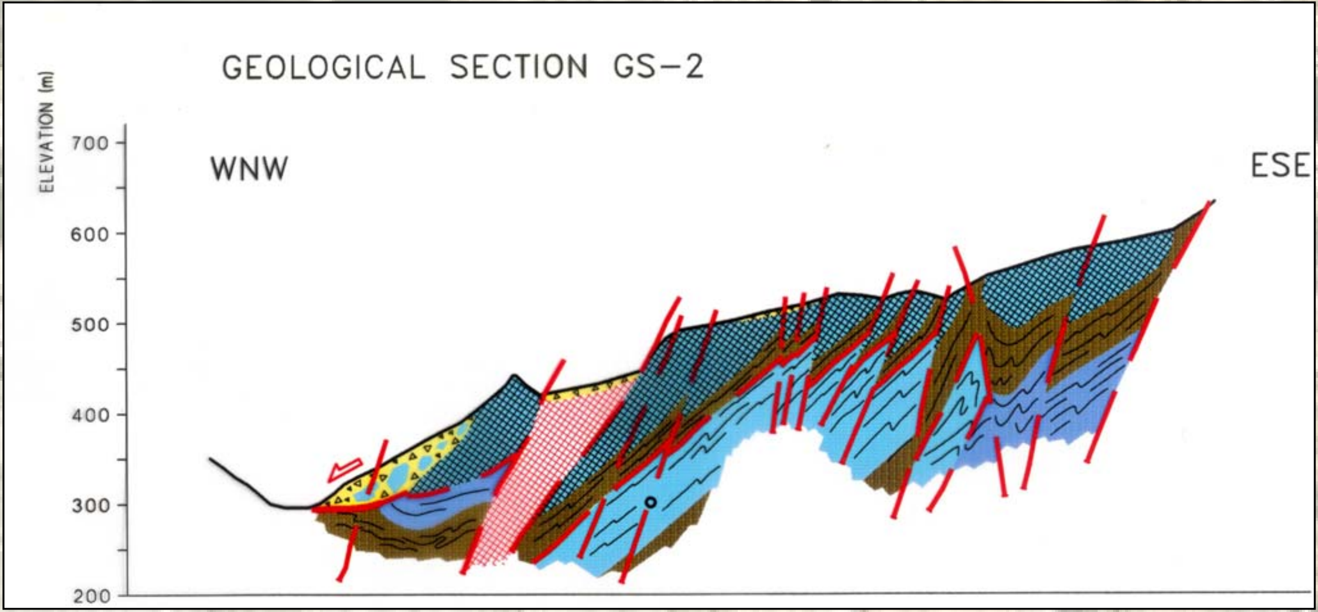
Case Studies

Geotechnical Hazard Assessment

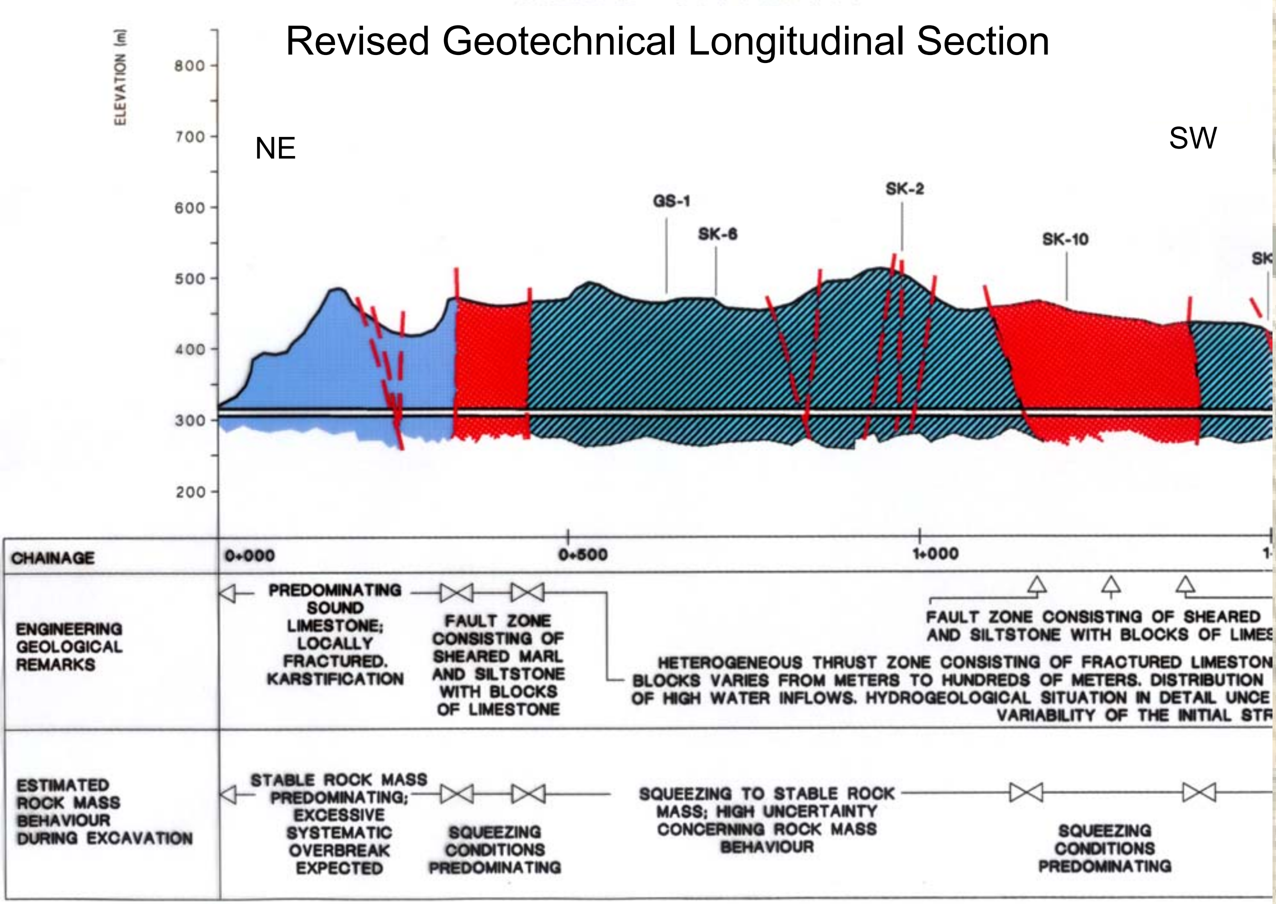


Hepp Kavsak, Turkey

Case Studies

Investigation

Geotechnical Hazard Assessment


Revised Geotechnical Longitudinal Section

CHAINAGE	0+000	0+500	1+000	1
ENGINEERING GEOLOGICAL REMARKS	PREDOMINATING SOUND LIMESTONE; LOCALLY FRACTURED. KARSTIFICATION	FAULT ZONE CONSISTING OF SHEARED MARL AND SILTSTONE WITH BLOCKS OF LIMESTONE	HETEROGENEOUS THRUST ZONE CONSISTING OF FRACTURED LIMESTON BLOCKS VARIES FROM METERS TO HUNDREDS OF METERS. DISTRIBUTION OF HIGH WATER INFLOWS. HYDROGEOLOGICAL SITUATION IN DETAIL UNCE VARIABILITY OF THE INITIAL STR	FAULT ZONE CONSISTING OF SHEARED AND SILTSTONE WITH BLOCKS OF LIMES
ESTIMATED ROCK MASS BEHAVIOUR DURING EXCAVATION	STABLE ROCK MASS PREDOMINATING; EXCESSIVE SYSTEMATIC OVERBREAK EXPECTED	SQUEEZING CONDITIONS PREDOMINATING	SQUEEZING TO STABLE ROCK MASS; HIGH UNCERTAINTY CONCERNING ROCK MASS BEHAVIOUR	SQUEEZING CONDITIONS PREDOMINATING

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Final Design / Construction

■

Final Determination of Support and Excavation (Type and Sequence)

■

Update of Construction Schedule and Costs

Geological Face Mapping and Geotechnical Monitoring

■

Specific Laboratory and in situ Testing

■

Probing ahead of the Face

- **Statistical and Probabilistic Evaluation of Data from Rock Mass Characteristics, Excavation, Support and Displacements**
- **Short - term Prediction**
- **Mechanical Analyses and Numerical Simulations**
  stress redistribution, displacements
- **Refinement of Mechanical and Hydraulic Models** by extrapolating data from face mapping, monitoring and short-term prediction

Final Design / Construction

Tunnel Construction

Geotechnical Tasks

- ➢ Geological Face Mapping
- ➢ Geotechnical Monitoring

Final Design / Construction

Objective of Geological Face Mapping

- Updating of predicted geological models
- Assessment of rock mass types
- Continuous short-term prediction
- Support with the interpretation of geotechnical measurements
- Documentation

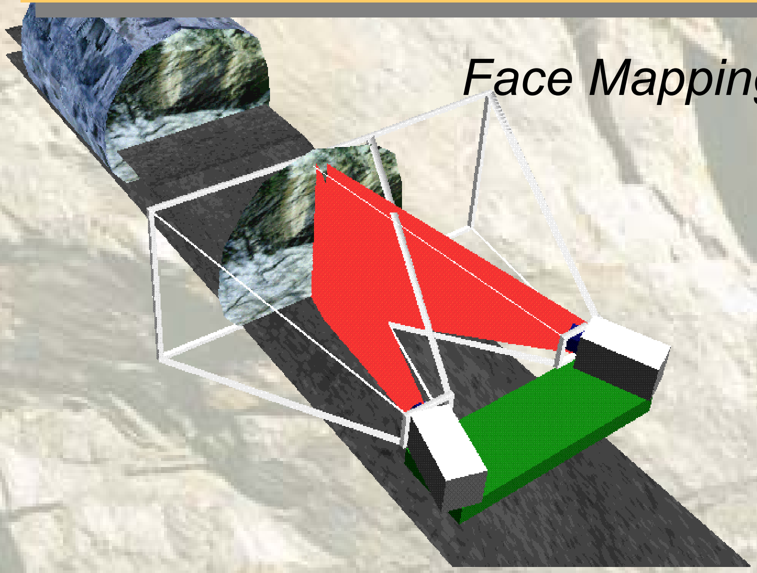
Final Design / Construction

Tasks

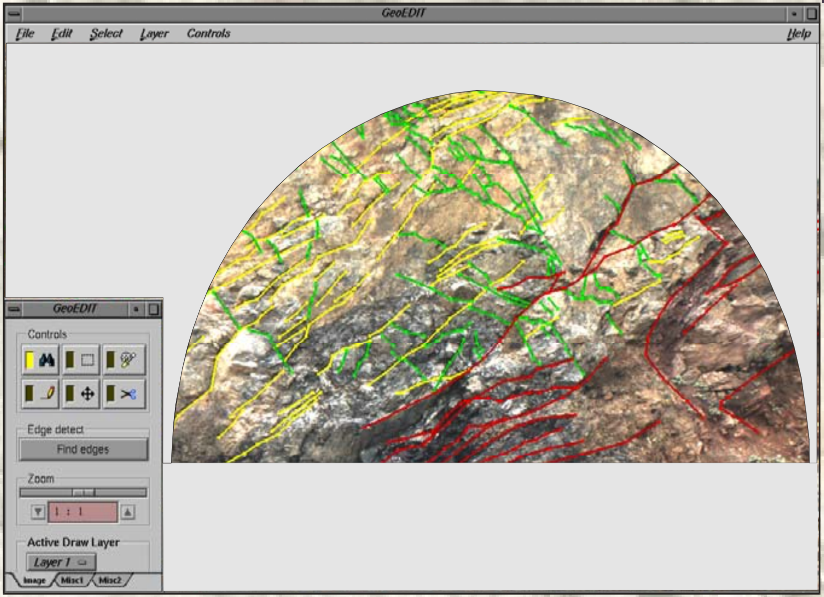
- **Mapping of tunnel faces and tunnel walls**
    - Continuous collection of relevant data
- **Continuous evaluation and interpretation of data**
    - Statistical Analyses
    - Continuous updating of predicted models
    - Continuous short-term prediction ahead of the face

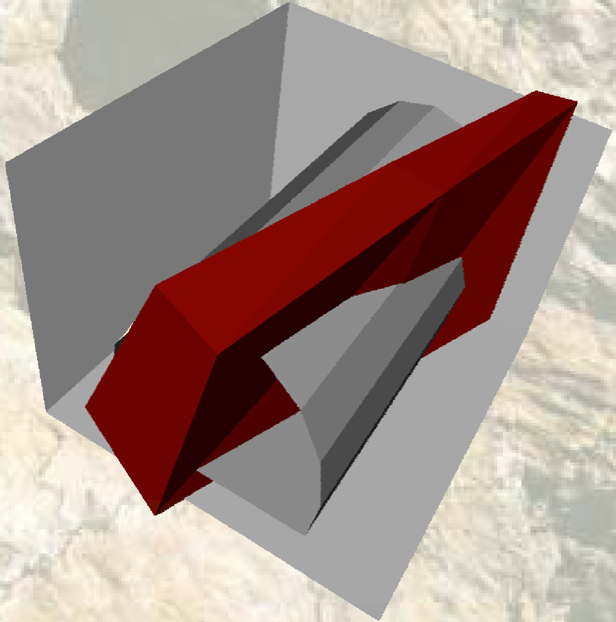
Final Design / Construction

Face Mapping /Monitoring



Face Mapping





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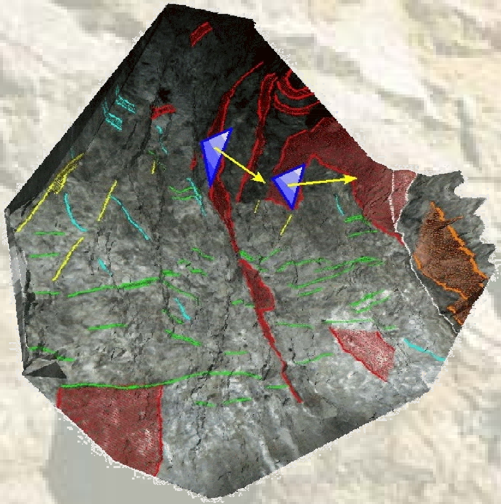
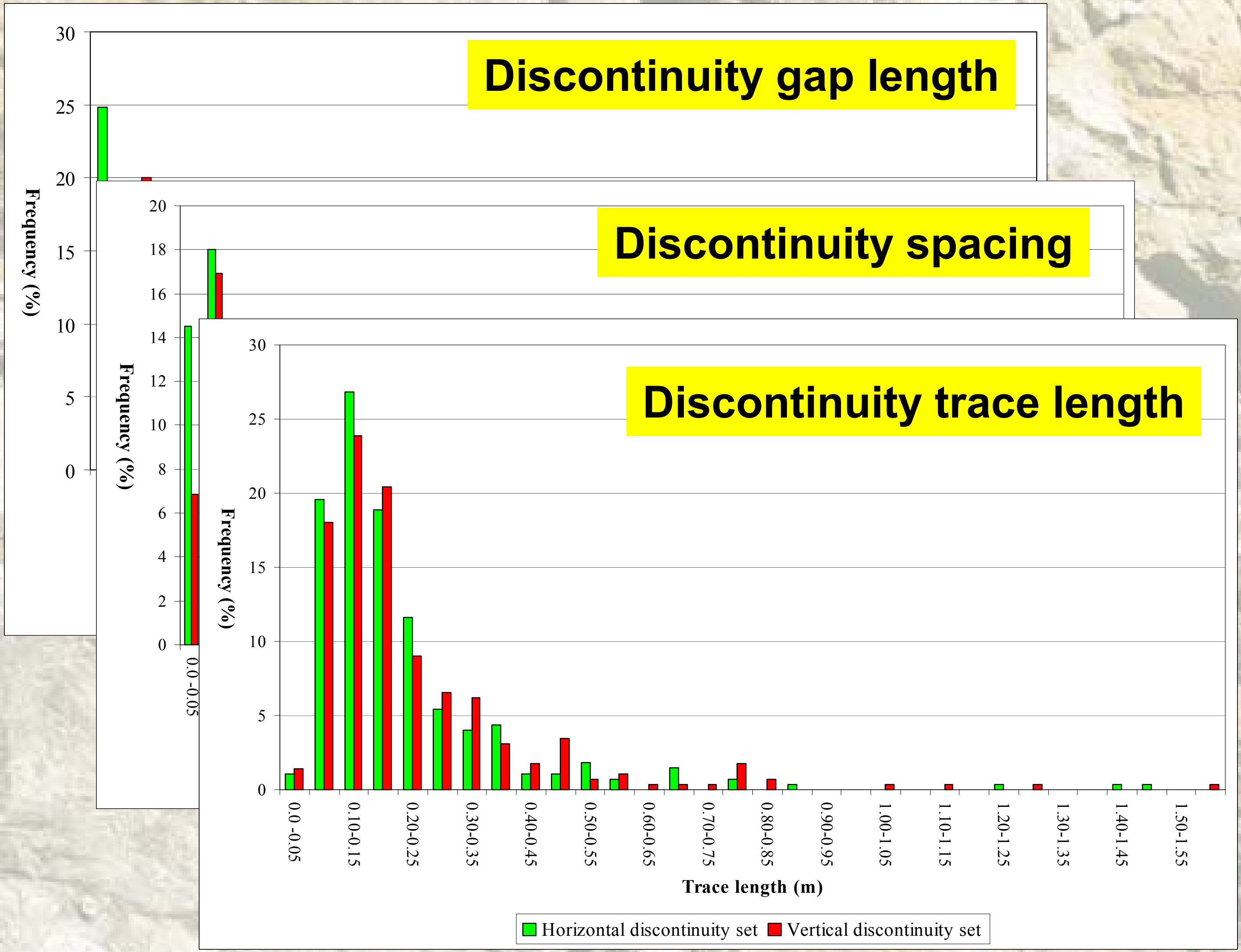
Final Design / Construction

Photo – Image Analyses



Final Design / Construction

Parameters of Discontinuities



Face Mapping /Monitoring

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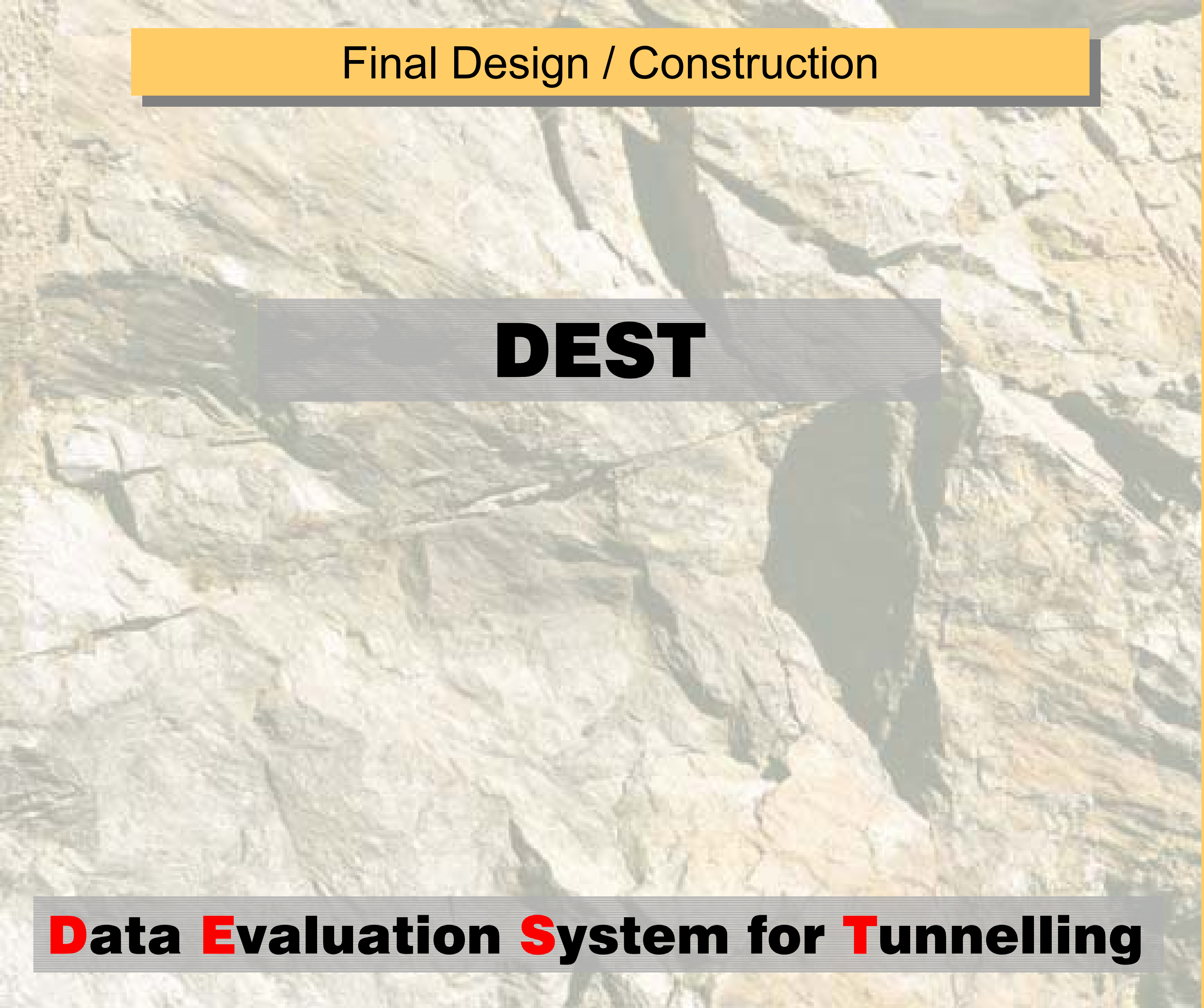
Final Design / Construction



DEST

Data Evaluation System for Tunnelling

Face Mapping /Monitoring

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Final Design / Construction

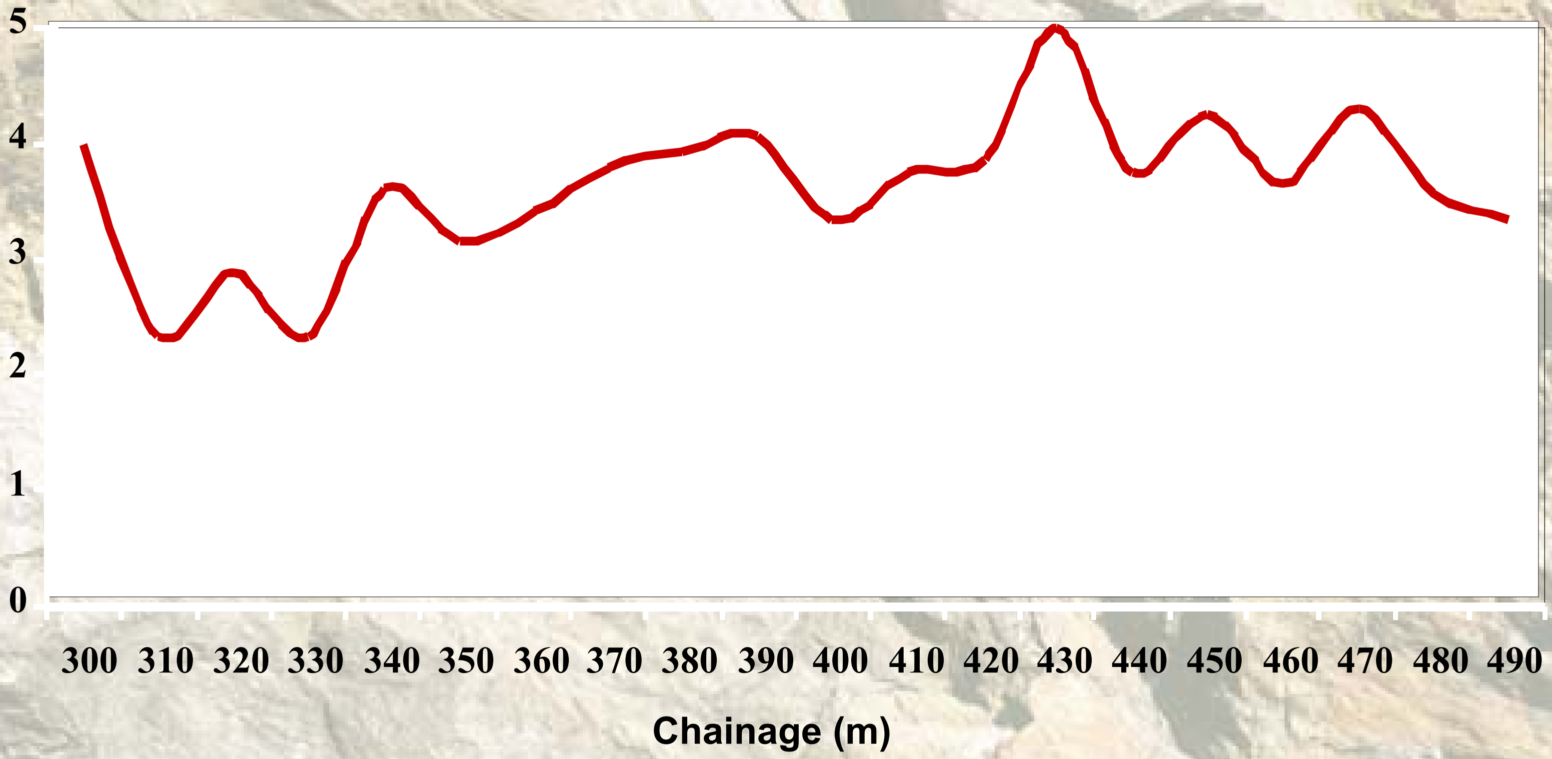
DEST

- **Geology**
  - **Face Mapping**
    - **rock:** lithology, colour, strength, general description
    - **rock mass:** joint block shape, joint block interlocking, weathering, loosening
    - **ground water:** amount / time, position of inflow, type of inflow
  - **Joints**
    - type, position, orientation, spacing, opening, infilling, trace length, termination, surface conditions
  - **Laboratory**
    - particle size distribution, clay minerals, mineralogical composition
- **Support**
  - **Support Timing**
    - shotcrete, welded mesh, ribs, rock bolts, total
  - **Rock Bolt Pattern**
  - **Temporary Rock Bolts**
  - **Additional Rock Bolts**
    - type, position, length, number
  - **Ribs / Welded Mesh / Shotcrete**
    - rib type, rib spacing, lattice type, shotcrete thickness, shotcrete consumption
  - **Face Support**
    - thickness of shotcrete / reinforced shotcrete, rock bolts
  - **Invert**
    - type, thickness, reinforcement, rock bolts
  - **Injection / Drainage**
    - type, position, pressure, type of grout
  - **Forepoling**
    - type, length, number
- **Monitoring**
  - **Convergence**
  - **Geodesic Measurement**
  - **Extensometer**
  - **Strain Gauge**
    - overburden, date, value, position
- **Excavation**
  - **Site of Excavation**
    - main excavation, cavern, shaft, niche, cross cut, etc.
  - **Part of Excavation**
    - top heading, bench, etc., date, type of excavation, round length, overbreak, shape of section, consumption of explosives / detonators, excavation class

Final Design / Construction

DEST

Trend Curve of Discontinuity Orientation Ratings



very favourable (=1), favourable (=2), fair (=3), unfavourable (=4), very unfavourable (=5)

Pilot Tunnel, Semmering Base Tunnel Project, Austria

Face Mapping /Monitoring

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DEST

Matrix of Zonation Based on Rock Mass Type and Normalized Support Quantity Value

Zonierungsmatrix nach Gebirgstyp und Stützmittelzahl (ÖNORM)

Anzahl der Zonen	2	3	4	5	6	7	8	9	10	11
Reduktion der Variation (%)	*46.31*	*63.94*	*72.02*	*75.82*	*78.22*	*81.72*	*83.92*	*86.97*	*88.16*	*89.12*
Zonengrenzen (m)	560	330	330	330	330	330	330	330	290	290
	990	560	560	560	530	490	490	490	320	320
		990	950	950	570	520	520	520	490	490
			990	970	950	570	570	560	520	520
				990	970	950	830	660	560	560
					990	970	950	830	660	660
						990	970	950	830	830
							990	970	950	950
								990	970	960
									990	970
										990

Stations 230 m – 1000 m

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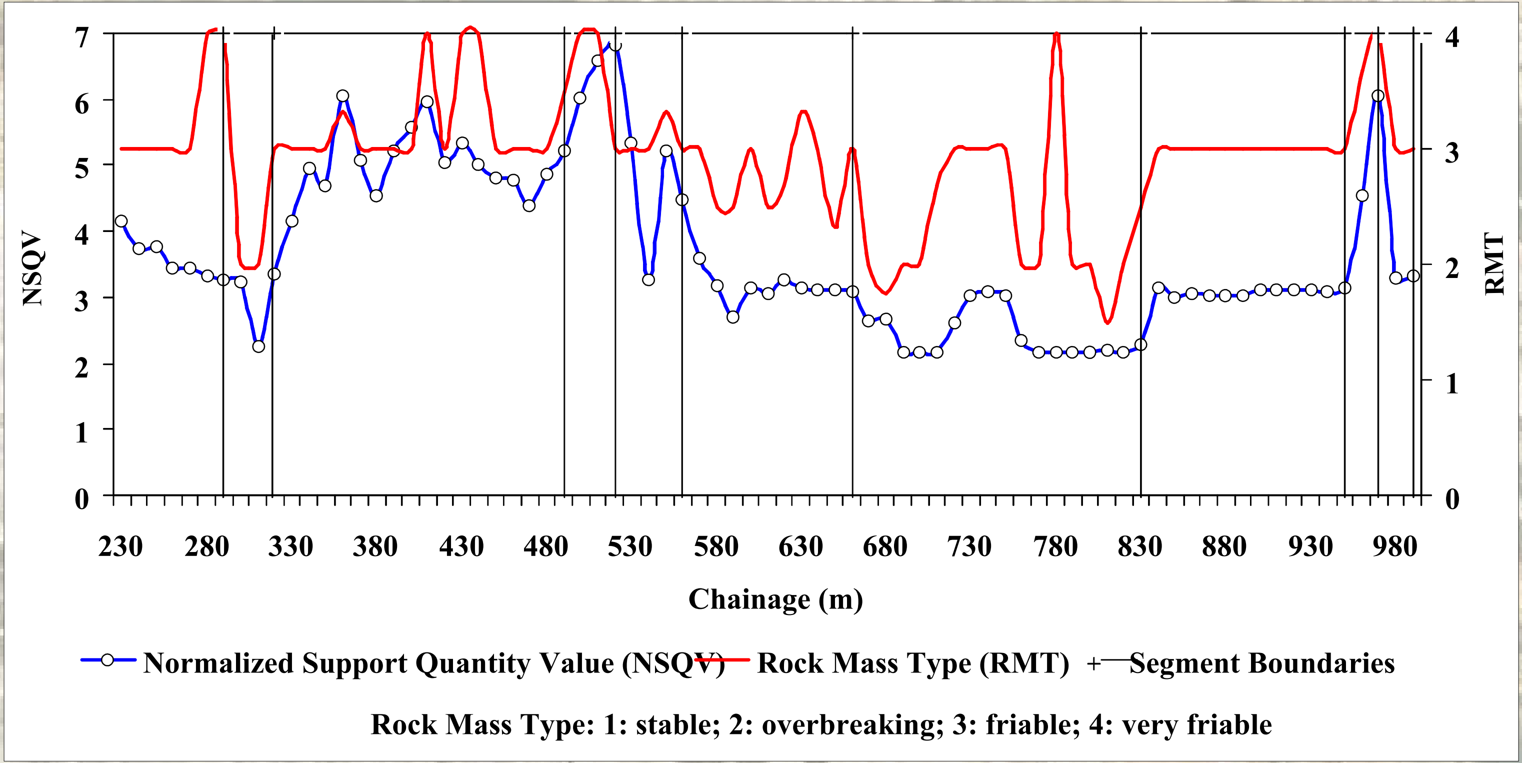
Zonation based on Rock Mass Type (RMT) and Normalized Support Quantity Value (NSQV)

Zonierungsmatrix nach Gebirgstyp und Stützmittelzahl (ÖNORM)



Rock Mass Type: 1: stable; 2: overbreaking; 3: friable; 4: very friable

Pilot Tunnel, Semmering Base Tunnel Project, Austria

Face Mapping /Monitoring

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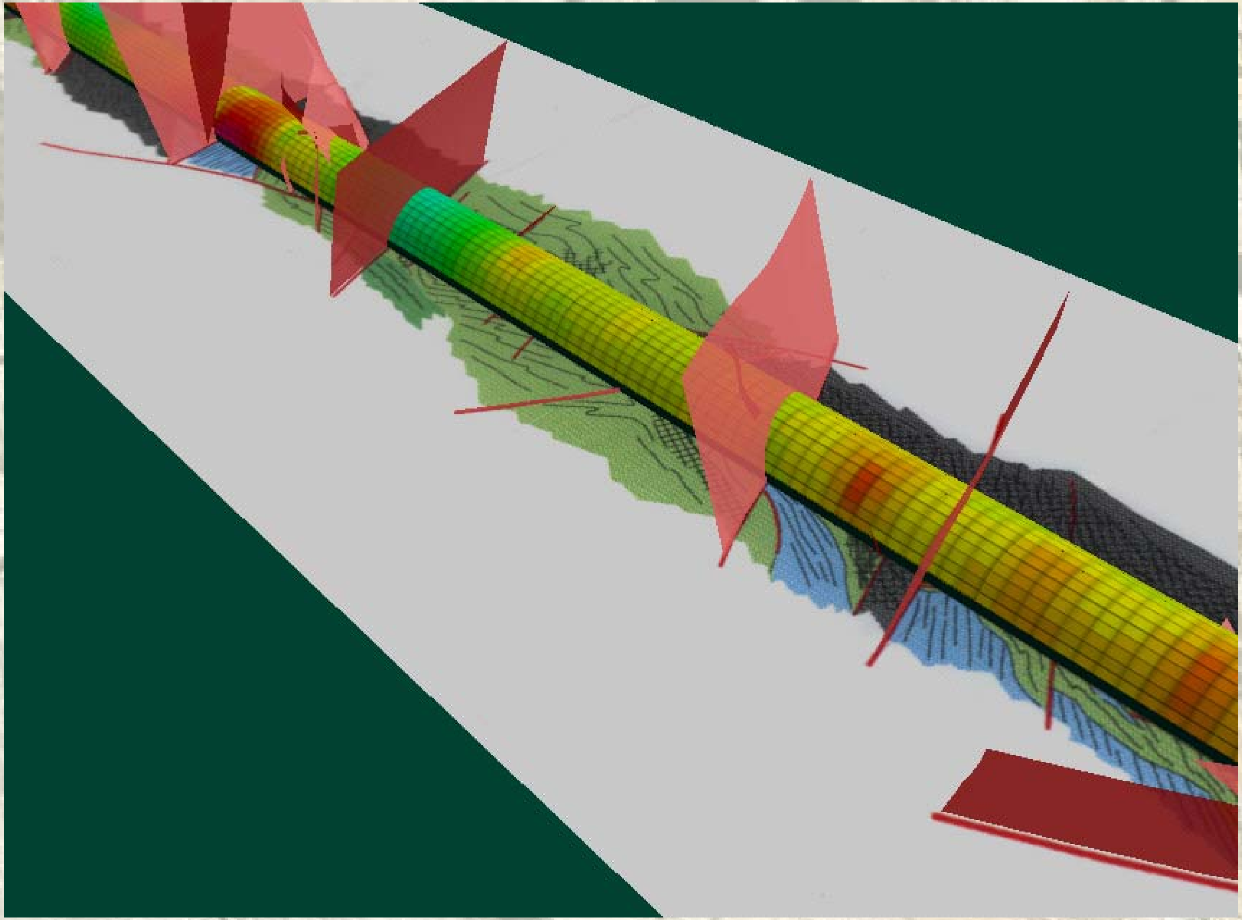
Final Design / Construction

Geotechnical Model



Galgenberg Tunnel, Austria

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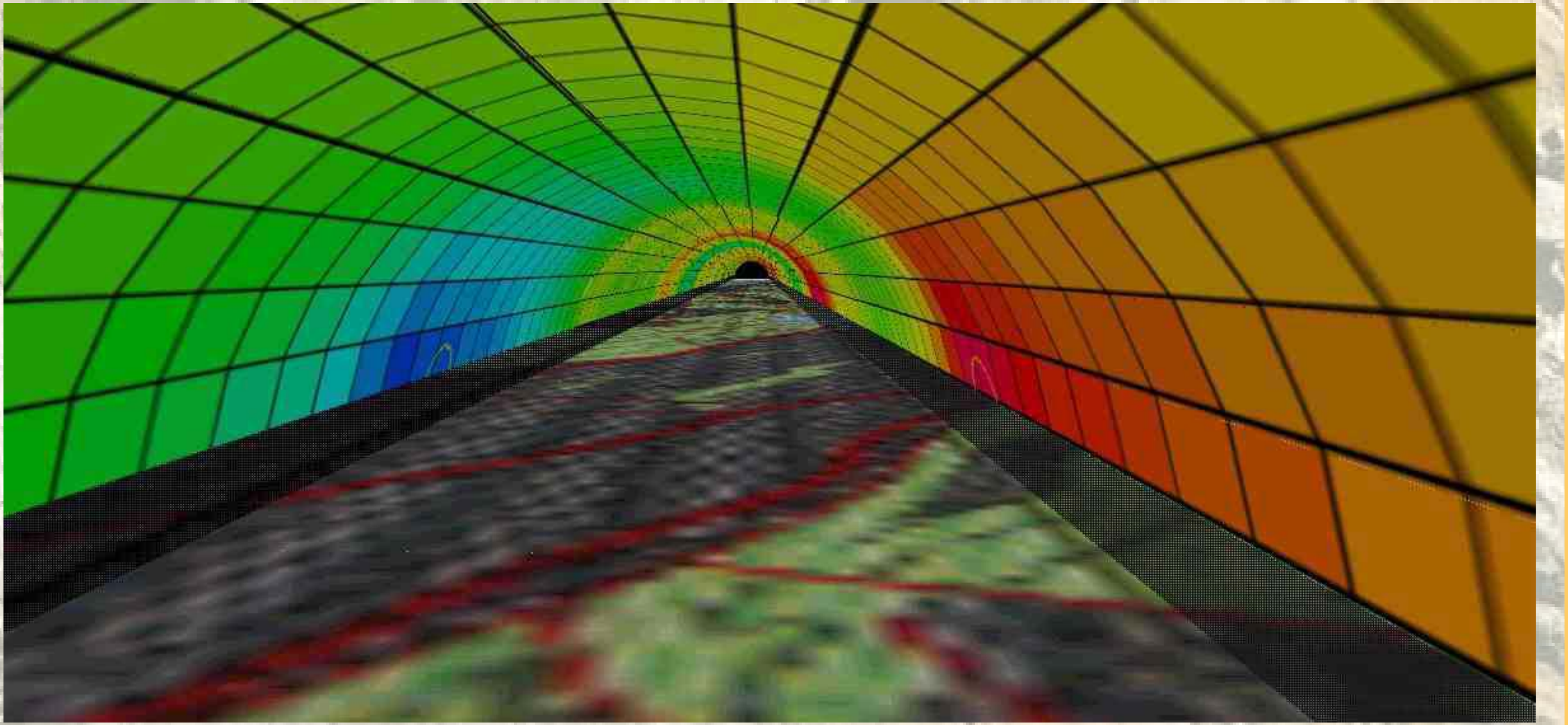
Final Design / Construction

Geotechnical Model



Galgenberg Tunnel, Austria

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MONITORING / SHORT–TERM PREDICTION

TARGETS

- Verify design assumptions
- Together with updated geotechnical model allow short term prediction
- Provide input for final design and optimization of excavation and support on site
- Prediction of final displacements
- Control stability
- Data collection for future developments (expert systems)

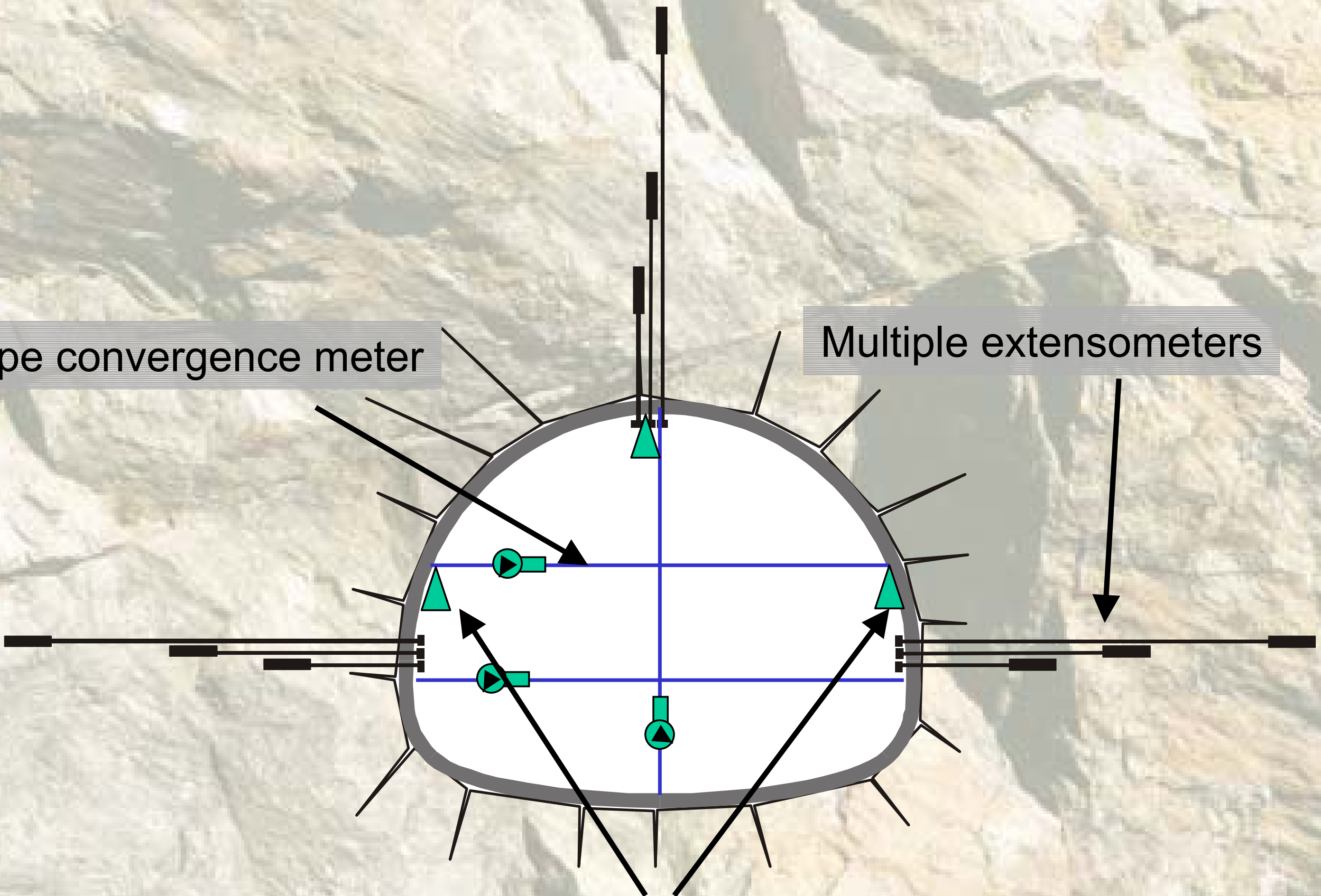
MONITORING / SHORT–TERM PREDICTION

METHODS

- Absolute displacements of tunnel wall with electronic total station
- Relative displacement measurements with precision measuring tape, extensometers, inclinometers
- strains

MONITORING / SHORT–TERM PREDICTION

METHODS



Tape convergence meter

Multiple extensometers

Levelling points

MONITORING / SHORT–TERM PREDICTION

ABSOLUTE DISPLACEMENTS

MONITORING / SHORT–TERM PREDICTION

INFLUENCING FACTORS

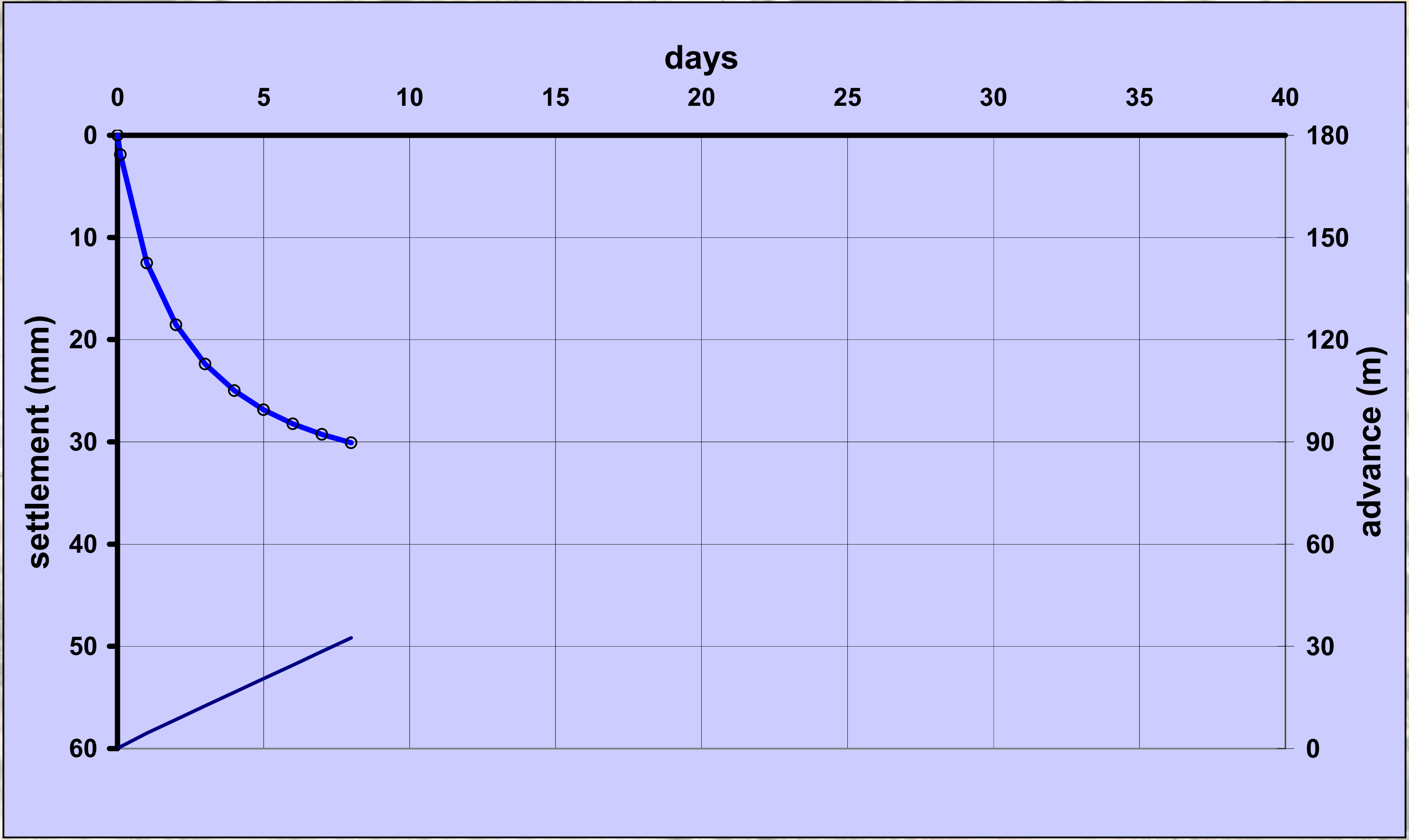
- **Displacements influenced by:**

  - Rock mass properties
  - Heterogeneity
  - Tunnel size
  - Primary stresses
  - Excavation sequence
  - Excavation rate
  - Support

MONITORING / SHORT–TERM PREDICTION

TIME – DISPLACEMENT

continuous advance



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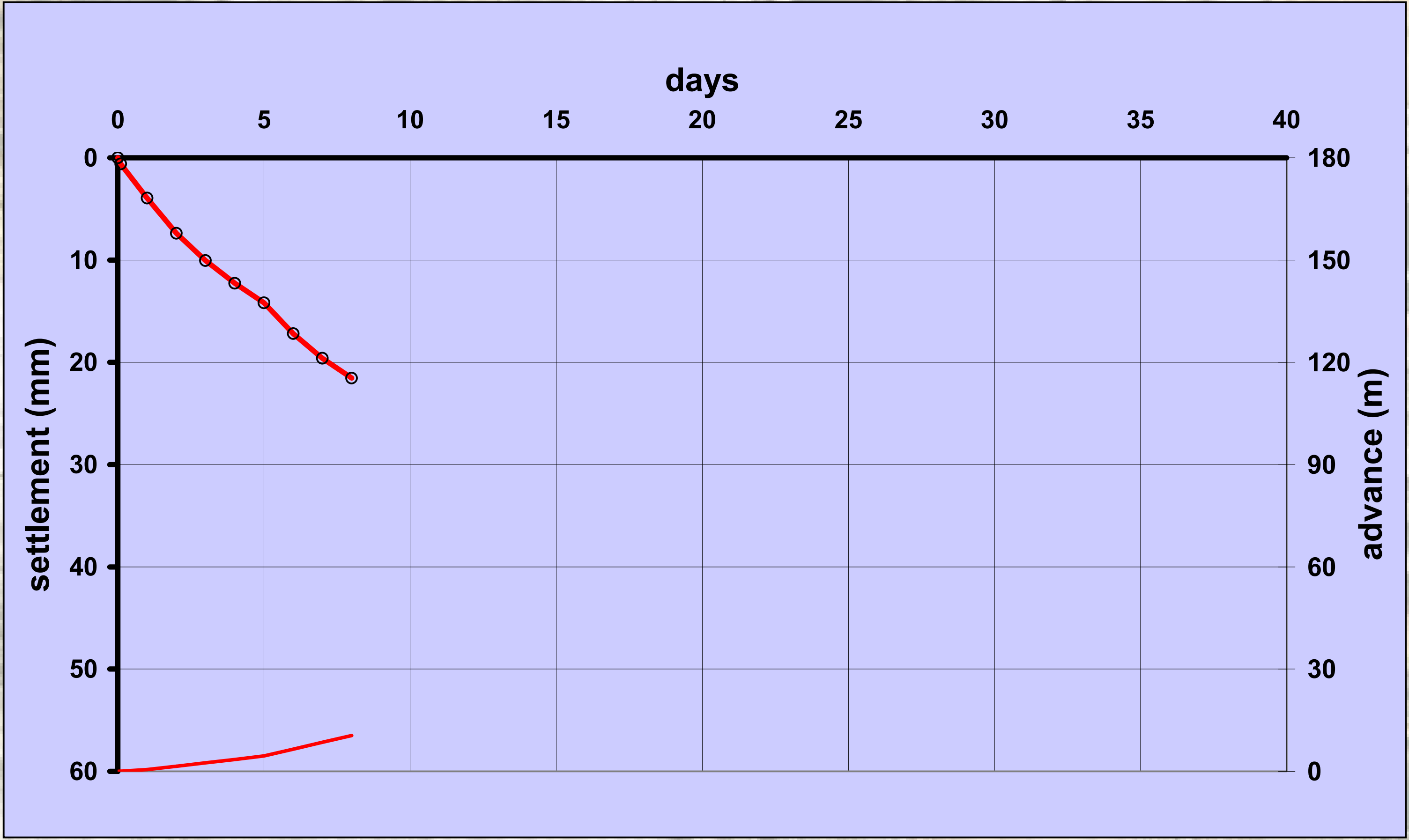
MONITORING / SHORT–TERM PREDICTION

TIME – DISPLACEMENT
discontinous advance



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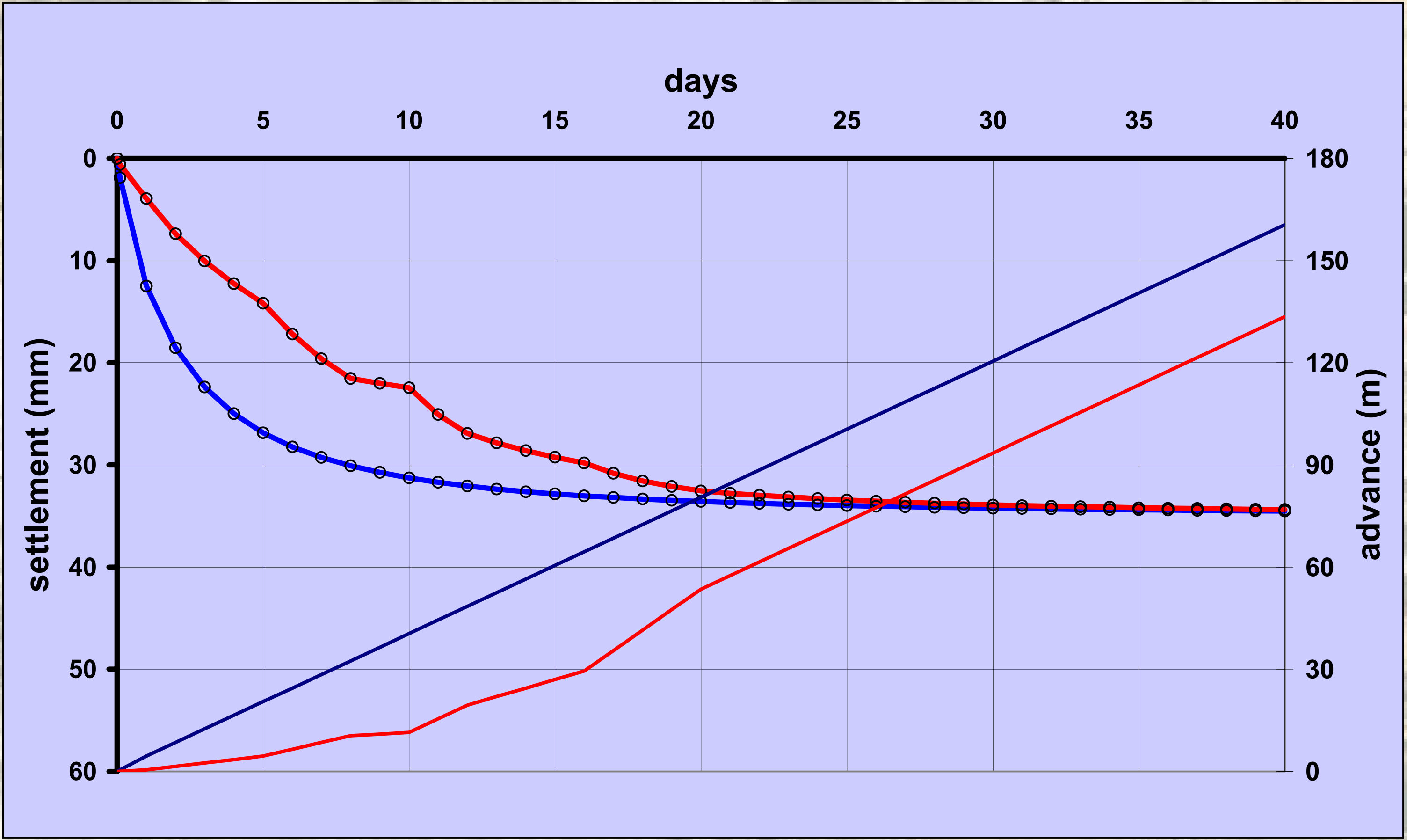
MONITORING / SHORT–TERM PREDICTION

TIME – DISPLACEMENT
comparison



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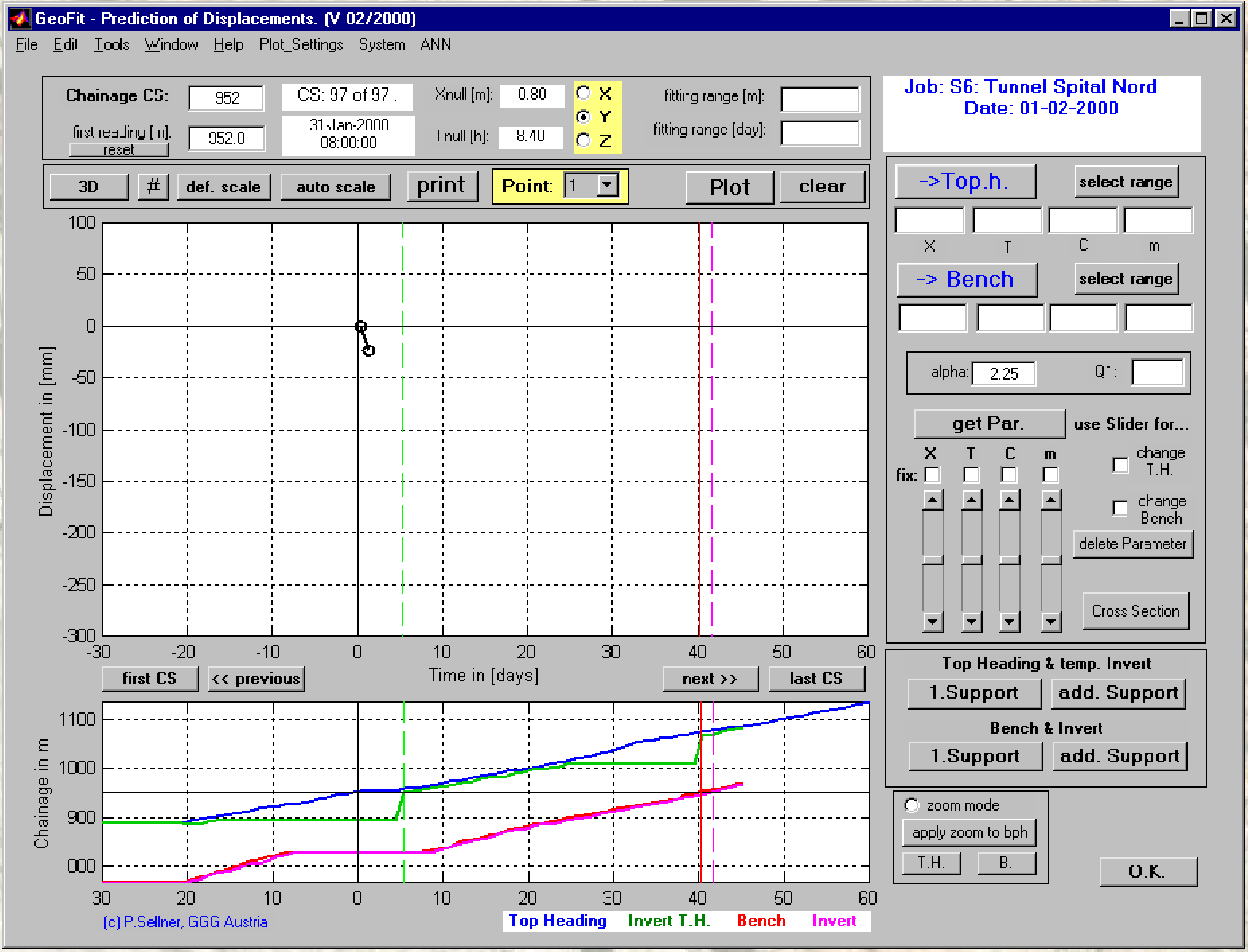
MONITORING / SHORT–TERM PREDICTION

PREDICTION OF DISPLACEMENTS



GeoFit - Prediction of Displacements. (V 02/2000)

Chainage CS: 952

CS: 97 of 97 .

first reading [m]: 952.8

31-Jan-2000 08:00:00

Xnull [m]: 0.80

Tnull [h]: 8.40

○ X ● Y ○ Z

fitting range [m]:

fitting range [day]:

Job: S6: Tunnel Spital Nord
Date: 01-02-2000

Point: 1

alpha: 2.25

Q1:

(c) P.Sellner, GGG Austria

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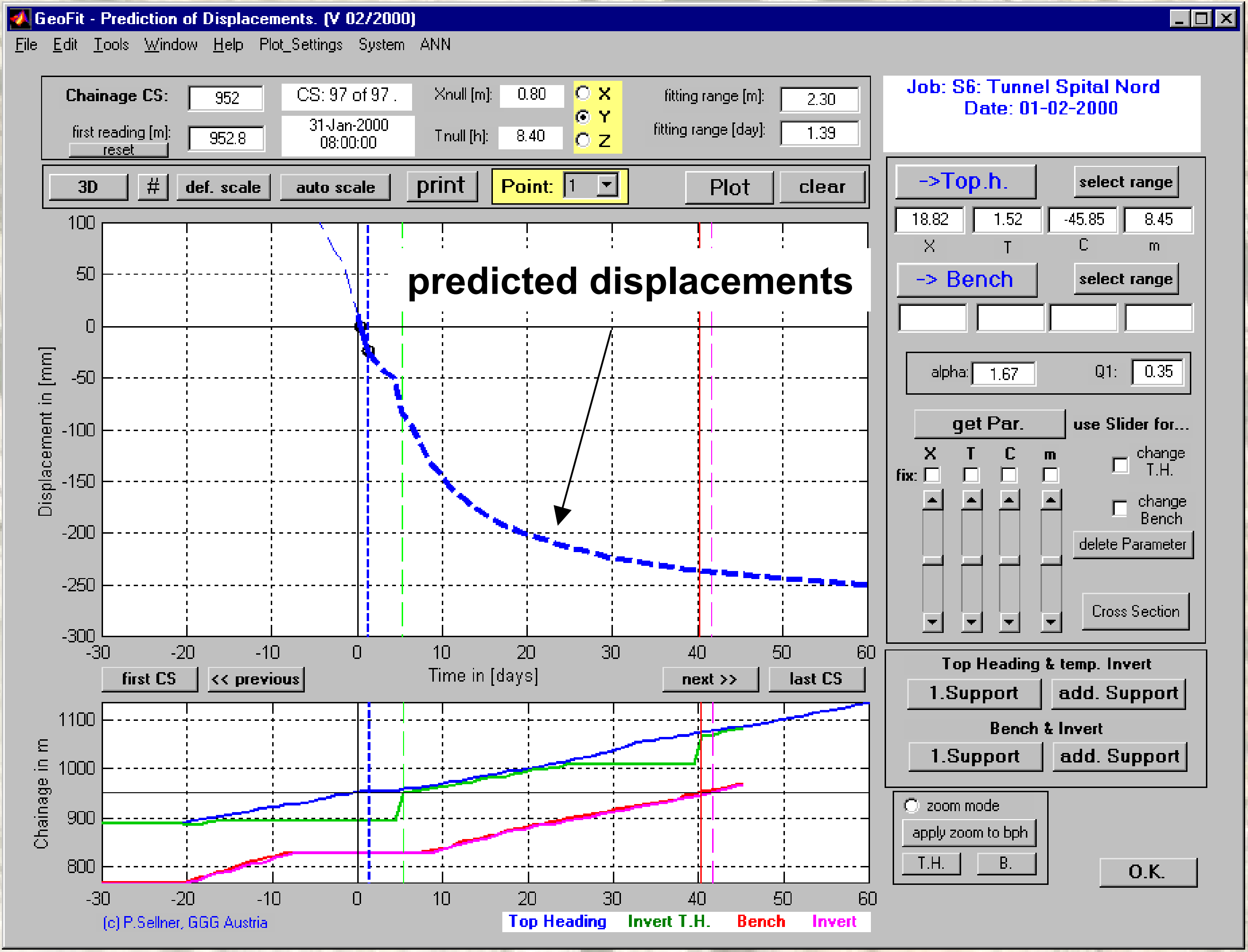
MONITORING / SHORT–TERM PREDICTION

PREDICTION OF DISPLACEMENTS



Chainage CS: 952

CS: 97 of 97 .

first reading [m]: 952.8

31-Jan-2000
08:00:00

Xnull [m]: 0.80

Tnull [h]: 8.40

○ X
● Y
○ Z

fitting range [m]: 2.30

fitting range [day]: 1.39

Job: S6: Tunnel Spital Nord
Date: 01-02-2000

Point: 1

X	T	C	m
18.82	1.52	-45.85	8.45

alpha: 1.67

Q1: 0.35

fix: X ☐ T ☐ C ☐ m ☐

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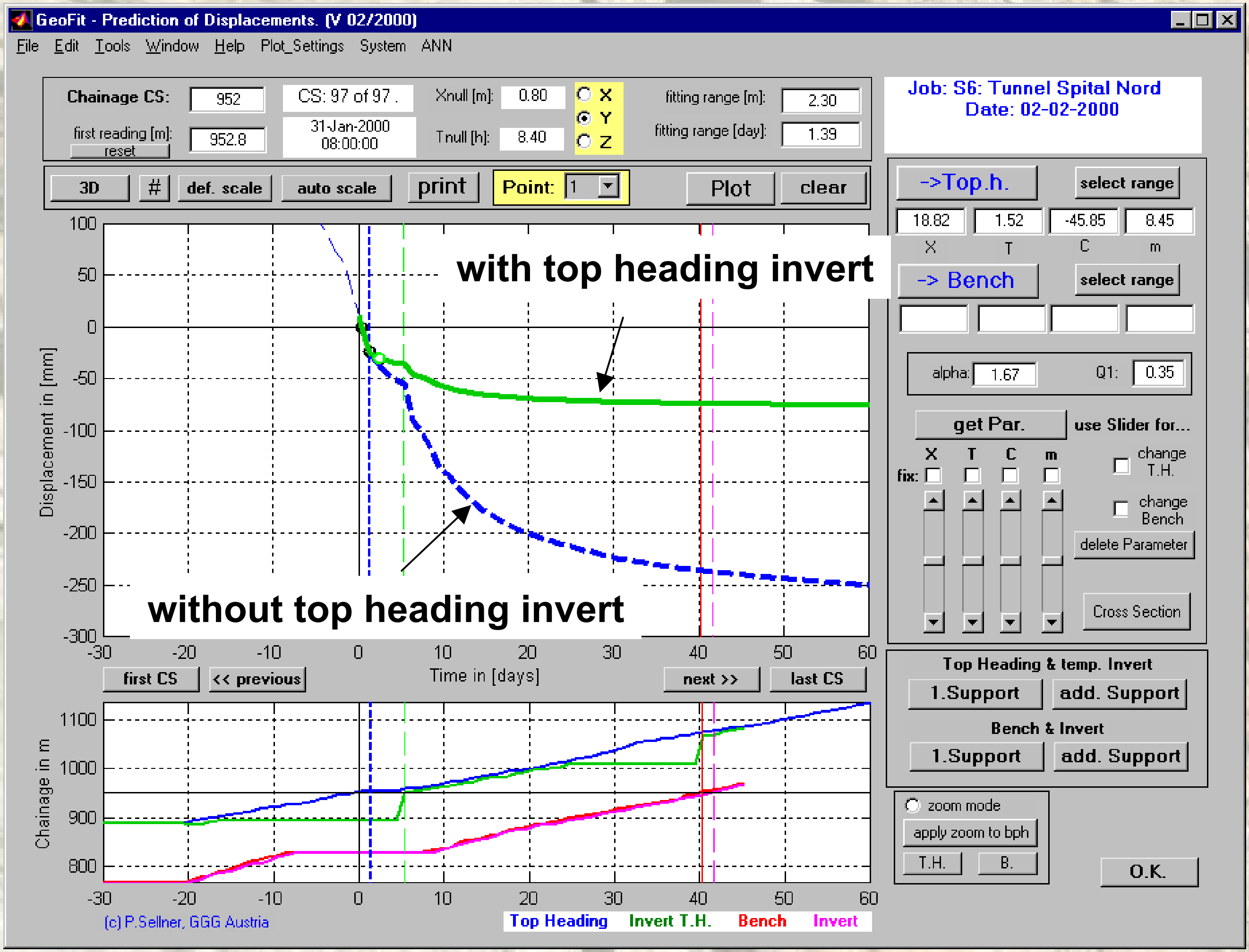
MONITORING / SHORT–TERM PREDICTION

DIFFERENT SUPPORT



GeoFit - Prediction of Displacements. (V 02/2000)

Chainage CS: 952

CS: 97 of 97 .

first reading [m]: 952.8

31-Jan-2000
08:00:00

Xnull [m]: 0.80

Tnull [h]: 8.40

○ X
● Y
○ Z

fitting range [m]: 2.30

fitting range [day]: 1.39

Job: S6: Tunnel Spital Nord
Date: 02-02-2000

Point: 1

X	T	C	m
18.82	1.52	-45.85	8.45

alpha: 1.67

Q1: 0.35

☐ X ☐ T ☐ C ☐ m

with top heading invert

without top heading invert

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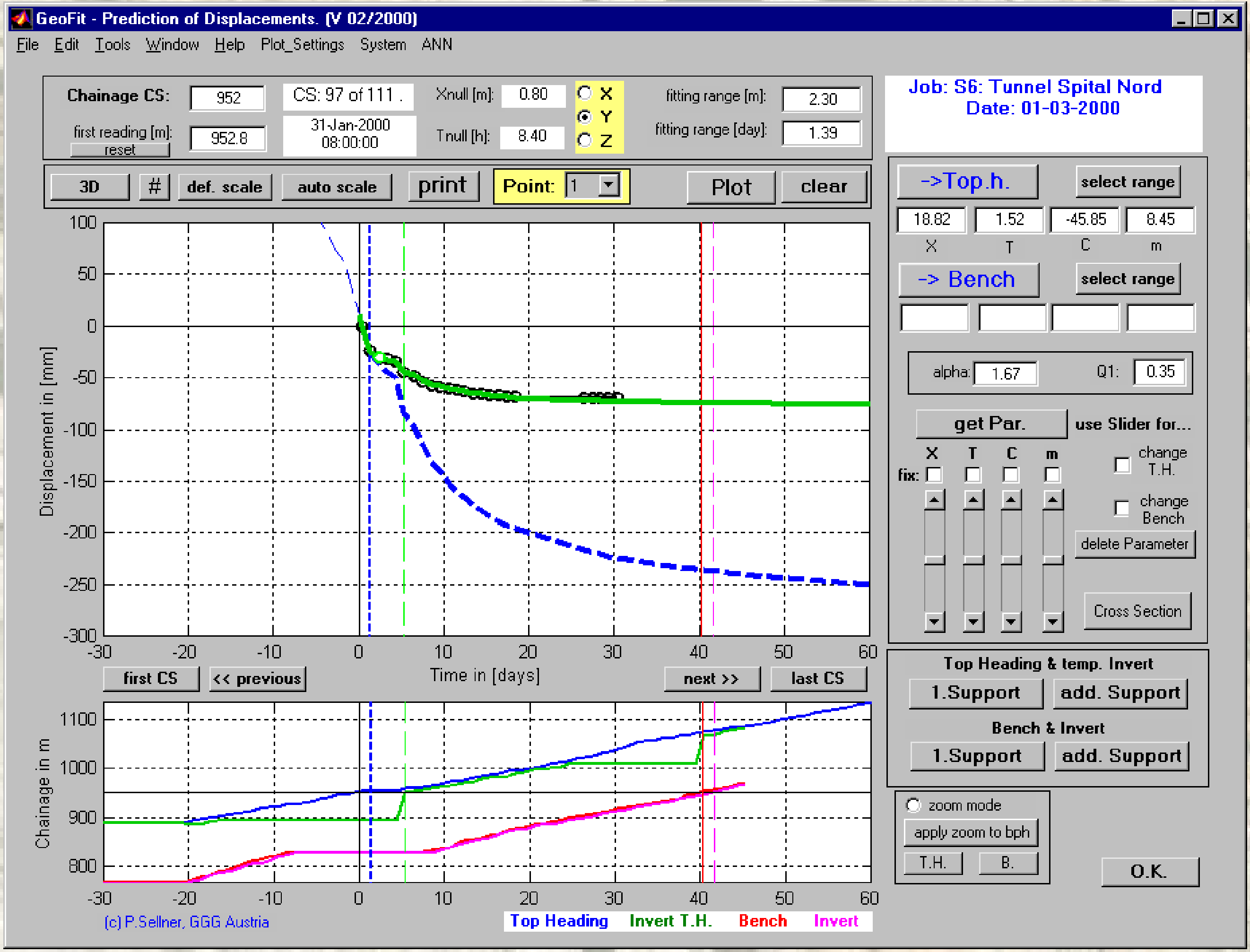
MONITORING / SHORT–TERM PREDICTION

COMPARISON PREDICTION - REALITY



GeoFit - Prediction of Displacements. (V 02/2000)

Chainage CS: 952

CS: 97 of 111 .

first reading [m]: 952.8

31-Jan-2000
08:00:00

Xnull [m]: 0.80

Tnull [h]: 8.40

○ X
● Y
○ Z

fitting range [m]: 2.30

fitting range [day]: 1.39

Job: S6: Tunnel Spital Nord
Date: 01-03-2000

Point: 1

18.82	1.52	-45.85	8.45
X	T	C	m

alpha: 1.67

Q1: 0.35

fix: ☐ ☐ ☐ ☐

☐ change T.H.

☐ change Bench

○ zoom mode

(c) P.Sellner, GGG Austria

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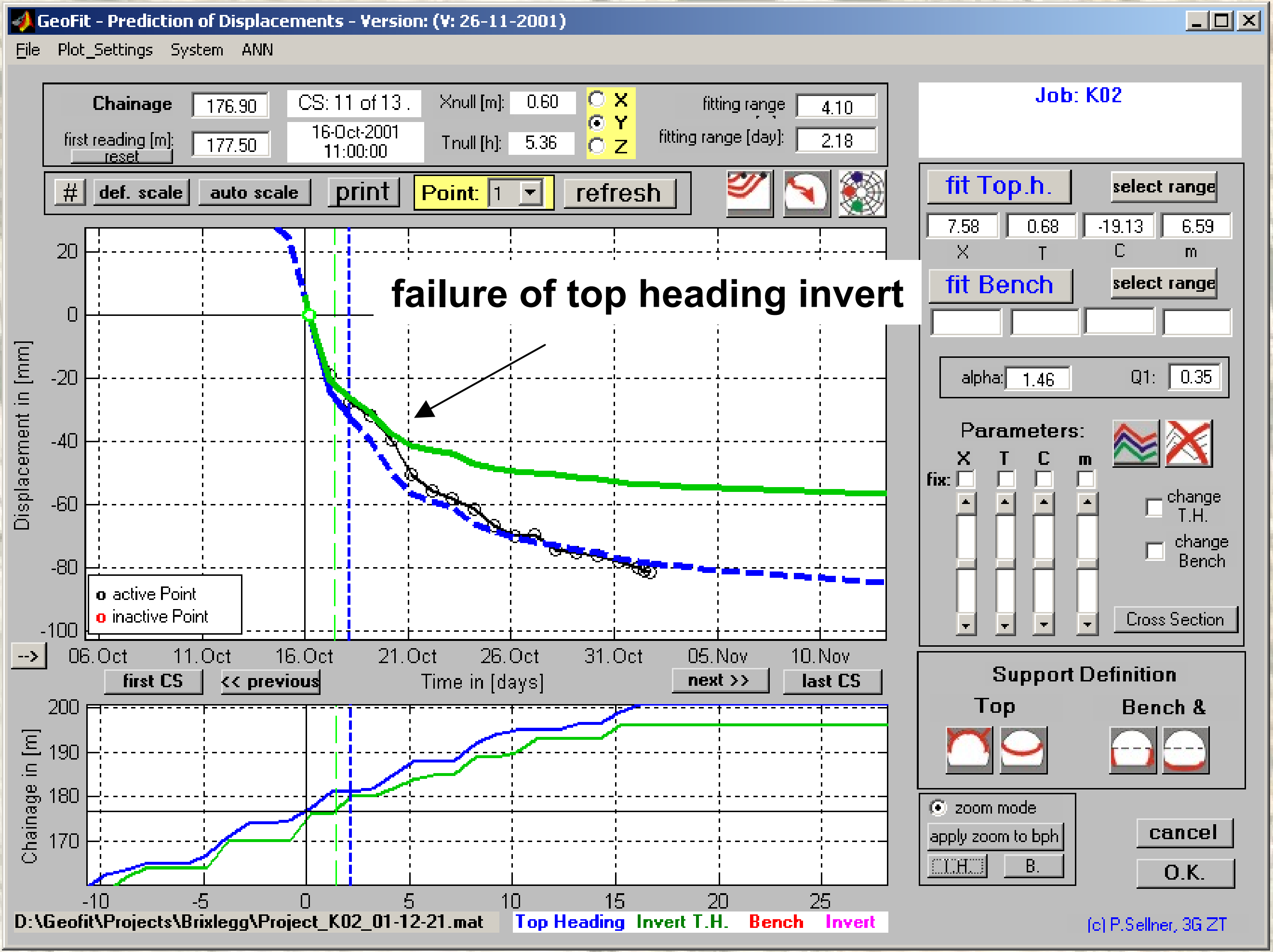
MONITORING / SHORT–TERM PREDICTION

DEVIATIONS FROM PREDICTION



GeoFit - Prediction of Displacements - Version: (V: 26-11-2001)

Chainage 176.90

CS: 11 of 13 .

first reading [m]: 177.50

16-Oct-2001 11:00:00

Xnull [m]: 0.60

Tnull [h]: 5.36

○ X
● Y
○ Z

fitting range 4.10

fitting range [day]: 2.18

Point: 1

Job: K02

fit Top.h.: X 7.58, T 0.68, C -19.13, m 6.59

alpha: 1.46

Q1: 0.35

Parameters: X T C m

fix: ☐ ☐ ☐ ☐

☐ change T.H.

☐ change Bench

● zoom mode

D:\Geofit\Projects\Brixlegg\Project_K02_01-12-21.mat

failure of top heading invert

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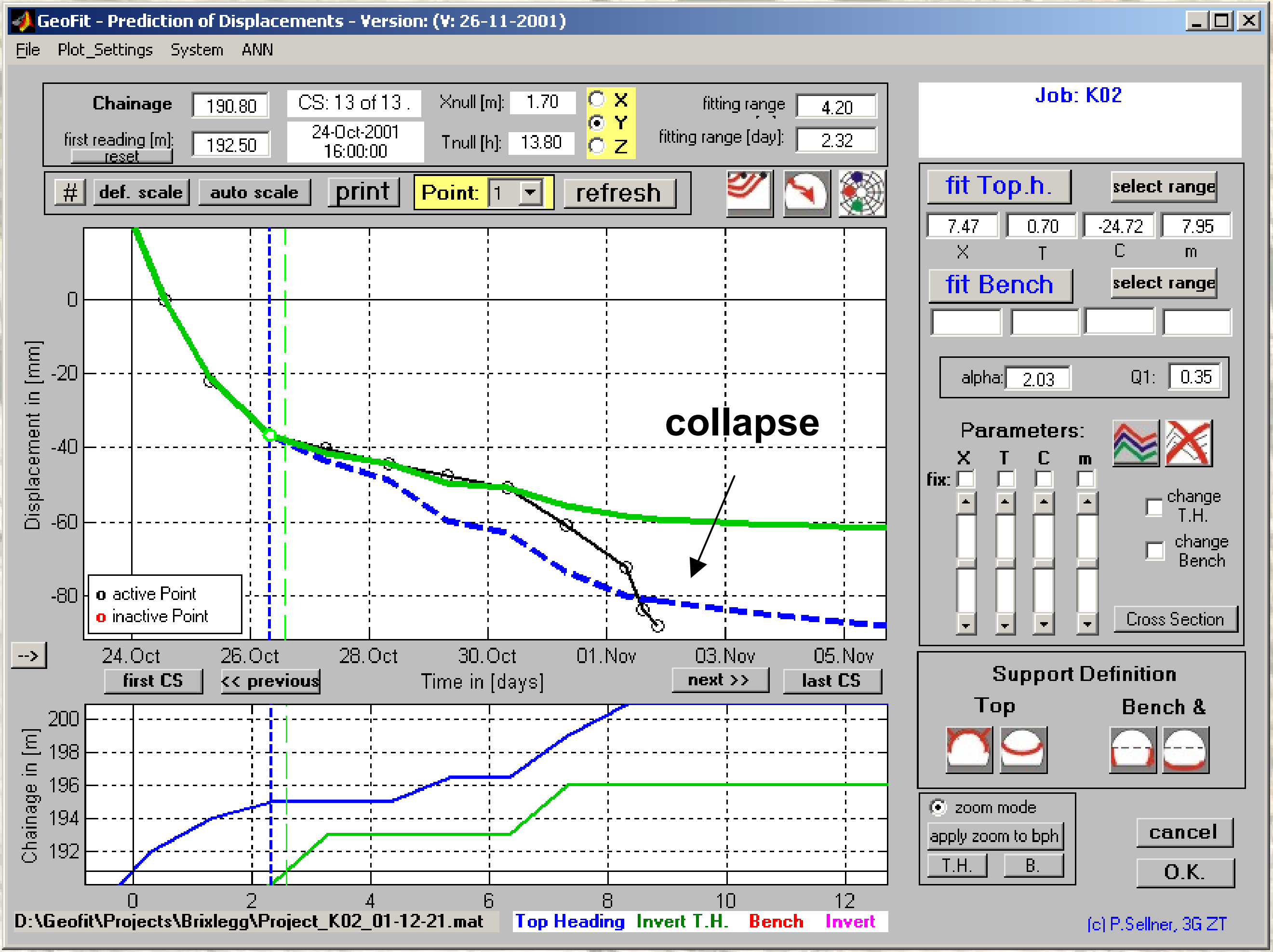
MONITORING / SHORT–TERM PREDICTION

DEVIATIONS FROM PREDICTION



GeoFit - Prediction of Displacements - Version: (V: 26-11-2001)

Chainage: 190.80

CS: 13 of 13 .

Xnull [m]: 1.70

first reading [m]: 192.50

24-Oct-2001 16:00:00

Tnull [h]: 13.80

○ X ● Y ○ Z

fitting range: 4.20

fitting range [day]: 2.32

Point: 1

Job: K02

fit Top.h.: X 7.47, T 0.70, C -24.72, m 7.95

alpha: 2.03

Q1: 0.35

Parameters: fix: X ☐ T ☐ C ☐ m ☐

☐ change T.H.

☐ change Bench

● zoom mode

D:\Geofit\Projects\Brixlegg\Project_K02_01-12-21.mat

collapse

Construction

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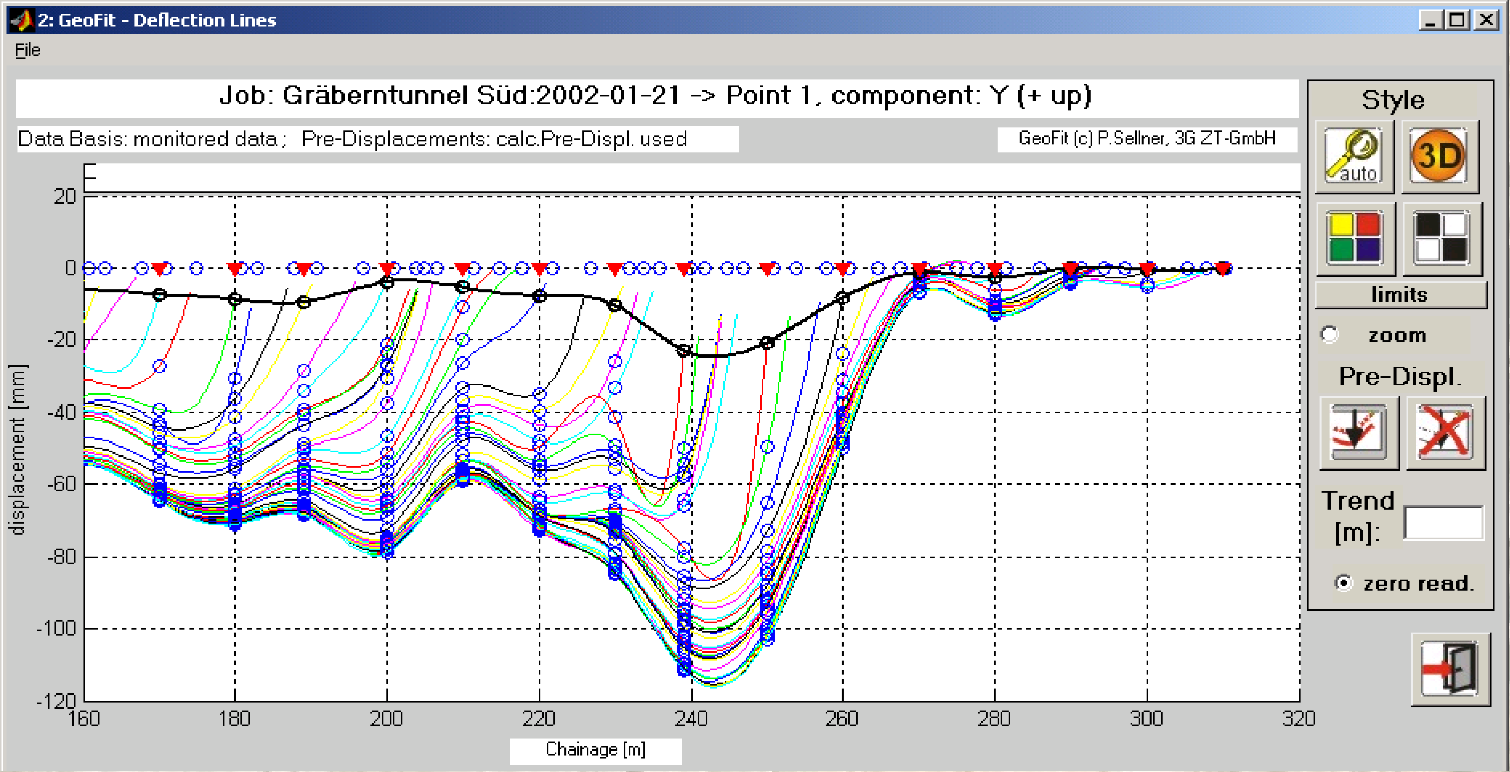
MONITORING / SHORT–TERM PREDICTION

Construction

ROOF SETTLEMENTS, DEFLECTION CURVES



2: GeoFit - Deflection Lines

Job: Gräberntunnel Süd:2002-01-21 -> Point 1, component: Y (+ up)

Data Basis: monitored data ; Pre-Displacements: calc.Pre-Displ. used

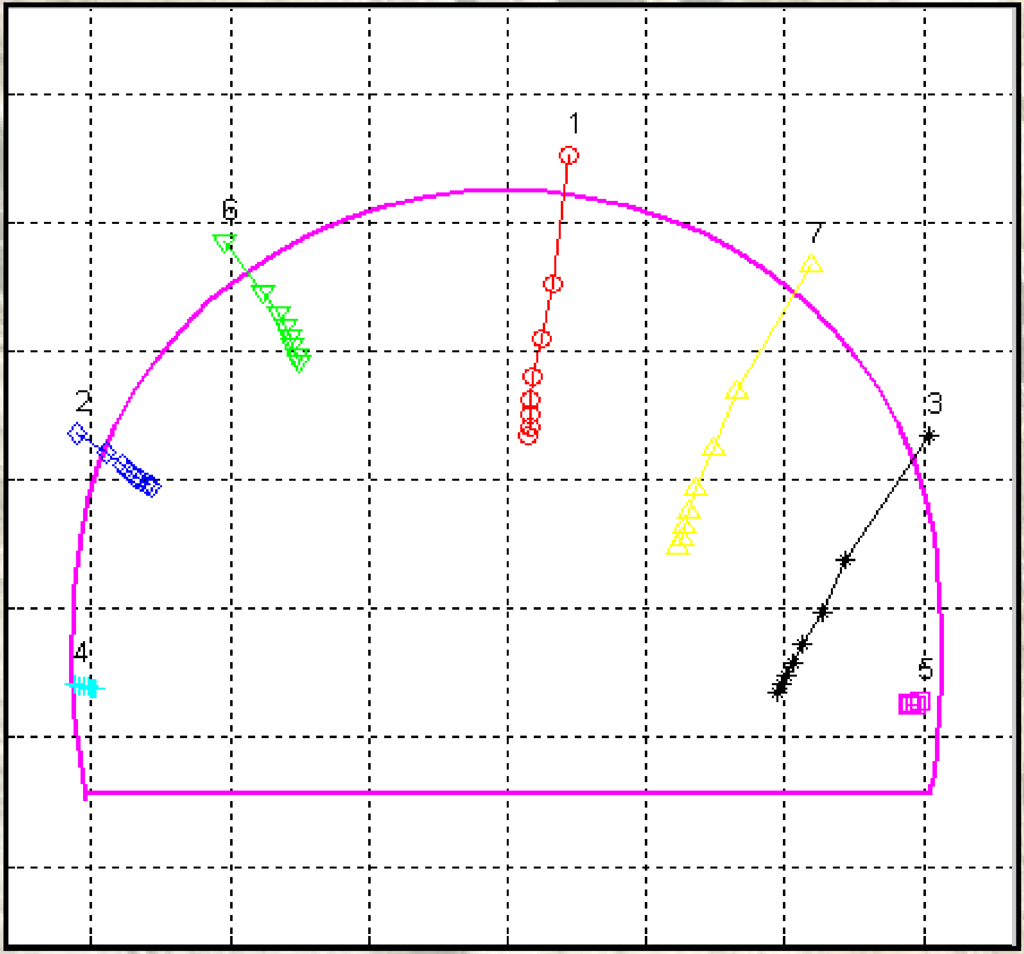
GeoFit (c) P.Sellner, 3G ZT-GmbH

Gräbern Tunnel, Austria

Gruppe Geotechnik Graz ZT GMBH

MONITORING / SHORT–TERM PREDICTION

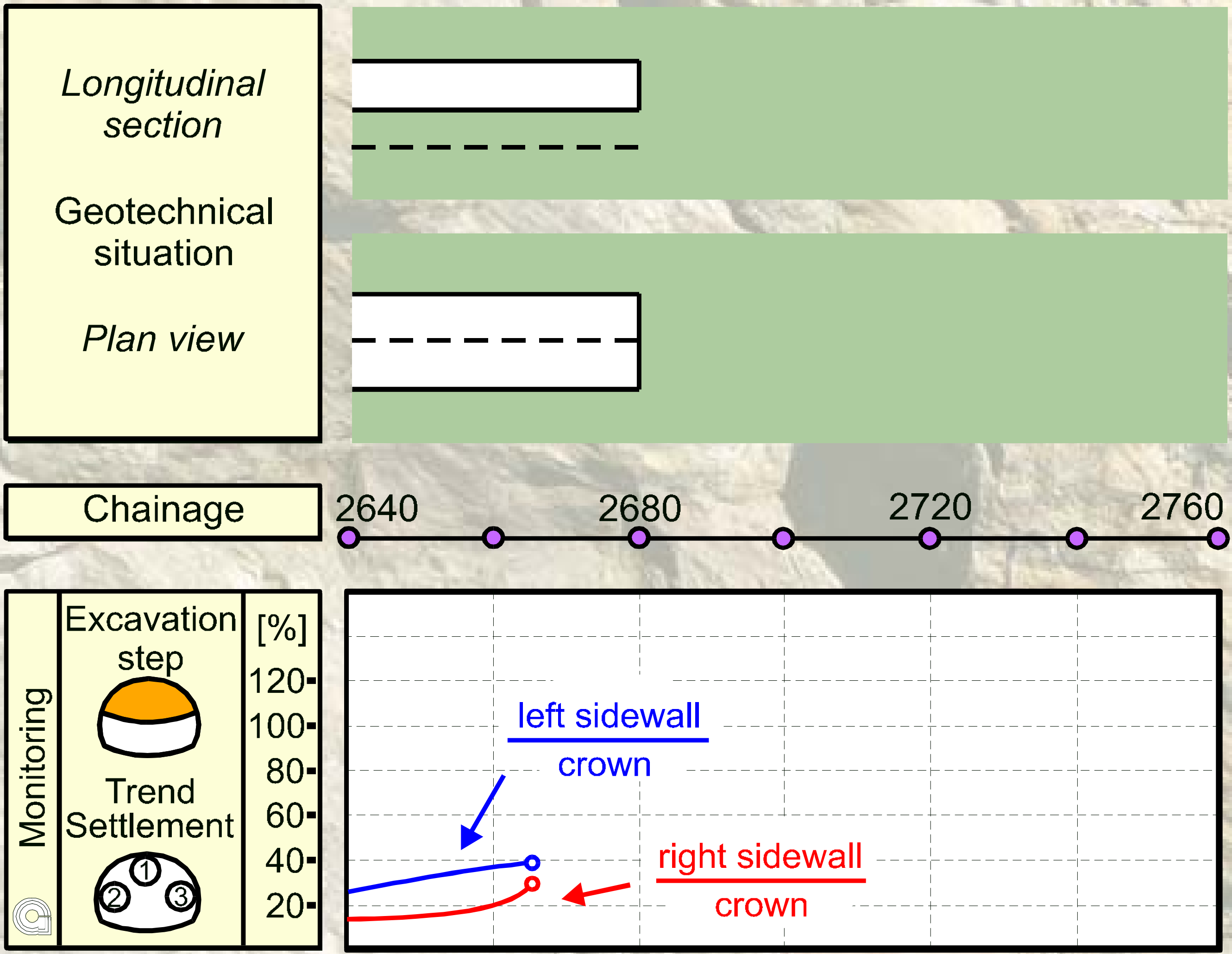
DISPLACEMENT VECTORS



Gräbern Tunnel, Austria

MONITORING / SHORT–TERM PREDICTION

DISPLACEMENT RATIO



Longitudinal section

Geotechnical situation

Plan view

Chainage

Construction

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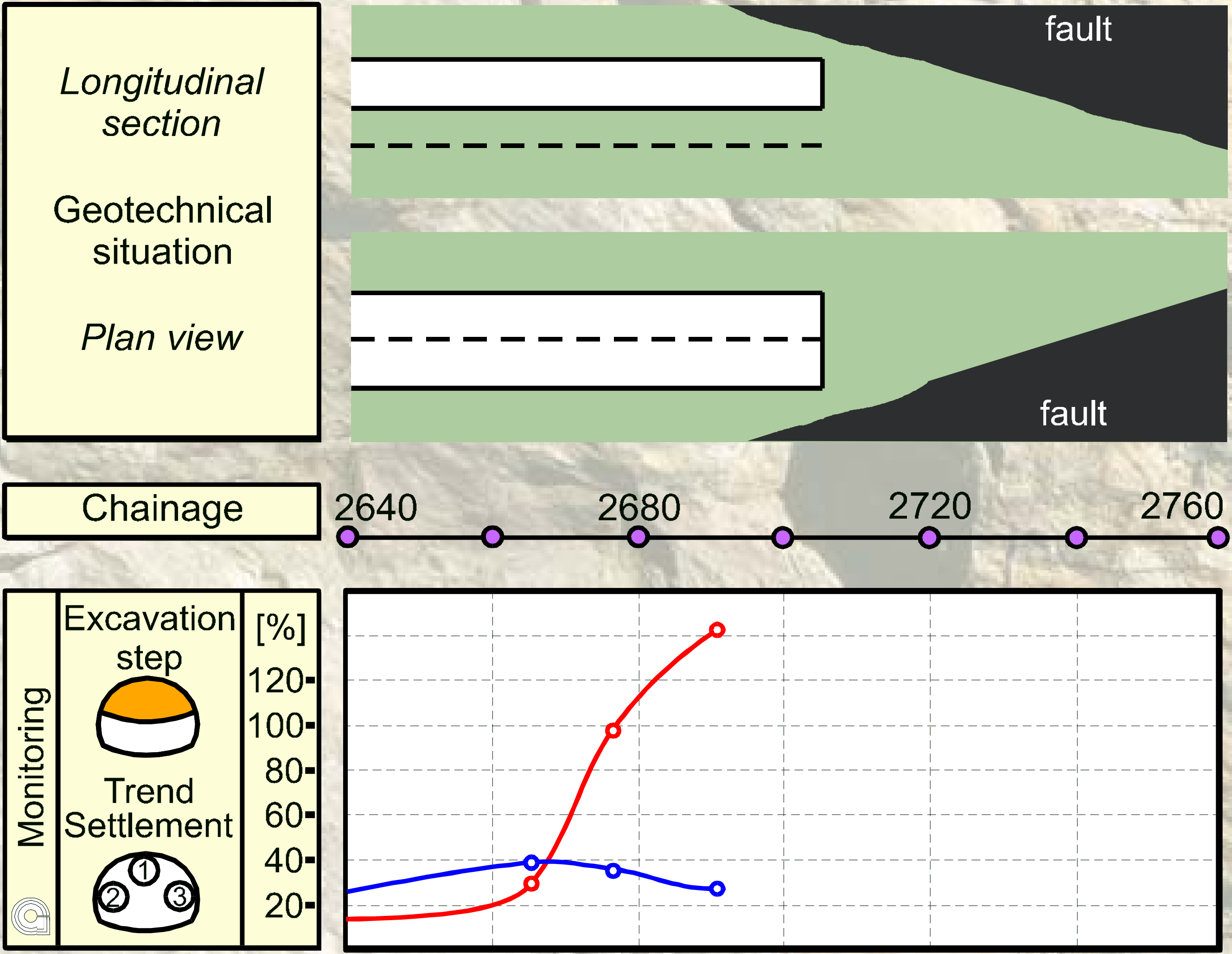
DISPLACEMENT RATIO

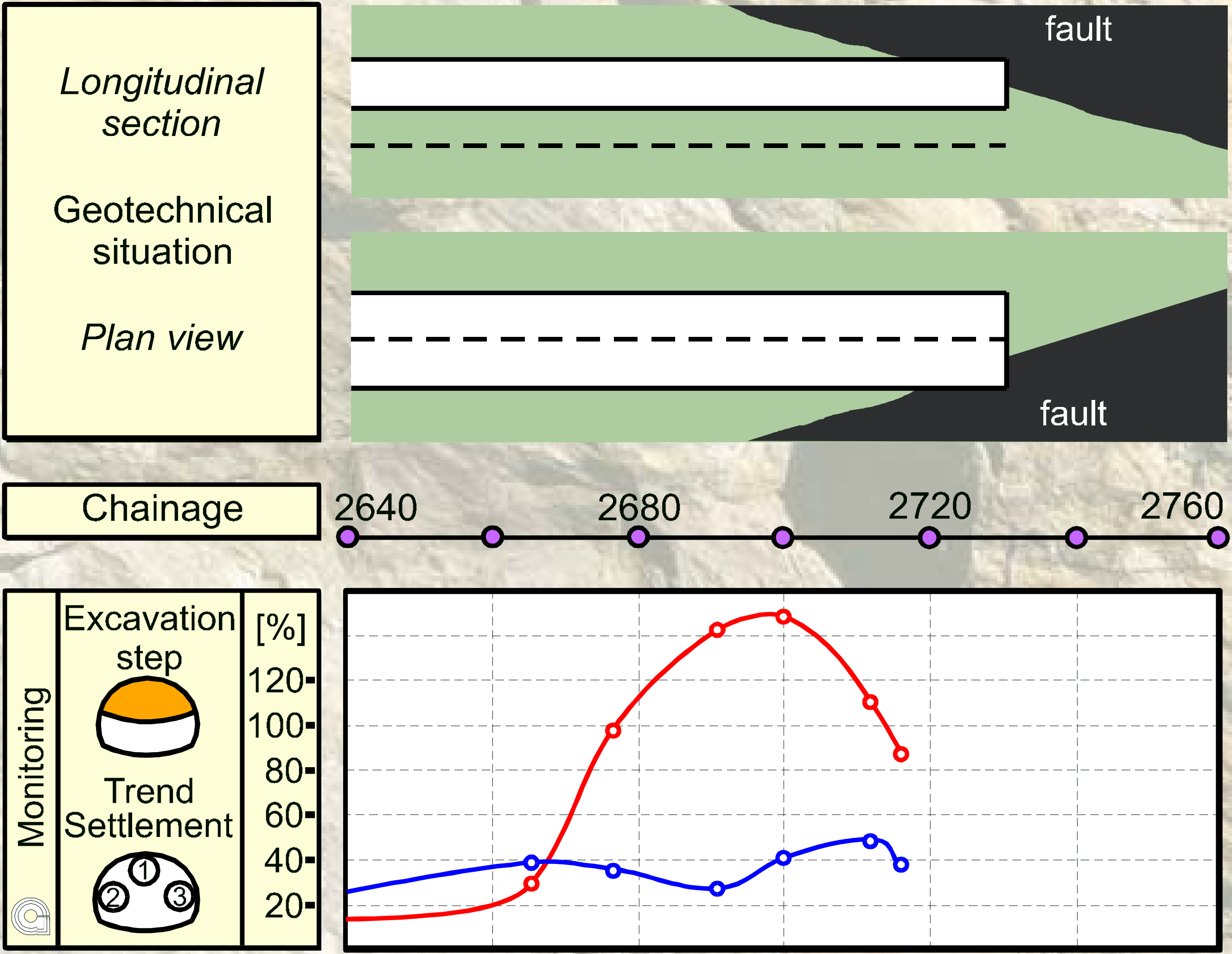


Construction

Gruppe Geotechnik Graz ZT GMBH

MONITORING / SHORT–TERM PREDICTION

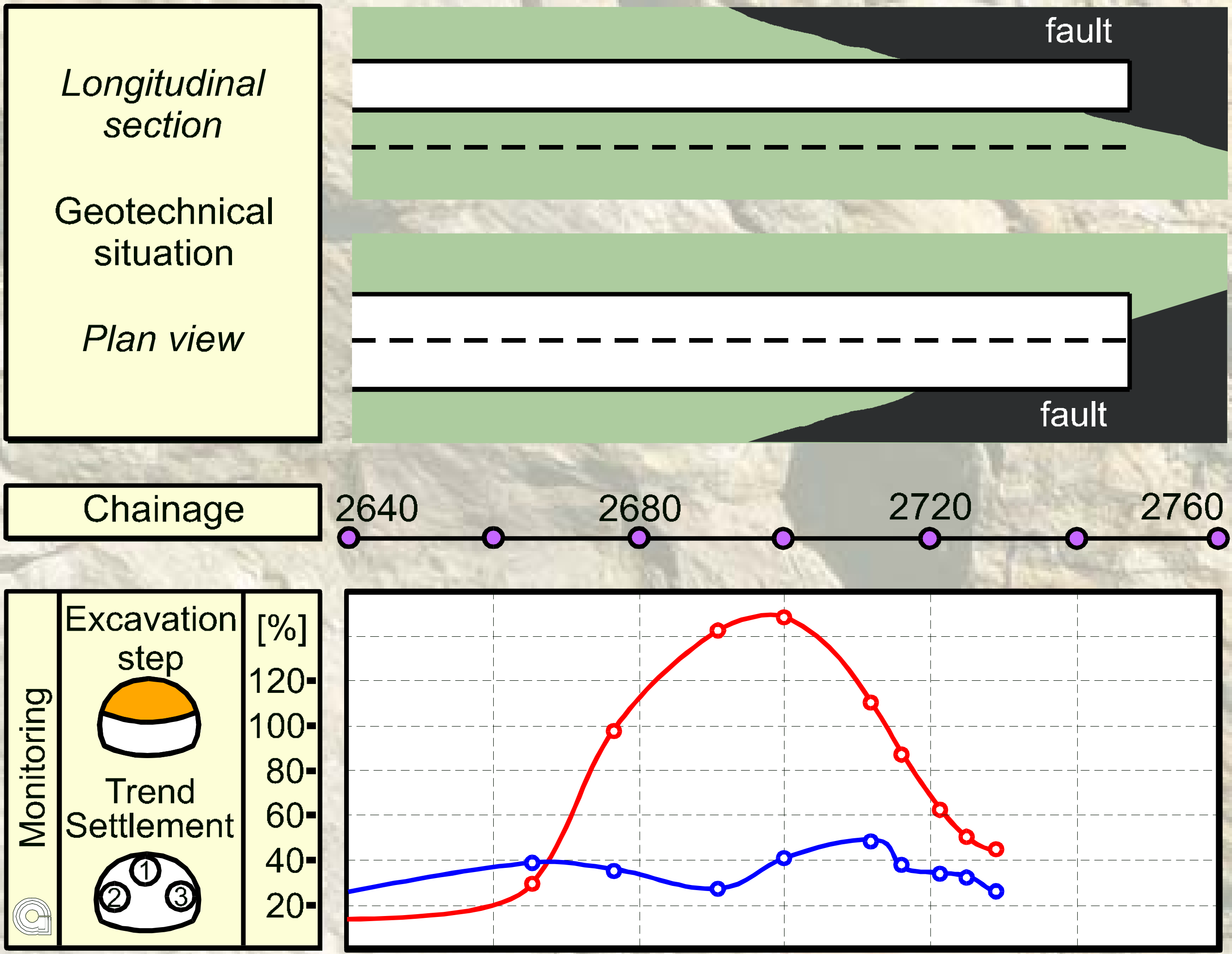
DISPLACEMENT RATIO



MONITORING / SHORT–TERM PREDICTION

Construction

DISPLACEMENT RATIO



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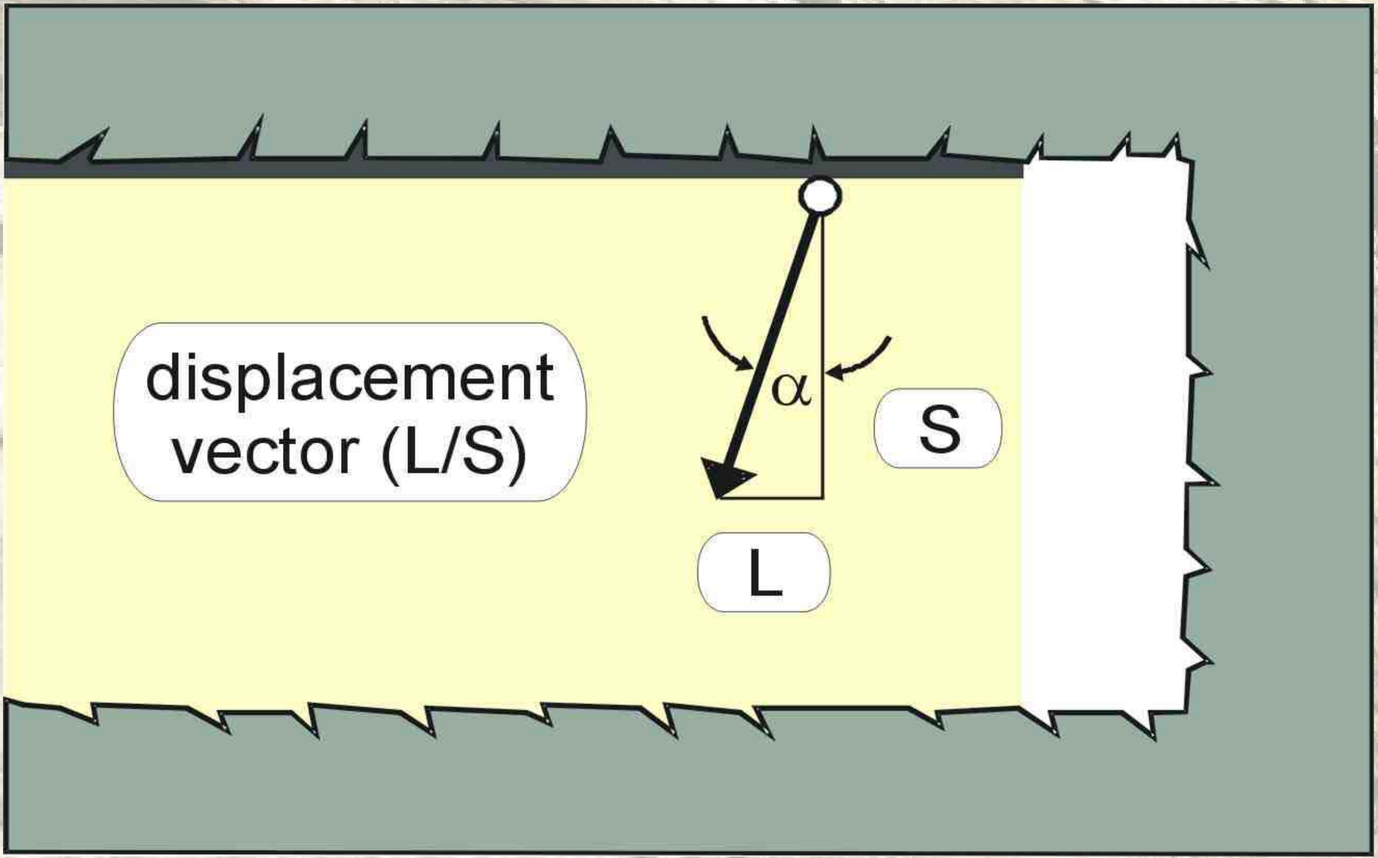
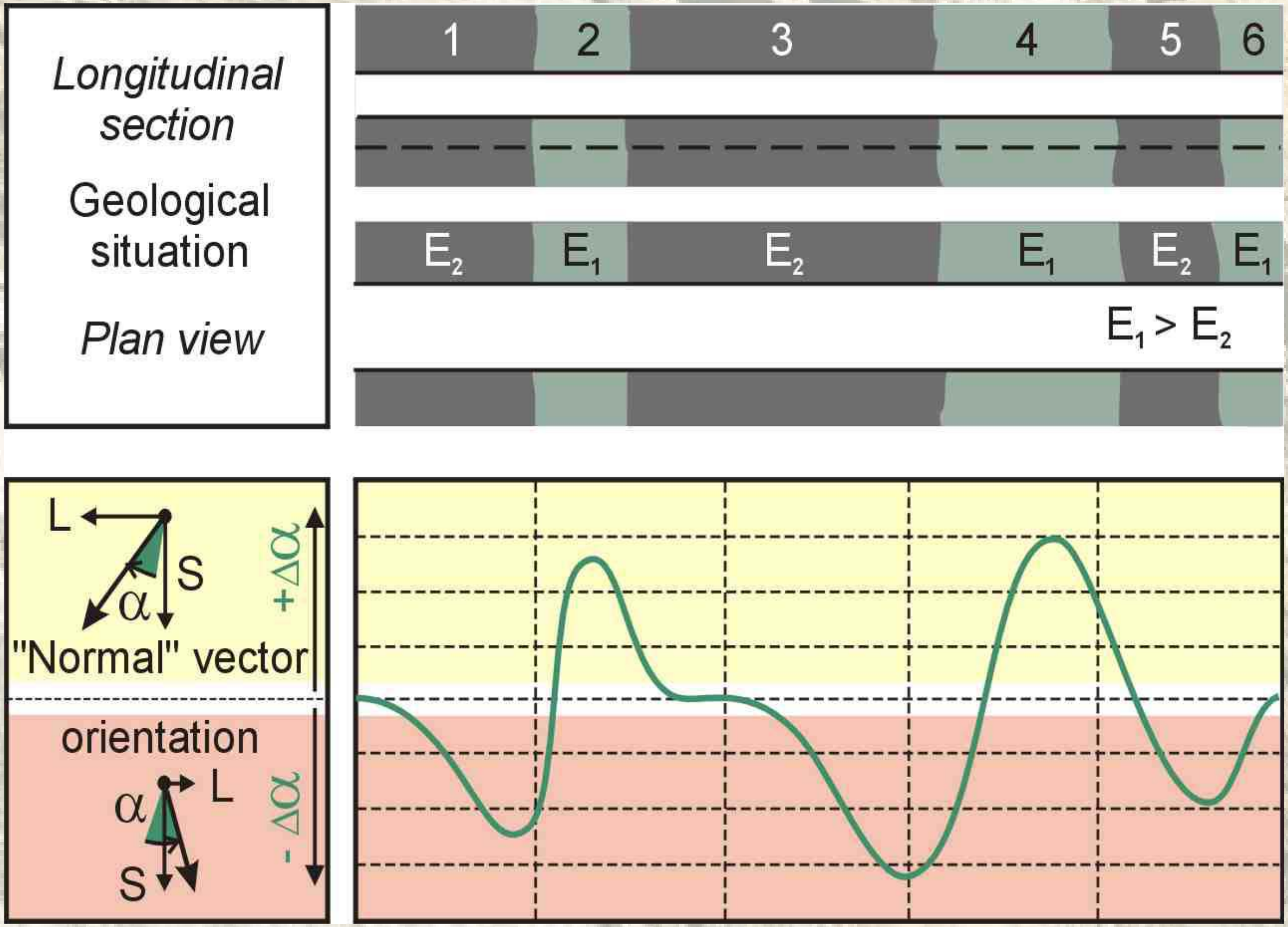
MONITORING / SHORT–TERM PREDICTION

DISPLACEMENT VECTOR ORIENTATION



MONITORING / SHORT–TERM PREDICTION

HETEROGENEITY – VECTOR ORIENTATION



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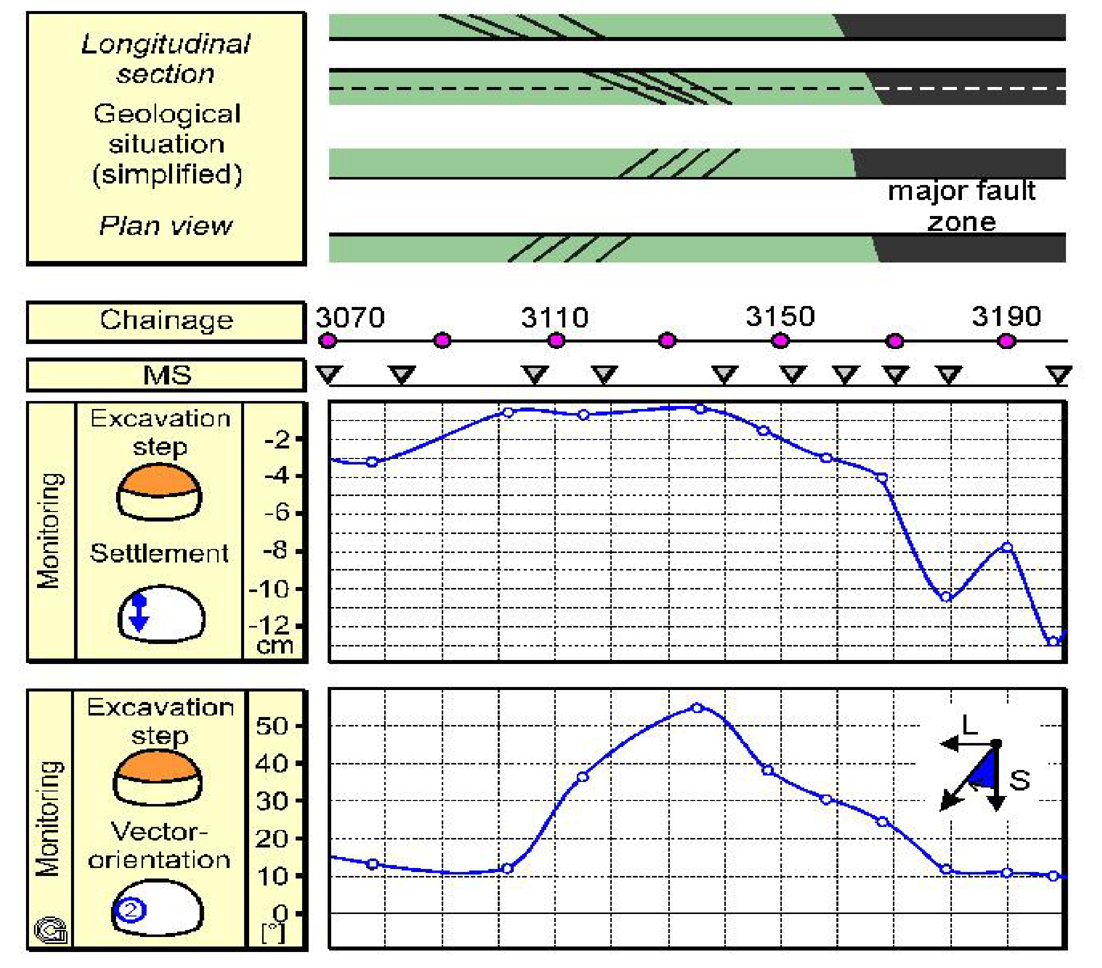
MONITORING / SHORT–TERM PREDICTION

SETTLEMENT & VECTOR ORIENTATION TRENDS



Construction

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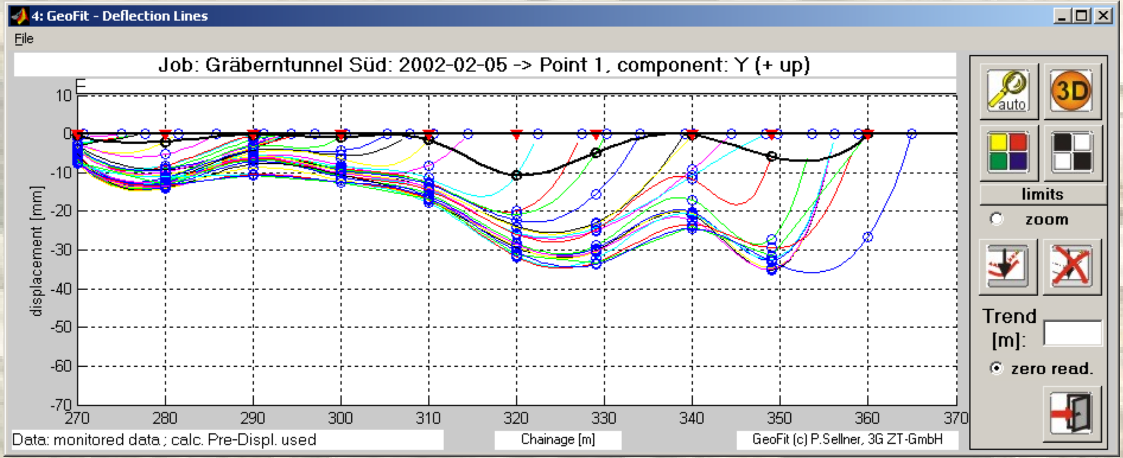
MONITORING / SHORT–TERM PREDICTION

DEFLECTION CURVE & VECTOR ORIENTATION TRENDS



4: GeoFit - Deflection Lines

File

Job: Gräberntunnel Süd: 2002-02-05 -> Point 1, component: Y (+ up)

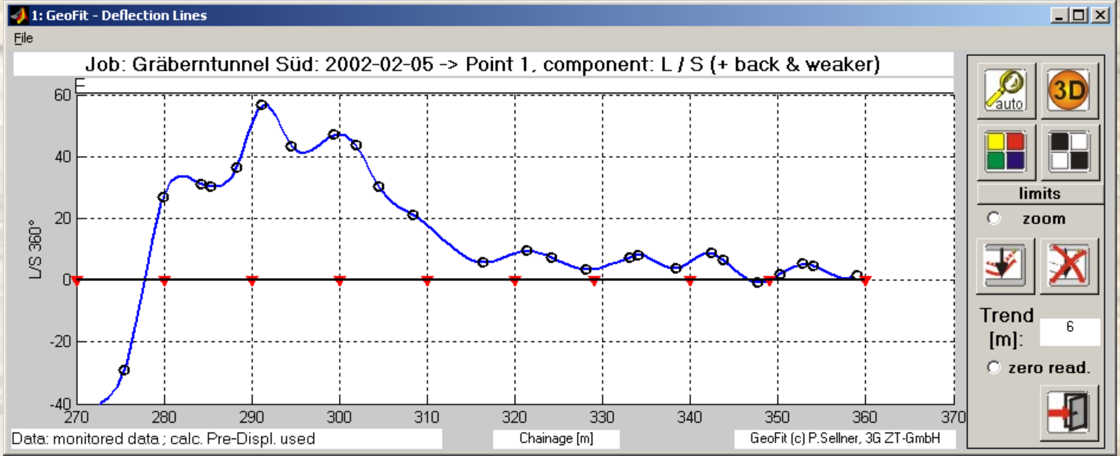
Data: monitored data ; calc. Pre-Displ. used

Chainage [m]

GeoFit (c) P.Sellner, 3G ZT-GmbH

Trend [m]:

● zero read.



1: GeoFit - Deflection Lines

File

Job: Gräberntunnel Süd: 2002-02-05 -> Point 1, component: L / S (+ back & weaker)

Data: monitored data ; calc. Pre-Displ. used

Chainage [m]

GeoFit (c) P.Sellner, 3G ZT-GmbH

Trend [m]: 6

○ zero read.

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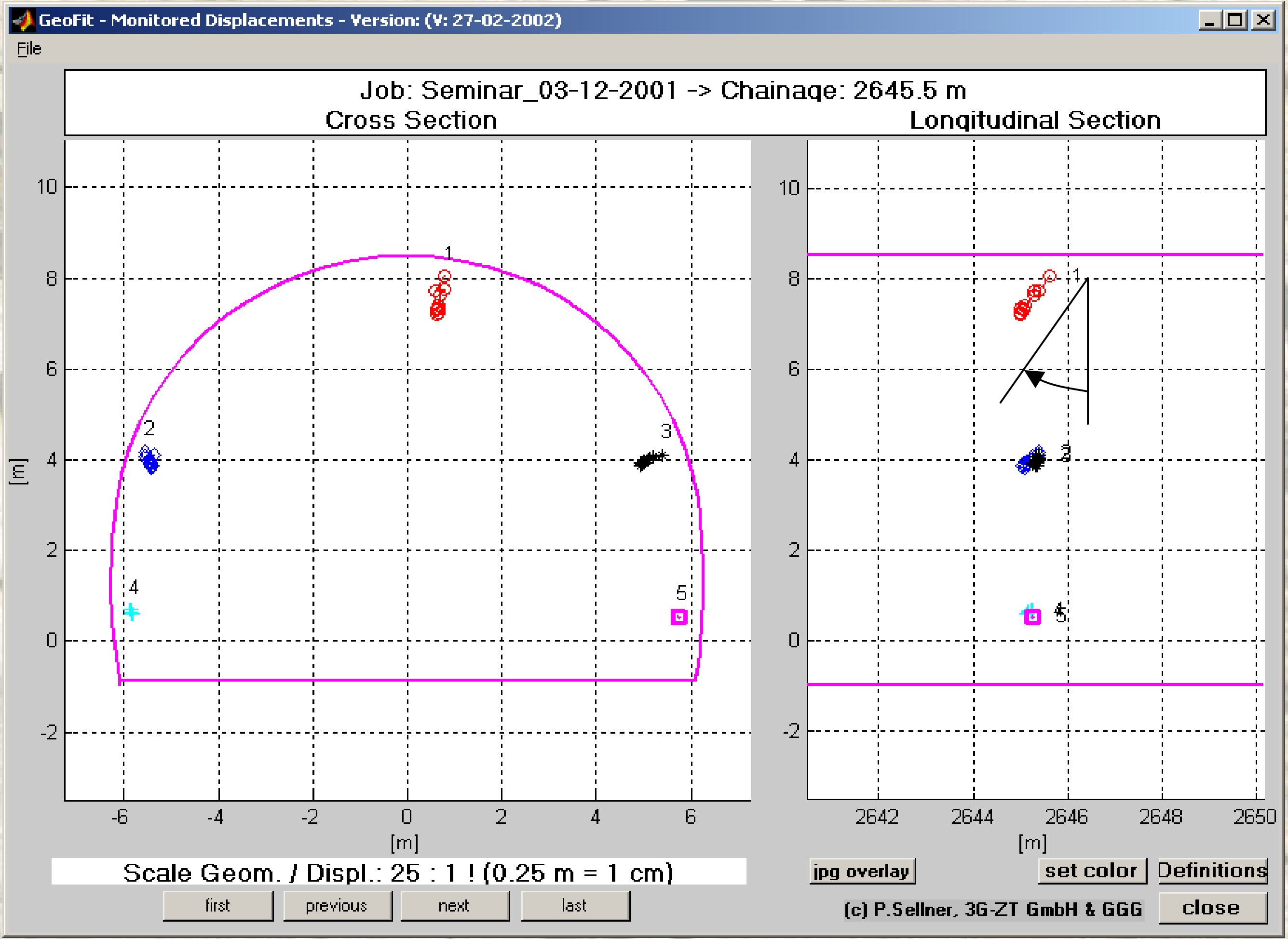
MONITORING / SHORT–TERM PREDICTION

DISPLACEMENT VECTORS



GeoFit - Monitored Displacements - Version: (V: 27-02-2002)

Job: Seminar_03-12-2001 -> Chainage: 2645.5 m

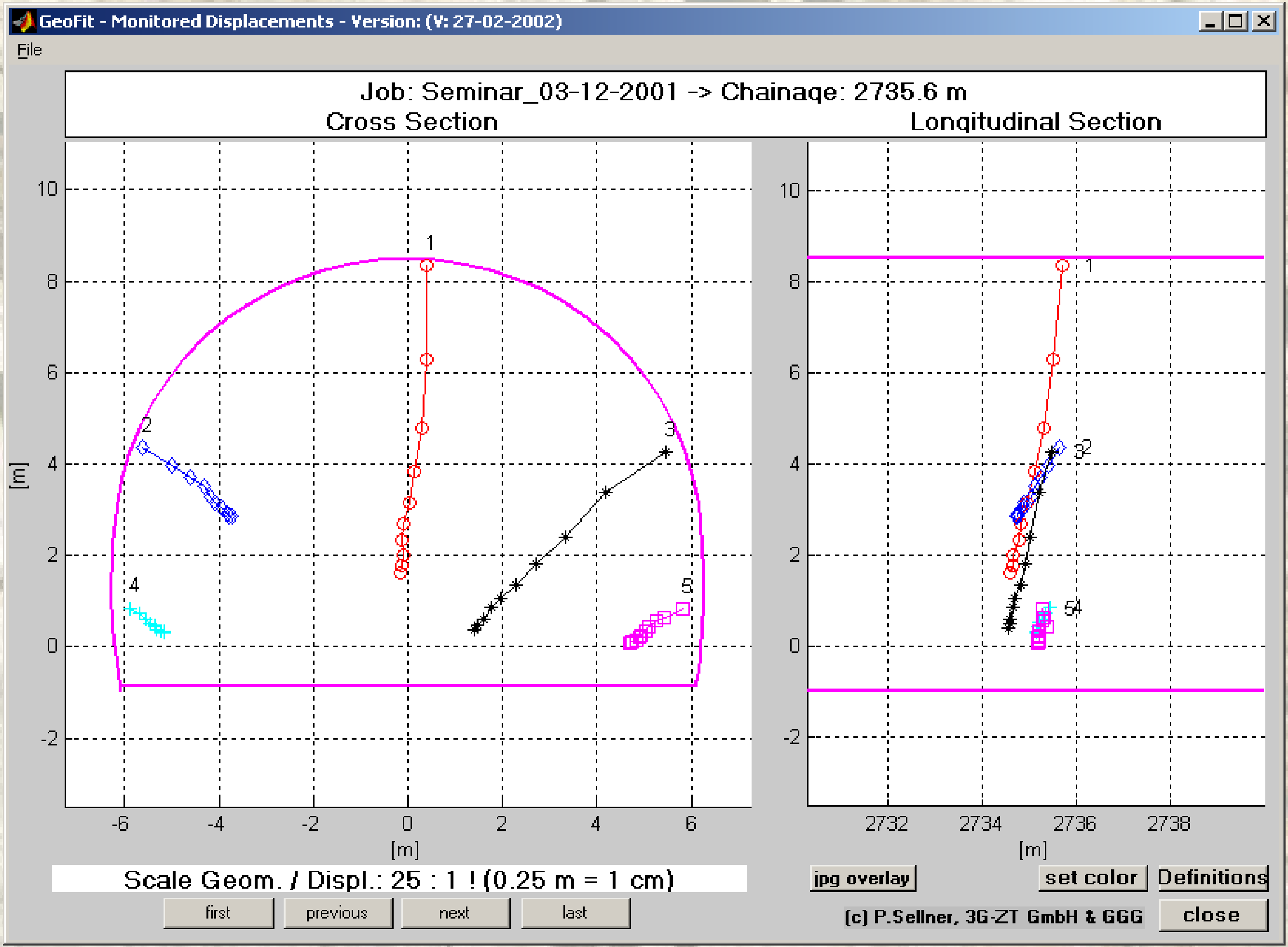
Scale Geom. / Displ.: 25 : 1 ! (0.25 m = 1 cm)

(c) P.Sellner, 3G-ZT GmbH & GGG

Inntal Tunnel, Austria

MONITORING / SHORT–TERM PREDICTION

DISPLACEMENT VECTORS



GeoFit - Monitored Displacements - Version: (V: 27-02-2002)

Job: Seminar_03-12-2001 -> Chainage: 2735.6 m

Scale Geom. / Displ.: 25 : 1 ! (0.25 m = 1 cm)

(c) P.Sellner, 3G-ZT GmbH & GGG

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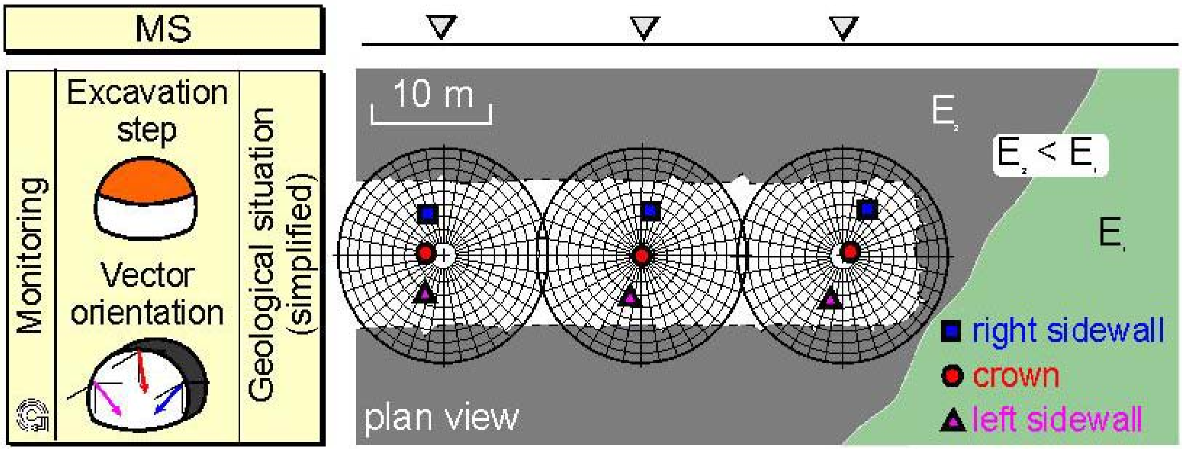
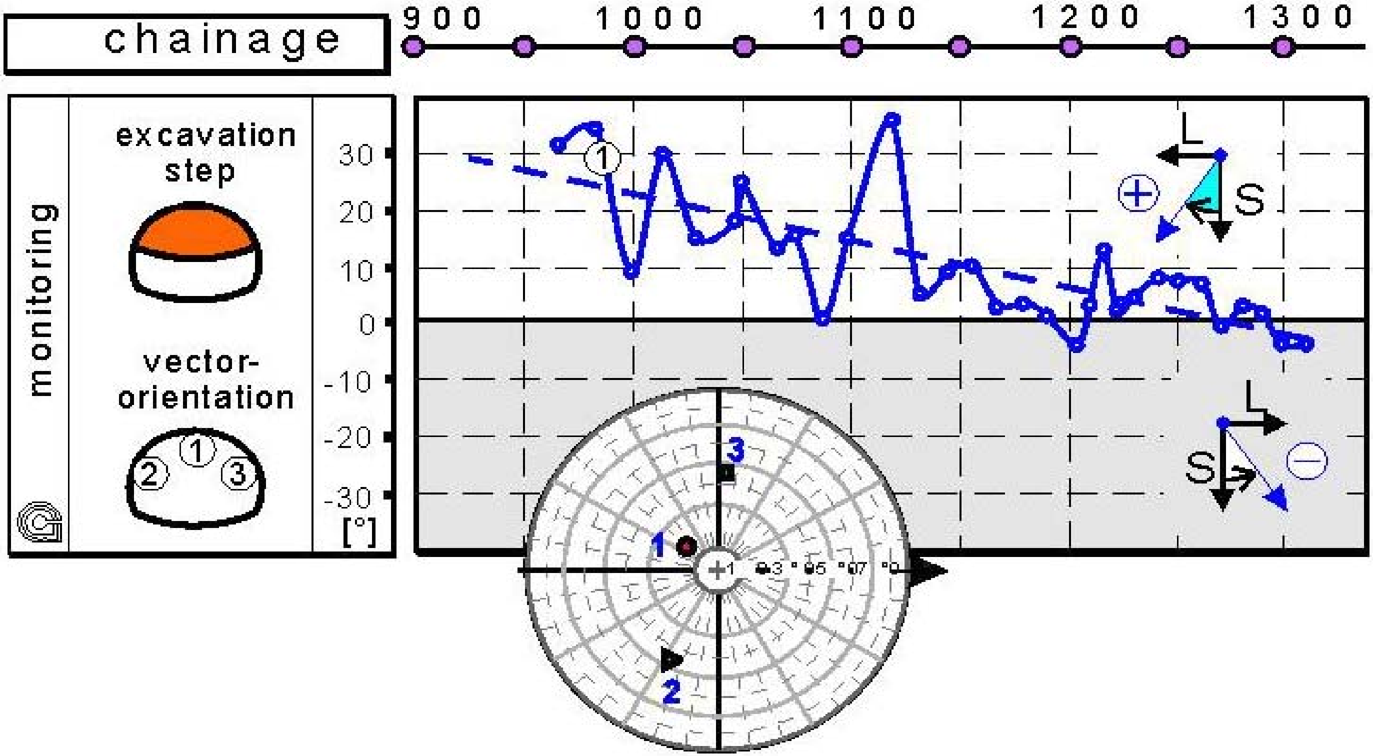
MONITORING / SHORT–TERM PREDICTION

SPATIAL DISPLACEMENT VECTOR



MONITORING / SHORT–TERM PREDICTION

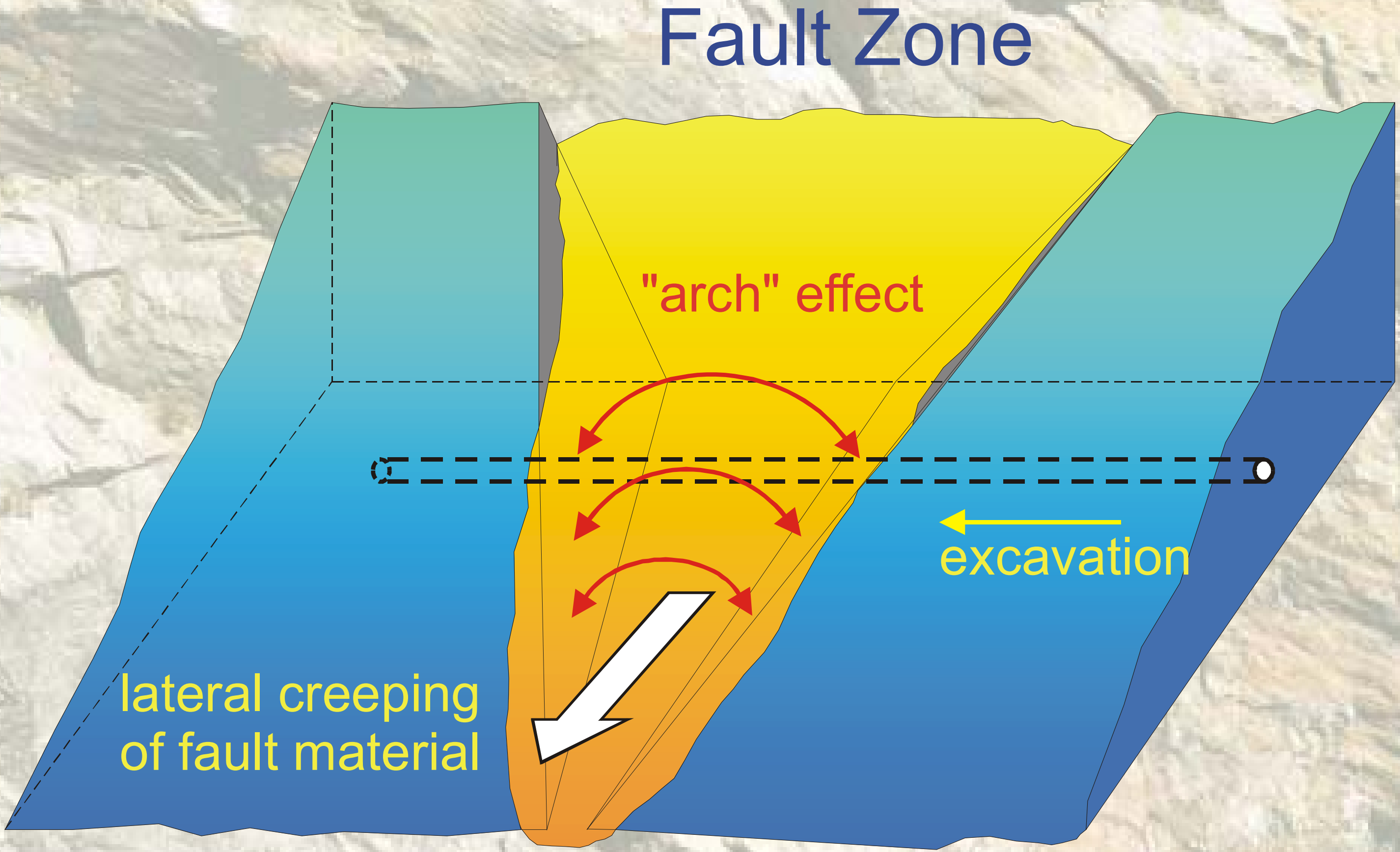
VECTOR ORIENTATION - TREND



Hinterberg Fault Zone, Galgenberg Tunnel, Austria

MONITORING / SHORT–TERM PREDICTION

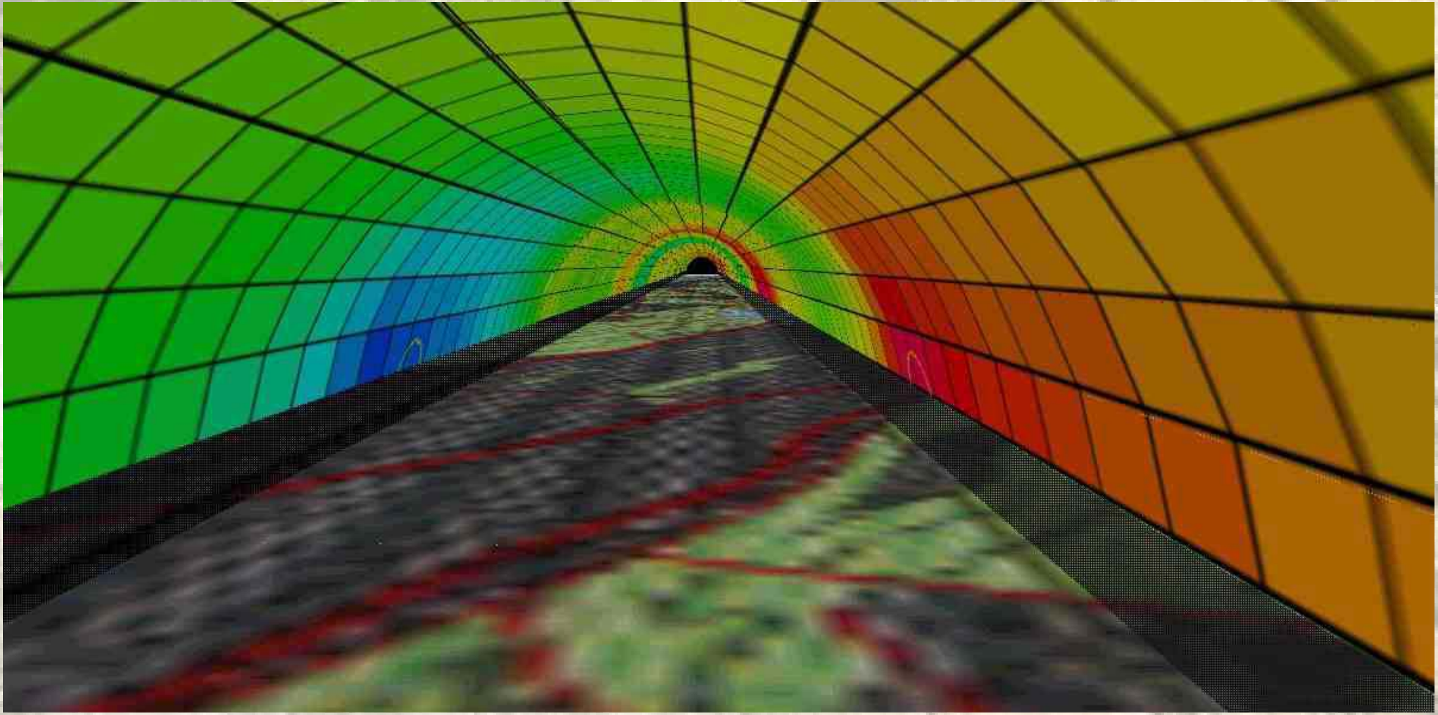
ARCH EFFECT



Hinterberg Fault Zone, Galgenberg Tunnel, Austria

MONITORING / SHORT–TERM PREDICTION

VISUALIZATION OF MONITORED DATA



Hinterberg Fault Zone, Galgenberg Tunnel, Austria

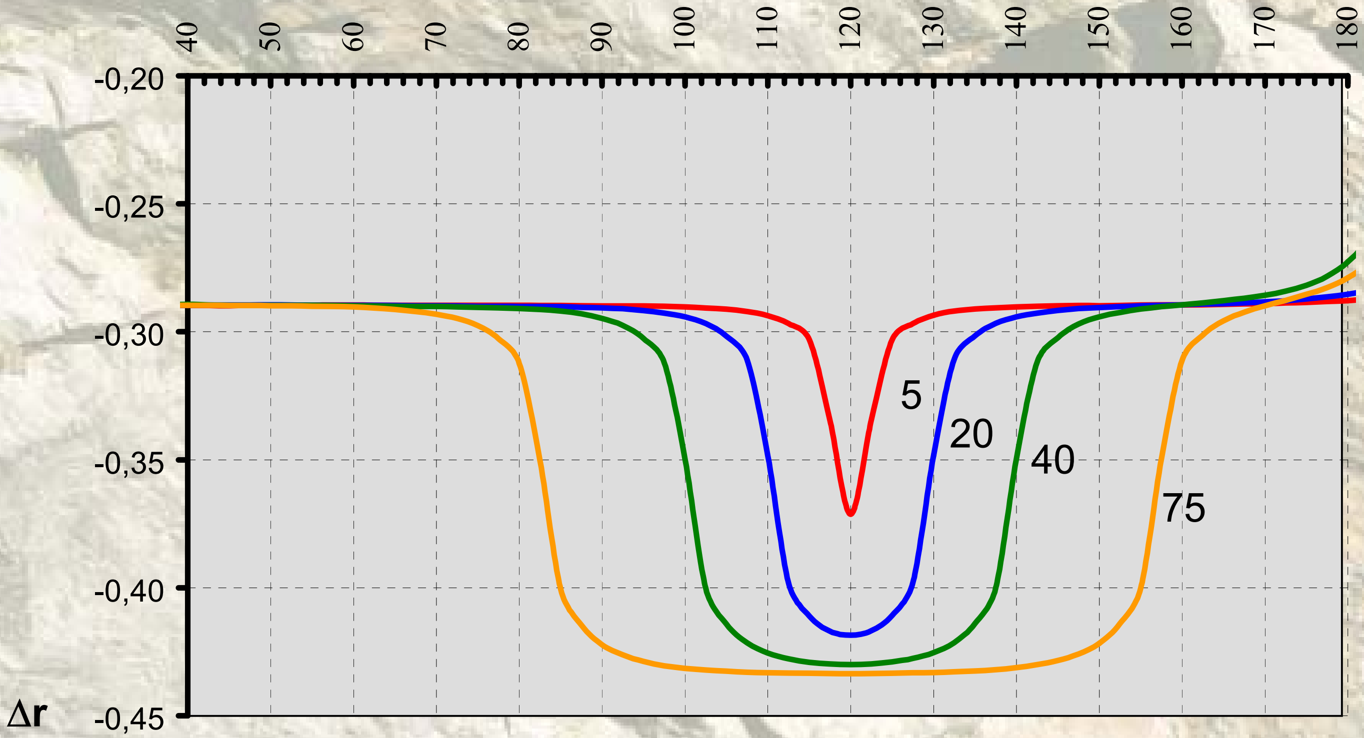
BIMROCK EFFECTS

- Mixed face conditions require different excavation methods on the same section
- Strong variation of rock mass quality
- Stress redistribution and deformations extremely influenced by arrangement of blocks and matrix
- Prediction of displacements and lining utilization extremely difficult
- Danger of brittle failures in blocks
- Difficulty to determine proper support

BIMROCK EFFECTS

DISPLACEMENTS IN MATRIX IN RELATION TO BLOCK DISTANCE PROBLEMS

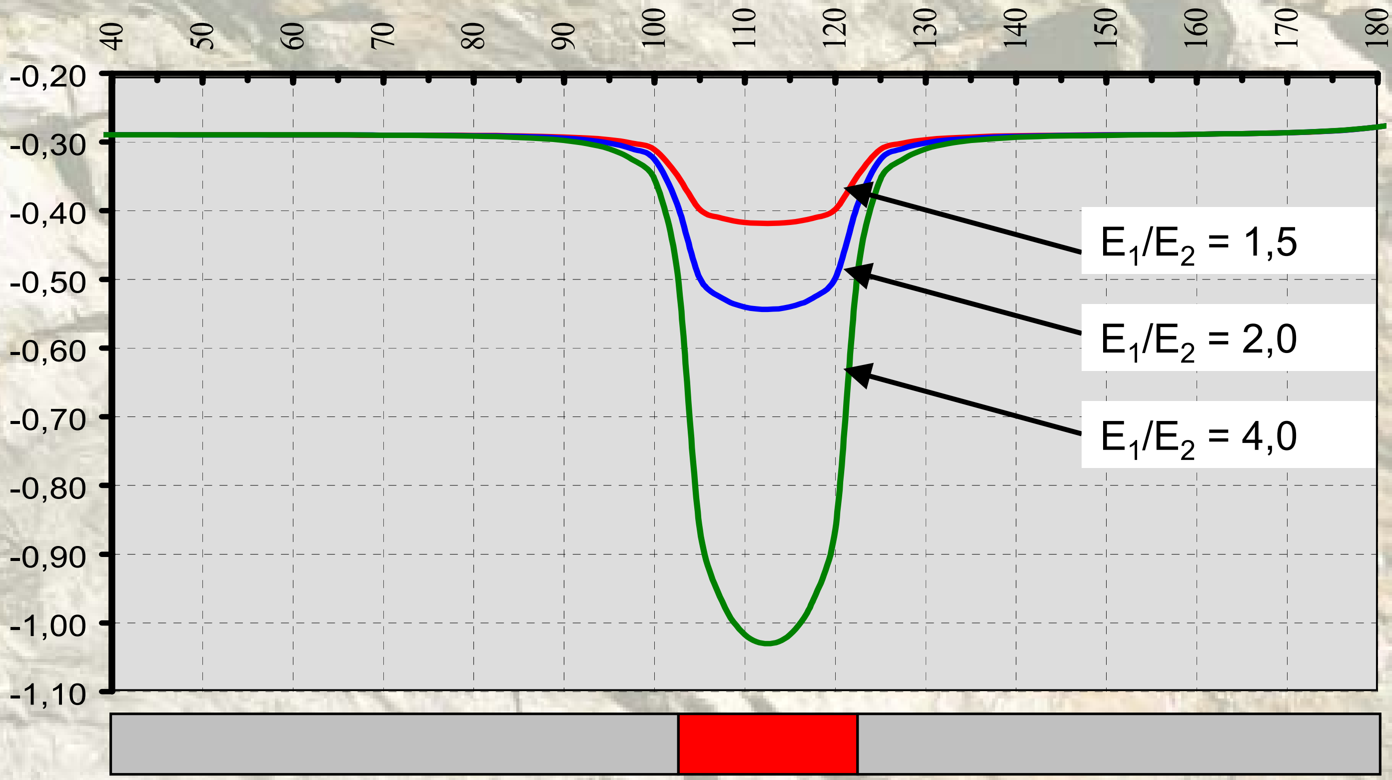
- Displacements depend on the length of the weak zone between two stiff blocks



BIMROCK EFFECTS

DISPLACEMENTS

- Final displacements influenced by zone length and stiffness contrast



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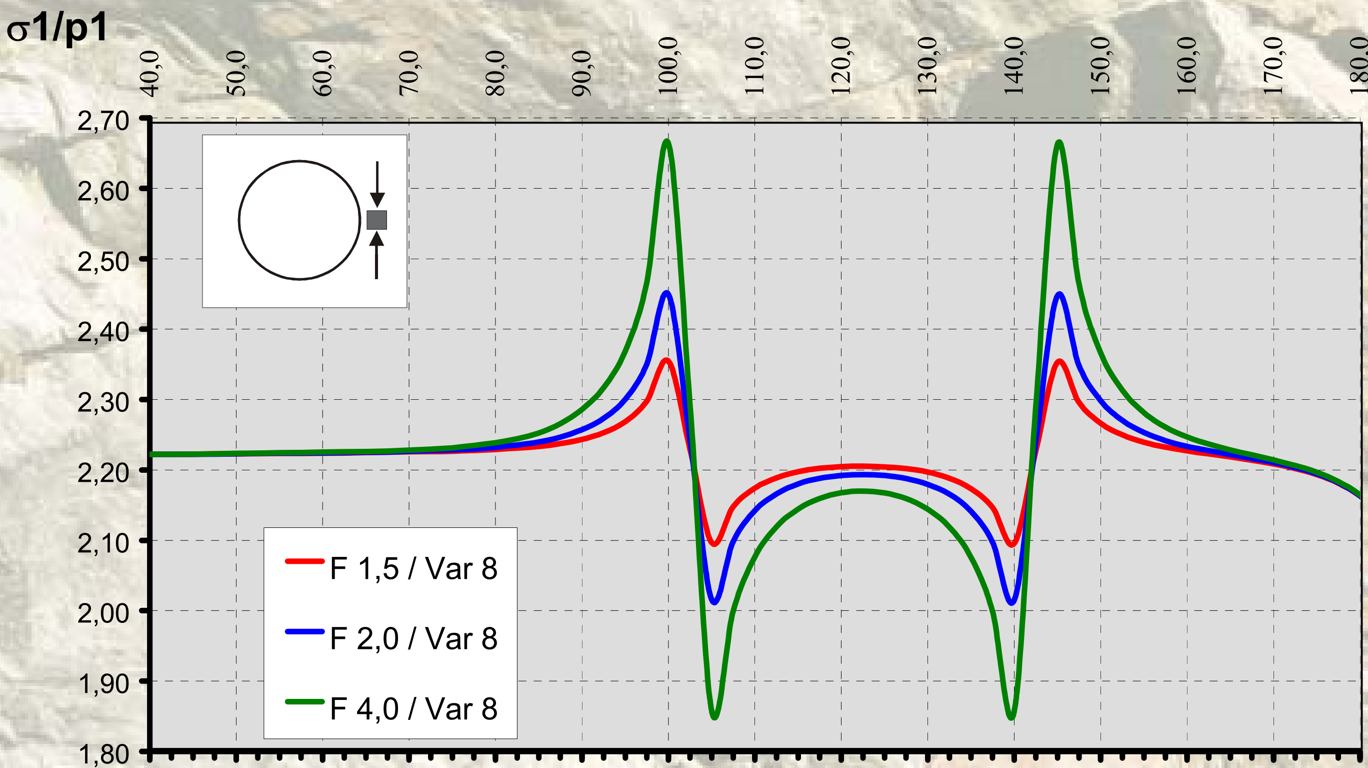
BIMROCK EFFECTS

STRESS DISTRIBUTION

- Stress concentation in blocks depend on stiffness contrast and distance between blocks



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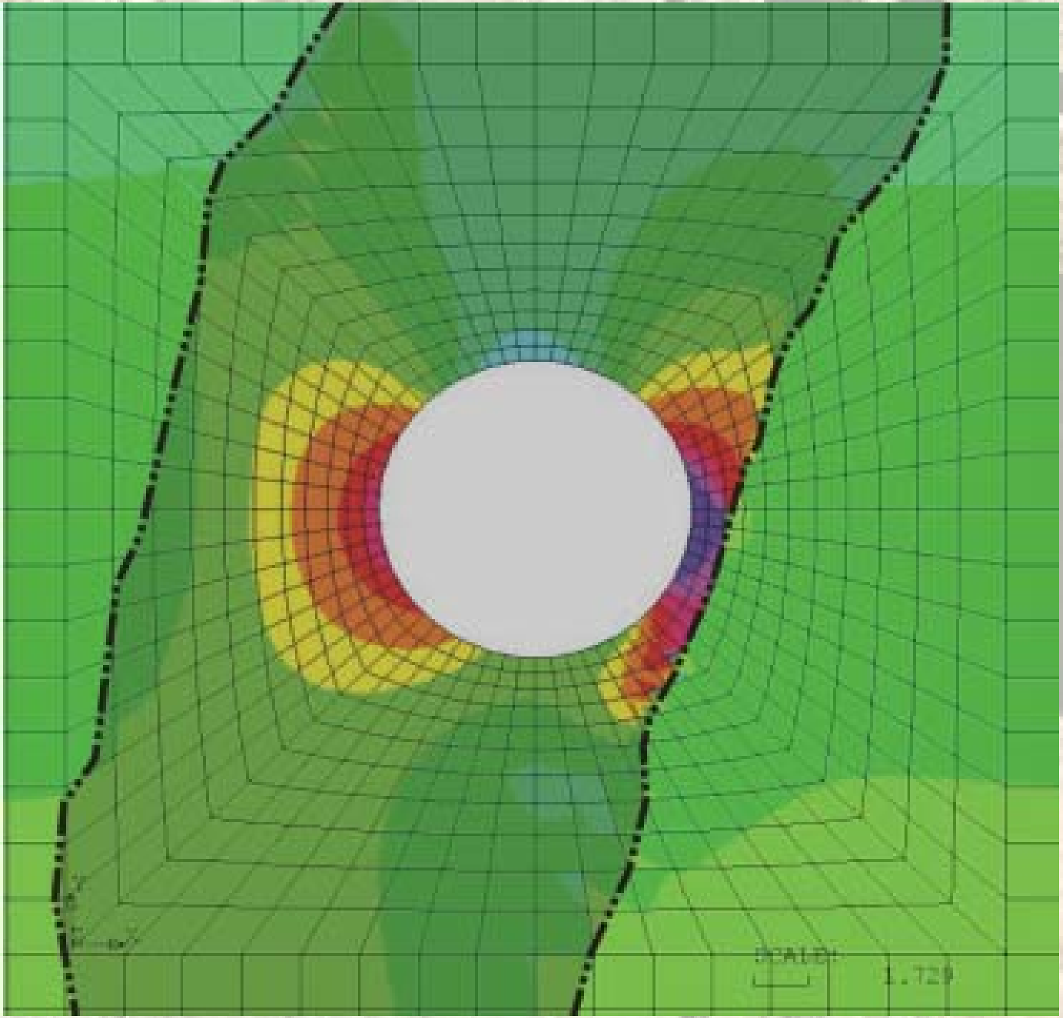
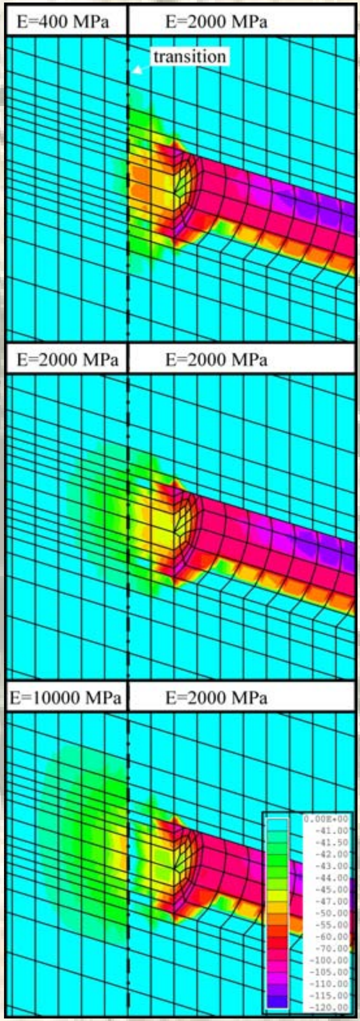
BIMROCK EFFECTS

STRESS CONCENTRATIONS





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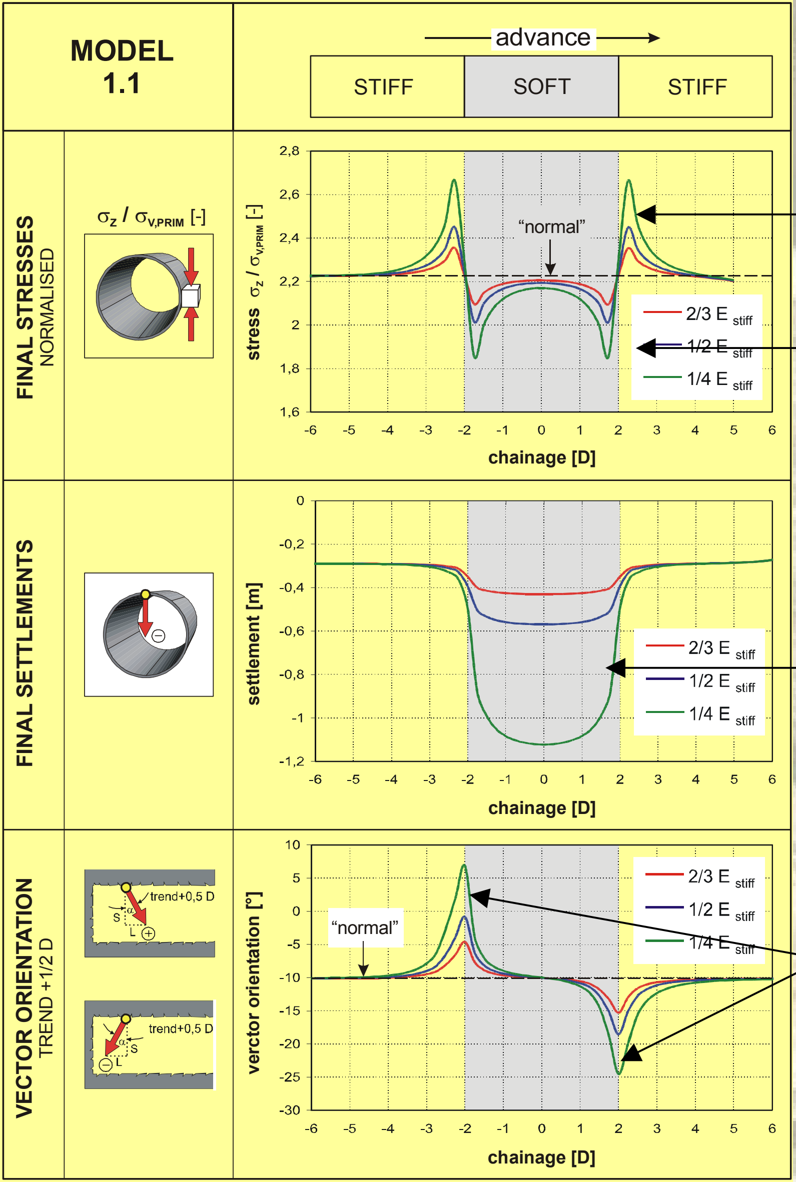
BIMROCK EFFECTS

STIFF-SOFT-STIFF



Relative stress increase in stiff material

Relative stress decrease in soft material

Trough shaped displacement

Change of displacement vector orientation near transition

BIMROCK EFFECTS

BLOCK REINFORCEMENT

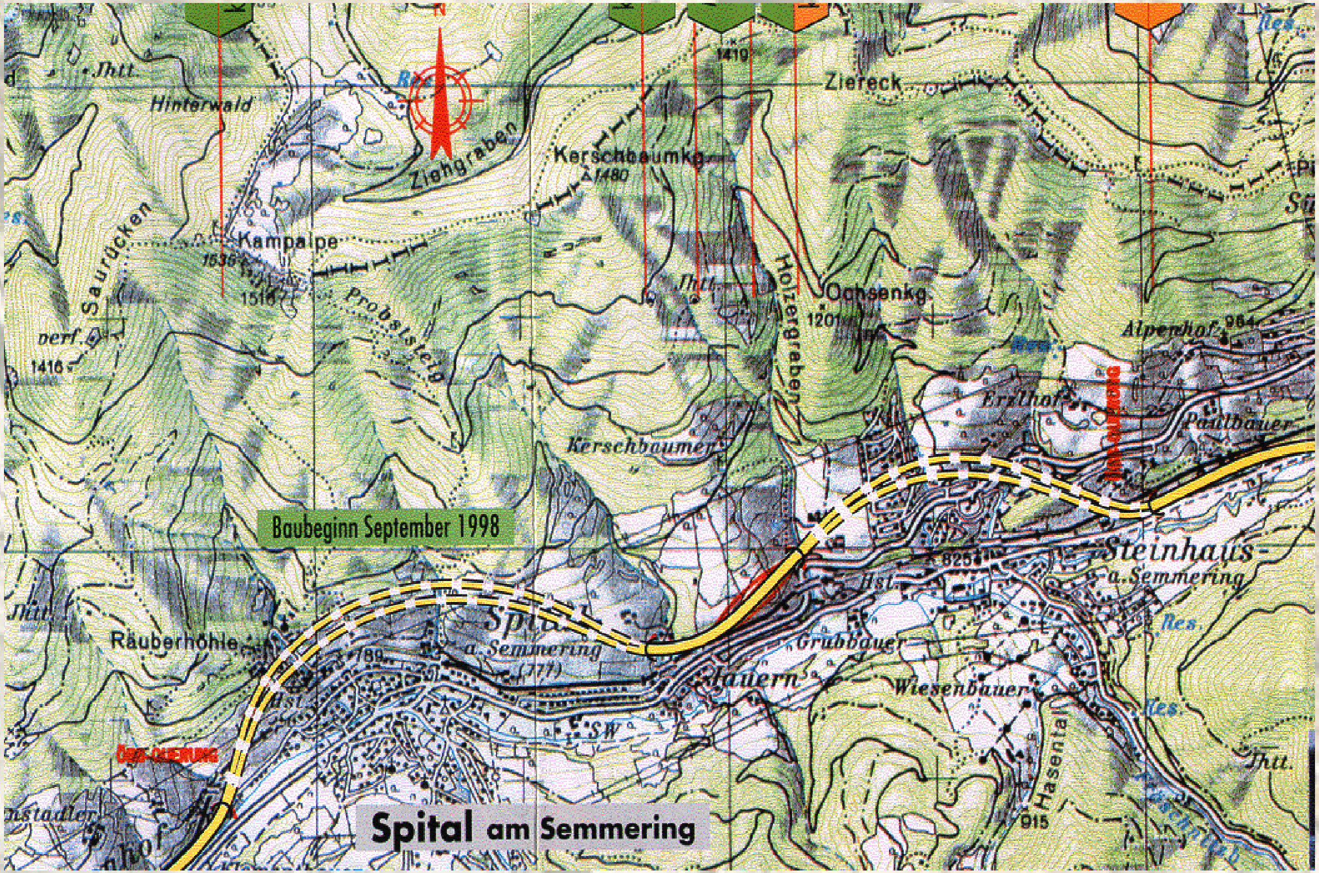
- Stress concentrations can cause brittle failure in stiff blocks
- Resulting stress redistribution leads to additional displacements in the matrix material

- Knowledge of the spatial distribution of blocks and matrix essential to properly estimate stress situation
- Short term prediction and prediction of displacements extremely important
- Support / reinforcement of blocks necessary to avoid brittle failure and long term stress redistribution, frequently mistaken for creeping

BIMROCK EFFECTS

CASE STUDIES

Location Map



Tunnel Spital, Austria

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BIMROCK EFFECTS

CASE STUDIES

Project data

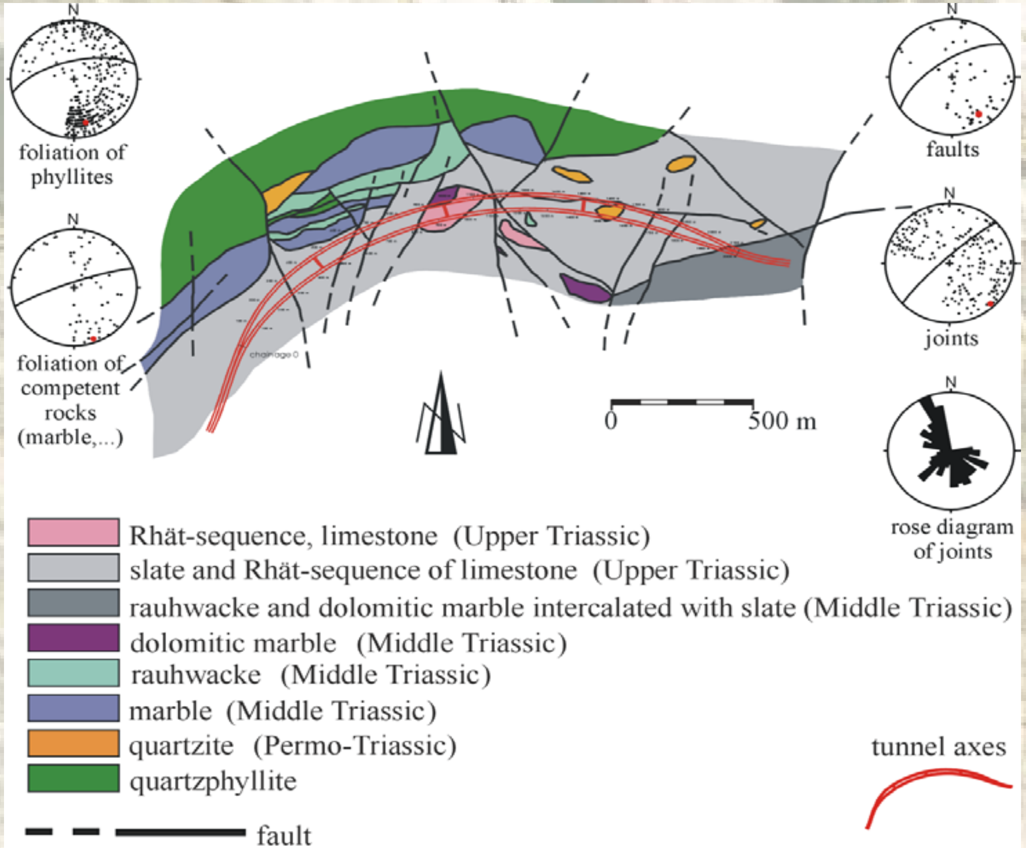
- Twin 2,2 km long freeway tunnels in the Semmering region, eastern Austria
- Alignment along a major fault zone
- Excavation area 70 – 90 m2
- Underpassing of a railway line and built up area
- Maximum overburden 80 m

Tunnel Spital, Austria

BIMROCK EFFECTS

CASE STUDIES

Geological overview

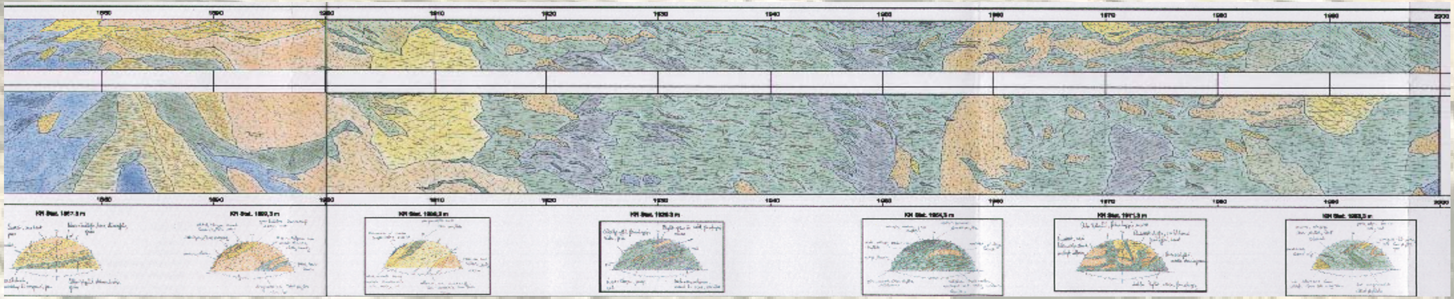


Tunnel Spital, Austria

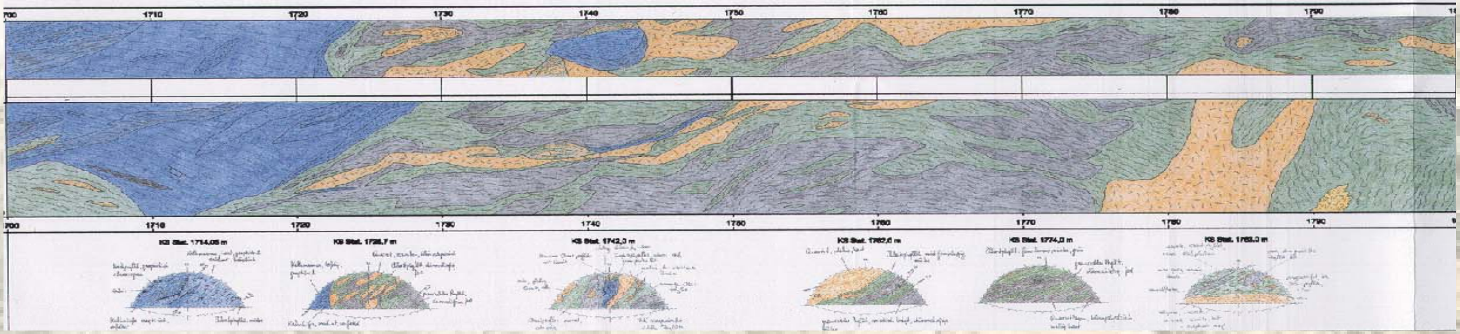
BIMROCK EFFECTS

CASE STUDIES

Geological overview



Nord tube: 1870-2000m



South tube: 1700-1800m

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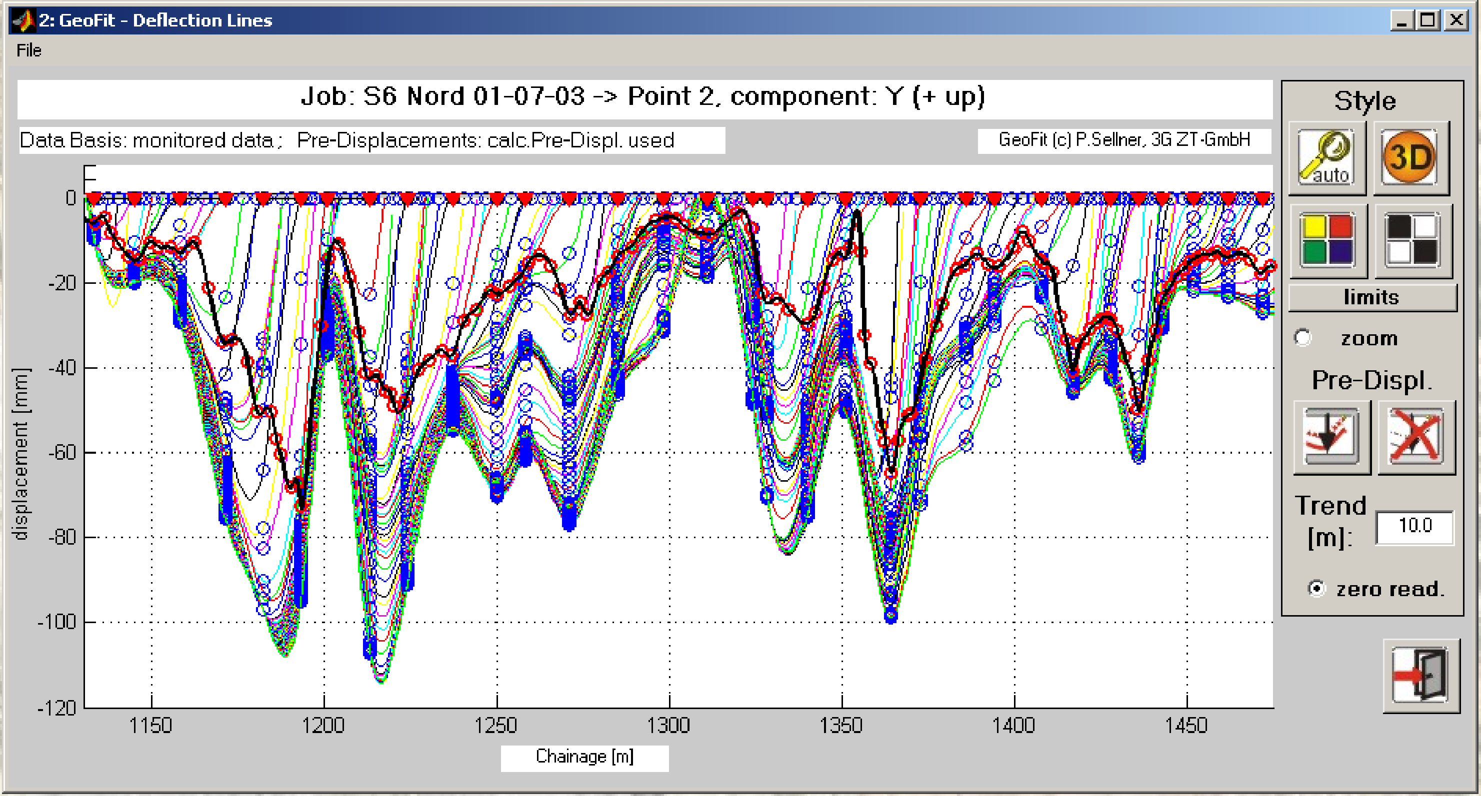
BIMROCK EFFECTS

CASE STUDIES

Heterogeneity - Displacements



2: GeoFit - Deflection Lines

File

Job: S6 Nord 01-07-03 -> Point 2, component: Y (+ up)

Data Basis: monitored data ; Pre-Displacements: calc.Pre-Displ. used

GeoFit (c) P.Sellner, 3G ZT-GmbH

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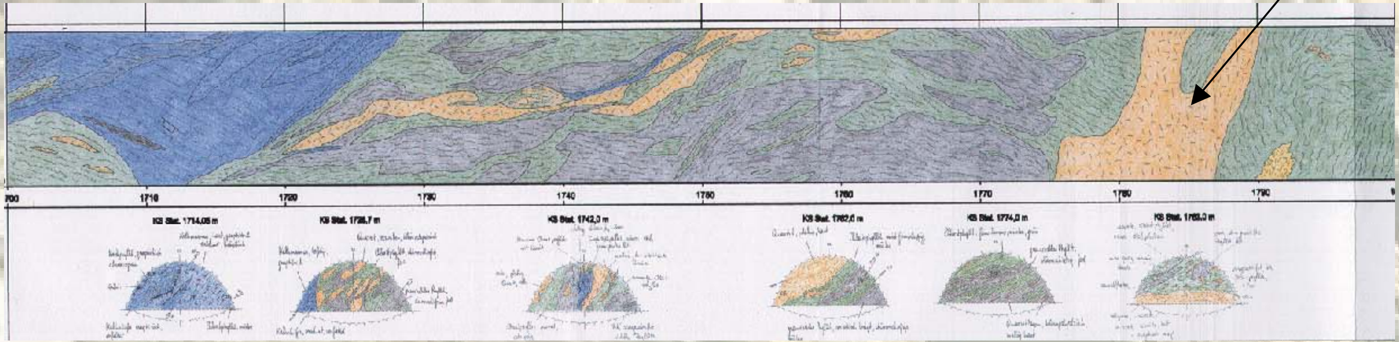
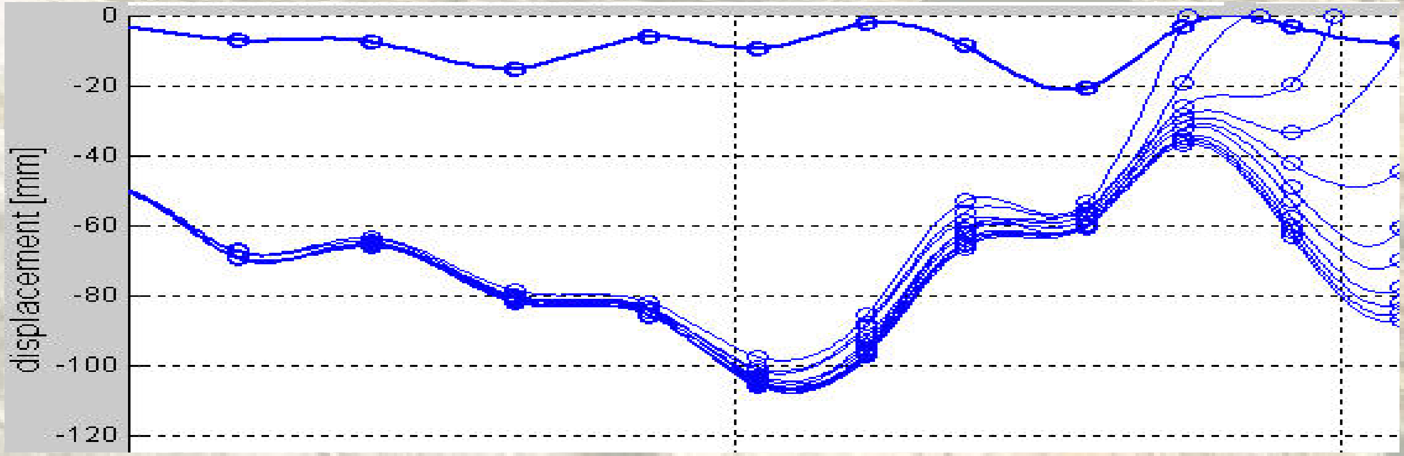
BIMROCK EFFECTS

CASE STUDIES

Block effect on displacement
settlement crown / top heading



Block



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BIMROCK EFFECTS

CASE STUDIES

Cross sections


1773


1785


1777


1788


1779


1790

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BIMROCK EFFECTS

CASE STUDIES

Bench excavation

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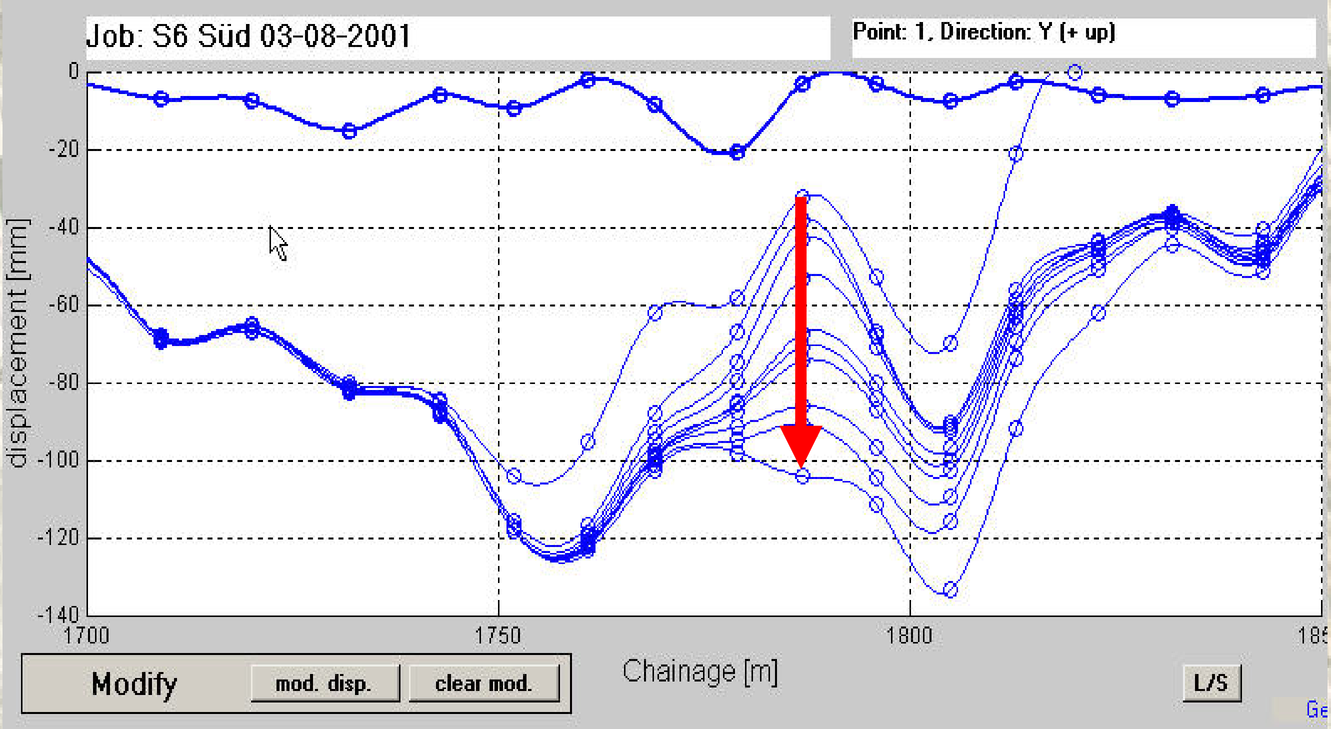
BIMROCK EFFECTS

CASE STUDIES

Failure of block

- During bench excavation the block fails, leading to additional 60 mm of settlement



Job: S6 Süd 03-08-2001

Point: 1, Direction: Y (+ up)

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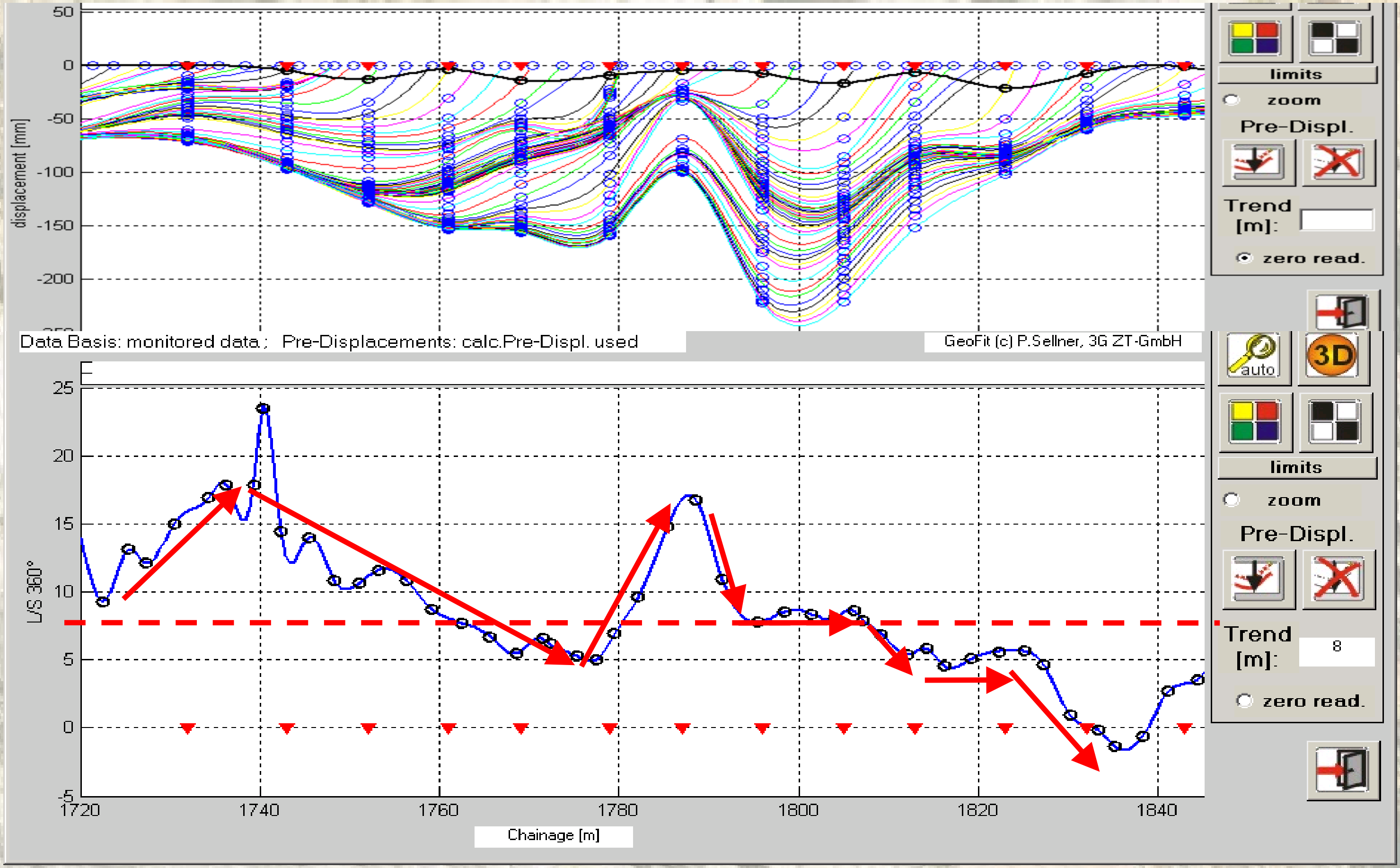
BIMROCK EFFECTS

CASE STUDIES

Final displacements & displacement vector orientation trend



Data Basis: monitored data ; Pre-Displacements: calc.Pre-Displ. used

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BIMROCK EFFECTS

CASE STUDIES

DAMAGES

cracks in the shotcrete on the southern sidewall

Tunnel Spital, Austria

BIMROCK EFFECTS

CASE STUDIES

Project Data

Single tube double track railway tunnel, length 5142 m, maximum overburden 260 m. Design from 1990 to 1992. The construction (three headings) started in June 1993 and was completed in April 1996.

Tasks

Geological – geotechnical site investigation from the feasibility study to the tender design. Consultant services during construction

Geology

Paleozoic graphitic phyllite, greenschist and marble as well as Permo-Triassic quartzite, quartzphyllite and agglomerate were subjected to intense Alpine thrusting and Tertiary strike-slip faulting

Galgenberg Tunnel, Austria

BIMROCK EFFECTS

CASE STUDIES

Collapse

A collapse with fatal accident happened on July 1994 at station 1330 m.
Eight meters of heavily supported tunnel section collapsed at the face.
A miner, including excavation equipment, was buried under the collapsed rock mass.
Redesign and maintenance work lasted for two months.
The excavation was resumed in October 1994.

Galgenberg Tunnel, Austria

BIMROCK EFFECTS

CASE STUDIES

Collapse

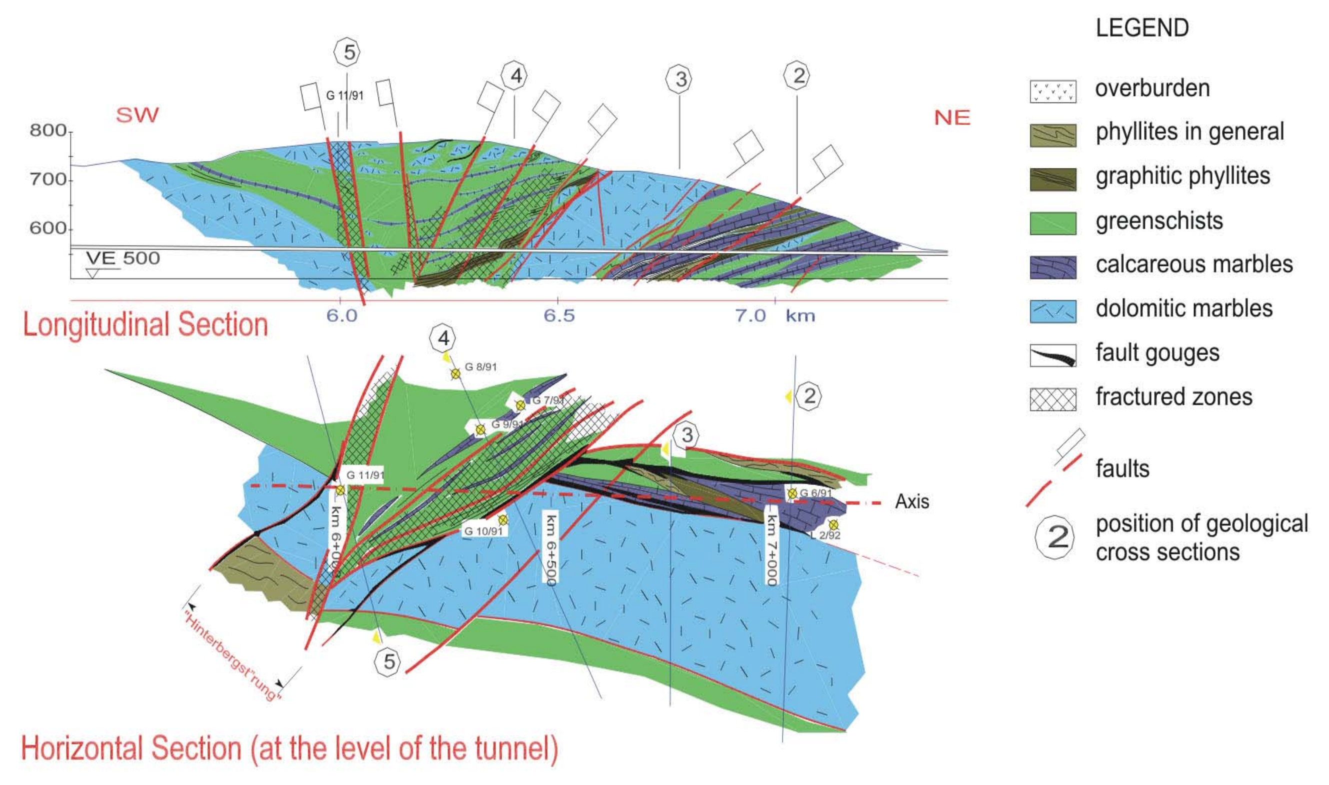
Collapse caused by brittle failure of stiff rock outside of excavation

Galgenberg Tunnel, Austria

BIMROCK EFFECTS

CASE STUDIES

HINTERBERG FAULT ZONE
Prediction


Longitudinal Section

Horizontal Section (at the level of the tunnel)

Galgenberg Tunnel, Austria

Construction

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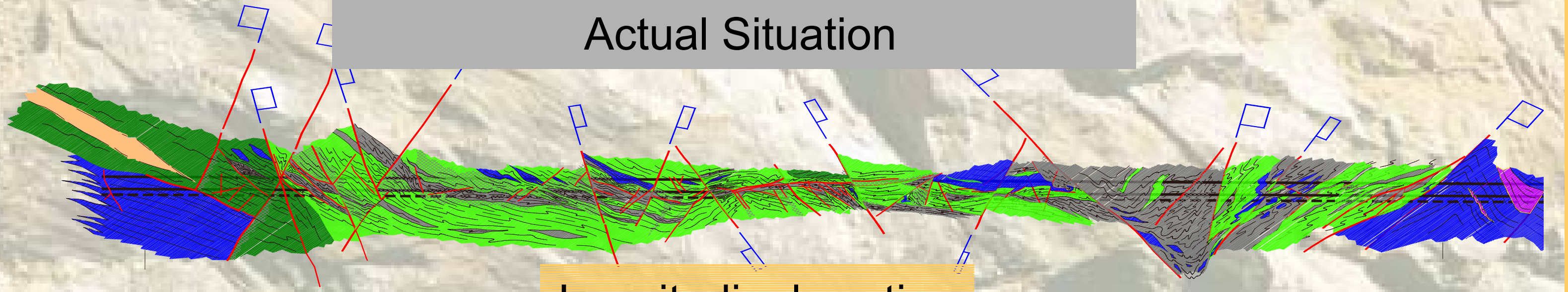
BIMROCK EFFECTS

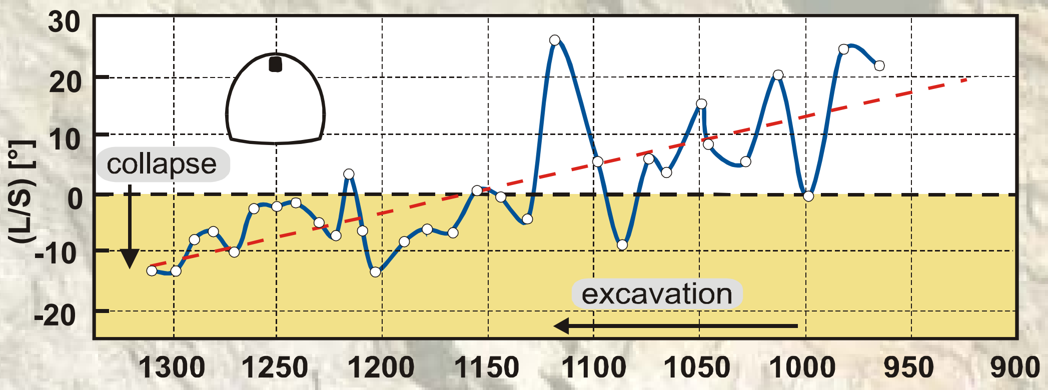
CASE STUDIES

HINTERBERG FAULT ZONE
Actual Situation



Longitudinal section

Plan view



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BIMROCK EFFECTS

CASE STUDIES

HABERL FAULT - IMPROVED PROCEDURE

Modification of excavtion and support – reduction of top heading heigth, yielding elements, regroutable rock bolts

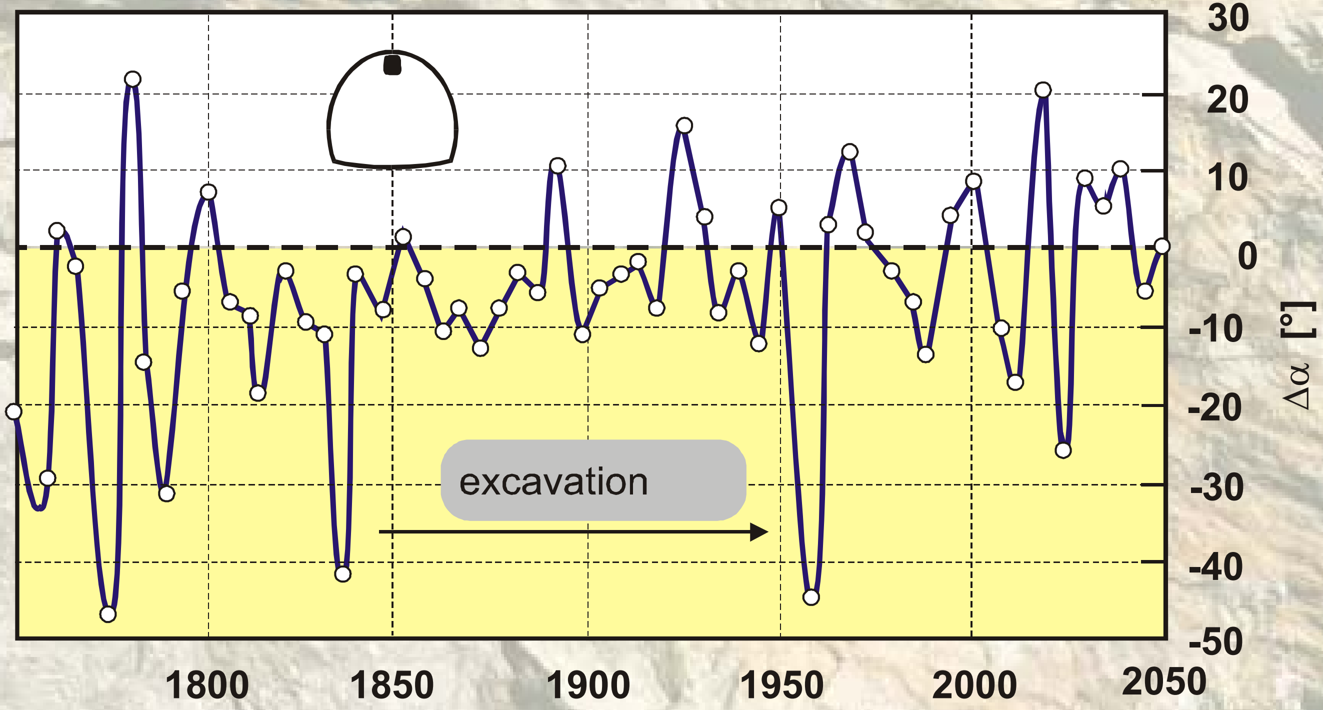
Galgenberg Tunnel, Austria

BIMROCK EFFECTS

CASE STUDIES

HABERL FAULT ZONE

Heterogeneity showing in strong variation of the vector orientation trend



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BIMROCK EFFECTS

CONCLUSION

- The complex spatial distribution of rock masses with different stiffness and strength makes prediction of behaviour difficult
- High displacments as well as differences in displacements can lead to severe damage of the (stiff) lining; thus flexible linings are required where bigger displacements are expected, and preferable even in shallow tunnels
- The analysis of the diplacement vector orientations can support the prediction of the location and distribution of blocks