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TUNNELLING IN TECTONIC MELANGES – ACCOMODATING THE IMPACTS OF GEOMECHANICAL COMPLEXITIES AND ANISOTROPIC ROCK MASS FABRICS

E.BUTTON, G.RIEDMÜLLER, W.SCHUBERT, K.KLIMA, AND E.MEDLEY

E. Button

Institute for Rock Mechanics and Tunneling, Graz University of Technology, Rechbauerstrasse 12, 8010 Graz, Austria

Fax: +43 316 873 8618, e-mail: button@fmt.tu-graz.ac.at

G. Riedmüller

Institute of Engineering Geology and Applied Mineralogy, Graz University of Technology, Rechbauerstrasse 12, 8010 Graz, Austria

Fax: +43 316 873 6871, e-mail: rdm@egam.tu-graz.ac.at

W. Schubert

Institute for Rock Mechanics and Tunneling, Graz University of Technology, Rechbauerstrasse 12, 8010 Graz, Austria

Fax: +43 316 873 8618, e-mail: schubert@tugraz.at

K. Klima

Institute of Engineering Geology and Applied Mineralogy, Graz University of Technology, Rechbauerstrasse 12, 8010 Graz, Austria

Fax: +43 316 873 6871, e-mail: klima@egam.tu-graz.ac.at

E. Medley

Exponent Failure Analysis Associates, 149 Commonwealth Drive, Menlo Park, CA 94025, USA

Fax: 650 328 3094, e-mail: emedley@exponent.com

Abstract Experiences from the construction of two shallow tunnels through a thrust melange are discussed. It is shown that complex geological environments, such as a melange zone, requires continuous geological and geotechnical characterisation as well as state of the art monitoring to comprehend the details of the melange's internal block / matrix structure and the effects on the excavation. The acquired data are used to determine the appropriate key parameters that sufficiently describe the expected rock mass behaviour. We discuss how the evaluation of three dimensional displacement data, combined with a continuous geological characterisation allows the optimisation of a tunnel construction in a tectonic melange.

Key words *Tunneling, Thrust melange, Rock mass characterisation, Displacement monitoring*

Introduction

Tectonic melanges (from French *mélange*, or "mixture") are defined as chaotic, heterogeneous geological mixtures of blocks, with different types and sizes, surrounded by weaker sheared finer-grained rocks (Raymond and Terranova 1984). The highly deformed "block-in-matrix" fabrics of melanges are formed by tectonic fragmentation and mixing of rocks in convergent plate boundaries of orogenic belts, e.g. Alps, Himalayas, the west Taiwan fold belt etc. In some mountain belts, such as the Californian Coast Ranges and the Taurus - Zagros mountains of Turkey and Iran, they form expansive fault-bounded regions thousands of square kilometres in area (Moore and Twiss 1995).

Over the last ten years, construction of tunnels has increased in mountainous regions of high geological complexity, and tunnelling in tectonic melanges has become necessary. Successfully developing this type of project challenges geologists, design engineers and contractors.

The enormous heterogeneity of a melange poses severe engineering problems. For the tunnelling community, one of the main construction problems is working with mixed face conditions, in which the working face contains materials with different excavation characteristics. This can have a significant impact on the excavation, for example complicating the construction logistics by forcing the use of different excavation techniques during a single excavation cycle, with attendant delays and cost increments. In our experience, the main geotechnical problems result from the significant spatial variations in rock mass stiffness and strength, which reduce the confidence of predictions, thereby adversely affecting the engineering and construction operation (Püstow et al. 2001; Button et al. 2002).

The heterogeneity of a melange rock mass, demands comprehensive characterisation, of the geological, geometrical, mechanical and hydraulic properties, even more than in other rock mass types. However, even when comprehensive investigations are performed, the complexity of the internal block/matrix structure may prevent the geotechnical investigations from yielding sufficiently precise rock mass models.

The rock mass strength of block-in matrix-rocks such as melanges, is mainly governed by strength contrasts between the blocks and matrix, the sizes of blocks, and block volumetric proportions (Lindquist 1994; Medley 1994a; Medley 1994b; Medley 1998; Medley and Goodman 1994). The rock mass behaviour, particularly during tunnelling, is primarily influenced by the local rock mass strength and very importantly by the location and size of significant blocks (Button et al. 2002). Hence, deficiencies in rock mass models are typically caused by a significant lack of geometrical and spatial information, particularly in accurate information on block sizes, block shapes, and block locations, all of which are virtually impossible to obtain in full.

Because of the often extreme difficulty of fully and accurately characterizing tectonic melanges, a typical geotechnical description of a tectonic melange may simplify the geological and geomechanical heterogeneity by assuming that the melange rock mass is a chaotic "pseudo - isotropic mixture" (Marinos and Hoek 2000). This type of simplification should be carefully assessed as recent experience from tunnel constructions in melanges of the Austrian Alps has shown that mechanical complexity and fabric anisotropies (resulting from the ductile – brittle tectonic development) can have a tremendous impact on the rock mass behaviour during tunnelling (Button et al. 2002; Dissauer et al. 2002). This is especially true when the block sizes approach the scale of the excavation. These features of a melange, which are particularly important for the prediction of the rock mass behaviour during tunnelling, can only be revealed by geotechnical investigations that are combined with detailed structural-geological analyses and, during the excavation, by state-of-the-art techniques to interpret the results of monitoring in real time. Such approaches, described in this paper, were developed during work over the last decade with the Spital and Steinhaus tunnel projects that are currently under construction in a thrust melange of the Austrian Alps.

The Spital and Steinhaus tunnels are dual-lane, twin bore tunnels constructed for the Semmering expressway S6 (Figure 1). The Spital tunnel is approximately 2,500 m long with approximately 500 m consisting of cut and cover construction. The distance between the bores is about 50 m over most of the tunnel length. The maximum overburden is 90 m, but averages 20 to 30 m. Construction of the tunnel started in September 1998 and was completed in November 2002 after severe time and cost overruns, due to unexpected difficulties during excavation (Dissauer et al. 2002) .

Figure 1

The Steinhaus tunnel is approximately 1,800 m long with approximately 100 m consisting of cut and cover construction. The maximum overburden is 50 m, but averages 20 to 25 m. The tunnel is scheduled to be completed in 2003 (Eberl 2002).

Regional Geology in the Area of the Spital and Steinhaus Tunnels

The tunnels are located within the “Semmering-Unterostalpine” nappe system. The tectonic units, which are separated by pronounced detachment zones, include a polymetamorphic crystalline basement and a low-grade metamorphic Mesozoic sequence (Neubauer and Genser 1990; Riedmüller et al. 2000). The tectonic melange was generated during thrusting within a ductile crustal environment. Blocks of various sizes and lithologies, were emplaced within a foliated matrix of intensely sheared phyllites. Significant blocks range in size from several meters to more then 500 m in length. The blocks are typically lenticular in shape and are oriented with their long axes sub-parallel to parallel to the NNW dipping foliation. Most block /matrix contacts are either composed of brecciated rocks or highly sheared fine-grained clayey gouge. Strike-slip faults associated with the Tertiary Mur-Mürztal fault zone overprint the original structures formed during thrust tectonics. This combination of tectonic events has created an extremely heterogeneous rock mass at the scale of the tunnel alignments, with a spatially complex distribution of strength and stiffness (Figure 1).

Characterization of the Internal Structure of a Melange Rock Mass

Incorporating research results from rock mechanics and structural geology into the evaluation of the rock mass and system behaviour provided a basis for understanding the complex spatial relationships and their effect on the behaviour during excavations. The local behavior of a melange rock mass is controlled by the size, distribution, and the position of the blocks related to the excavation, as well as variations in the strength of the matrix, which in turn influence the appropriate tunnel excavation and support methods.

Figure 2

Figure 3

Accordingly, in melange rock masses the geologist needs to make predictions about the rock mass conditions ahead of and surrounding the excavation. The distribution of blocks and the variation in matrix properties can be estimated and correlated with careful evaluation of the observed rock mass conditions and their trends by understanding the types, kinematics, and relative magnitudes of the tectonic deformations that created the anisotropic fabric of the melange.

The typical anisotropic fabric of tectonic melanges, resulting from ductile to brittle deformation histories, is found from the micro- to the mega-scale. The apparent scale independence allows relatively small-scale observations made at successive faces during the tunnel excavation to be extended to three-dimensional rock mass modelling and short-term predictions ahead of the face. For example figure 2 shows a small block of rauwacke (cellular dolomite) immediately surrounded by sheared graphitic phyllite and chlorite phyllite, which was exposed during the excavation for the east portal of the Steinhaus tunnel. Figure 3 shows a large quartzite block surrounded by sheared graphitic phyllite that was encountered during the Steinhaus tunnel excavation at approximately station 400 of the south bore. On the basis of geologic observations and interpretations, extensional and compressive domains due to brittle faulting can be identified at small scales, which then provide information as to the states of initial, pre-excavation stresses and ground conditions. For instance, extensional fault kinematics, usually found in larger elongated blocks, indicates reduced lateral ground pressure and attendant risks of ground water inflow and overbreak.

The geometry of blocks (aspect ratio and volume) is influenced by the original structures of the parent rock mass such as bedding thickness, fault zone thickness, fault spacing and roughness, etc., metamorphic reactions, the amount of local strain accumulated around the blocks; and whether the deformation that occurred during formation of the melange was ductile, transient, or brittle.

Research in structural geology suggests that the size and shape of blocks is a function of how they were formed, their tensile strength, and the block/matrix strength contrasts. The latter influences the transmission of tractions. Higher strength parent rock masses can result in larger blocks with higher aspect ratio's then weaker materials that will break apart more easily (Mandal et al. 2001), frequently creating chains of smaller blocks separated by secondary shear zones.

Experimental data show that most blocks in a frictional material become stable when they are oriented at angles between 5° and 25° to the shear direction (Grotenhuis et al. 2002; Mancktelow et al. 2002). Blocks with large aspect ratios tend to stabilize at the lower end of this range. Blocks with smaller aspect ratios tend to be inclined with angles in the upper portion of this range. Additionally, the long axes of some blocks may become sub parallel to secondary shear zones. Shear localization is one process that will allow a blocks orientation to stabilize (Grotenhuis et al. 2002). This process results in a stable geometric configuration consisting of blocks surrounded on all sides by sheared matrix, the fabric that is typically observed in tectonic melanges. The sheared, slickensided block/matrix contacts control the shear strength of failure surfaces that may subsequently develop around the blocks (Grossauer 2001).

Evaluation of Monitoring Data and Rock Mass Behaviour

The geotechnical engineer must work with the geologist in evaluating displacement measurements, as the system behaviour is governed to a great extent by the rock mass that is not observed at the tunnel face. Therefore, by combining careful mapping and recording of geotechnically and geologically relevant key parameters with the 3-D displacement data, important features and indicators can be identified and used to determine excavation and support methods for the upcoming sections.

The rock mass behaviour during excavation depends largely on the local volumetric block proportion (ratio of representative block volume of to the relevant rock mass volume) in the immediate vicinity of the excavation area, the sizes, shapes and positions of blocks, the relative deformability and strength of blocks and matrix and the effect of ground water. On the one hand the heterogeneity of a tectonic melange leads to stress concentrations in the blocks, whereas, on the other hand, there will also be relatively high deformations in the matrix during the tunnel excavation. The stress concentrations occurring in the blocks may lead to sudden brittle failure of the blocks (Schubert and Riedmüller 2000 a, 2000 b) while matrix deformation can be time dependent.

It is emphasised that the rock mass structure outside the excavation area dominates the rock mass response. Isolated blocks within the excavation perimeter may contribute to the face stability, but only temporarily influence the overall stability of the tunnel. Our evaluations of displacement monitoring data, such as displacement vector plots, time histories and deflection and trend lines (Schubert and Budil 1995; Vavrovsky and Schubert 1995; Steindorfer 1997; Schubert et al. 2002), indicate that the displacement magnitudes generally increase with decreasing block volumetric proportion. Furthermore, the position of the stronger blocks relative to the perimeter of an excavation plays a key role in the behaviour of the surrounding rock mass.

Figure 4

In Figure 4a the results of 3-D numerical simulations are displayed. The simulations were performed with the numerical code BEFE (Beer 1999) assuming elastic material behaviour. For this discussion we used these simulations as a simple model to demonstrate the general response of a soft zone crossing the excavation (Grossauer 2001). The results in the upper graph show the increase in the maximum stress at the sidewall, normalized by the vertical stress, when entering and exiting the soft zone. The middle graph shows the increase in settlements for the crown point. While the lower graph demonstrates how the vector orientation (ratio of longitudinal deformation to settlements) changes when entering and exiting the soft zone. Figure 4b shows the results of a 2-D simulation performed to investigate the potential for stress concentrations in blocks depending on their location; also performed with BEFE (Beer 1999). The stress concentration in a block intersected by the tunnel excavation can clearly be seen.

An illustration of this phenomenon (typical for the behaviour in both tunnels) is provided from our experience investigating the south bore of the Spital tunnel. Figure 5 shows the documented geology presented as a plan view (lower) and a longitudinal section (upper) for the south bore of the Spital tunnel from station 1700 to 1800 (Heim 2001). At about station 1,700 the tunnel excavation exited from a large marble block and entered a matrix dominated section composed of sheared chlorite phyllites and graphitic phyllites with blocks of quartzite and marble). At approximately station 1,760, a quartzite block was observed in the upper left section of the top heading. From station 1,775 to 1,785 another large quartzite block was located in the bench. At station 1,790 a NE trending, high angle fault zone displaced this block and overprinted the matrix rocks creating a complexly folded and sheared zone 20 m thick. The excavation entered the next block dominated zone at about station 1,850.

Figure 5

Figure 6

Figure 7

Figure 8

The displacement plots shown in the following sections were created with the program GeoFit® (Sellner 2000; Sellner and Schubert 2000; http://www.3-g.at). Figures 6 shows the displacement vectors for the matrix dominated rock mass at station 1,769. This deformation style is typical for these rock mass conditions. The deformation consists of more or less homogeneous settlements with magnitudes in the range of 10 to 20 cm. The decreased deformation magnitudes for points 6 and 7 is due to their later installation time during the bench excavation.

Figure 7 shows the displacement vectors for a block-influenced rock mass at station 1,779. The anisotropic deformation results from the size and position of the quartzite block encountered during the bench excavation. The block extends from the rock mass at the right side of the tunnel, across the bench ending at the left tunnel boundary. The block limited the vertical settlements on the right side of the tunnel and initially on the left side. When the bench excavation removed most of the block the left side displayed similar behaviour to the previous measurement section. This considerable difference in displacement magnitudes between left and right sides of the tunnel imposed a sufficient torque on the lining that caused the shotcrete in the right upper sidewall to crack over a distance of 25 m (Figure 8).

Deflection lines are used to display the development of displacements with time and position along the tunnel excavation. The deflection lines are created by connecting the displacements at each measurement section that are recorded on the same day. A trend line is created by extracting values from the deflection lines at a constant distance behind the measurement section (Steindorfer 1997). The displacement trend lines assist in the short term prediction techniques as discussed in (Steindorfer 1997; Schubert et al. 2002). In Figure 9, deflection lines for the settlements of points 4 and 5 are displayed from station 1,720 to 1,850, the approximate extent of the encountered brittle fault zone. The displayed measurements begin with the settlements caused by the top heading excavation, and show the additional deformations resulting from the bench excavation. There is some effect on the final deformation magnitudes from the block encountered from stations 1,757 to 1,768 on point 4 while little effect is seen on point 5. The stabilizing effect of the block encountered between stations 1,771 and 1,789 and the extent of the region which is influenced by it can clearly be seen for both points.

The evaluation of deformations along the tunnel axis together with the results of geologic face mapping allows one to clarify the influence of the complex structure of a tectonic melange on the rock mass behaviour during the excavation of the tunnel.

Short term predictions of the rock mass conditions ahead of the tunnel face are based on displacement analysis techniques (Schubert and Budil 1995; Vavrovsky and Schubert 1995; Steindorfer 1997; Grossauer 2001; Schubert et al. 2002). Figure 10 shows the vector orientation trend for both points 4 and 5 calculated 8 m behind the advancing face. There are differences between the two plots that indicate that the rock mass qualities are different for each side of the excavation, as shown in Figure 9.

Figure 9

Figure 10

A brief discussion on the interpretation follows. The "normal" vector orientation is between 8° and 10° against the excavation, which is in the range reported in previous evaluations (Steindorfer 1997). Increasing trends indicate weaker material ahead of the face, while decreasing trends indicate stiffer material. The slope indicates the relative difference between the material properties as shown in Figure 4a. In extensive zones, the vector orientation will return to the "normal" value before indicating the next transition. There is a good agreement between the interpretation of the vector orientation trends and the observed geologic conditions and system behaviour. Due to the complexity of the rock mass structure, it must be emphasized that in combination with the geological mapping that multiple evaluation methods must be applied and evaluated to make short term predictions in real time. In some cases it may be necessary to verify the predictions by probing ahead of the face.

The techniques illustrated here require constant and consistent collection of real time data, face mapping and analysis, which can only be achieved through cooperation between geologists, engineers, contractors, and owners.

When tunnelling in a melange, severe problems can occur from unexpected ground water inflows. Large blocks with sizes exceeding several tens of meters may act as aquifers, or "perched water lenses", and indeed, large blocks provide water in rural parts of Northern California (Medley 1994). The stiff blocks typically have a higher fracture permeability and storativity then the weak, soft matrix rocks. This situation can create significant water and seepage forces between the blocks, matrix and the excavation, resulting in a high potential for collapses. Several such critical situations associated with severe overbreaks were encountered during the excavation of the Spital tunnel. One of these resulted in a short-term water inflow up to 100 liters/sec leading to a top heading collapse (Dissauer 2002).

Determination of Support and Excavation Sequences

During the design phase, melange rock mass types must be defined considering possible block locations and sizes with different material qualities. The defined rock mass types are then used to evaluate the rock mass behaviour types considering the projects influencing factors. Once rock mass behaviour types are defined, different support and excavation methods can be evaluated (Schubert et al. 2001; Goricki 2002). Due to the extreme heterogeneity of melange rock masses at the scale of tunnelling interest, the actual conditions will likely vary considerably from those anticipated from the results of geological mapping and subsurface investigations (exploration drilling and geophysical surveys). Because of the in-situ heterogeneity, it is inappropriate and simplistic to use rock mass characterizations founded on the principles of homogenising the rock mass behaviour from generic parameters collected during investigations or at the tunnel face. In other words, classification schemes such as Q or RMR (Barton et al. 1974; Barton 1998; Bieniawski 1989) will fail to adequately determine optimum support requirements and appropriate excavation methods. Note that in blocky rock, it is equally, if not even more cogently necessary to avoid a generic classification system to detect and treat potentially sliding or falling blocks.

Despite high investigation efforts during the design phase, the selection of the appropriate support and excavation methods, particularly in a tectonic melange, demands short term predictions during construction. This prediction has to be based on a careful evaluation of monitoring data and continuous updating of the three-dimensional geological model, which must include a representative rock mass volume

The tunnel excavation in tectonic melanges is usually performed by subdividing the excavation into top, bench and invert headings with a primary lining consisting regularly of steel ribs, grouted bolts, shotcrete and wire mesh. Subdivision of the top heading and/or additional face support may be necessary in sections dominated by weak matrix rocks. From our experience, matrix dominated by clayey gouge typically contain swelling clay minerals (Klima et al. 1988; Riedmüller 1978). Therefore, a strong invert support is recommended due to the potential for volume increase by osmotic swelling as well as stress-induced shear failures with high radial displacements (Einstein 2000).

Opportunities to reduce the support and increase round lengths when excavating larger competent blocks have to be carefully checked by constantly reviewing displacement monitoring data and performing short-term predictions of the ground ahead of the face. It is vital that it be understood that larger blocks accumulate stresses, which under certain strength and/or kinematic conditions, may cause an unexpected and sudden failure.

It is also emphasised that the abruptly changing rock mass conditions in a tectonic melange require a strong but also ductile support, rather than the intuitively attractive option of increased stiff support. Such ductile support can be achieved by installing yielding support elements, such as “Lining Stress Controllers” which homogenise the stress distributions in the lining as well as maximize the utilization of the shotcrete as its strength develops with time (Moritz 1999; Schubert 1995; Schubert et al. 2000).

Conclusions

There is a small but growing appreciation amongst geo-practitioners of the often extreme geological, geometric, geomechanical and geohydrological heterogeneity of tectonic melanges and other block-in-matrix rocks. Any attempt to geotechnically homogenize the highly complex geological environments of tectonic melanges by the commonly used quantitative rock mass classification systems leads to an inappropriate design and construction. Rather, tunnelling in a tectonic melange requires continuous modelling of the spatial distribution of blocks and matrix ahead of the face and around the tunnel. This can be achieved by now available state-of-the art monitoring and evaluation techniques combined with geological face mapping which consider the key features of block-in matrix-rocks. Strong variations in the displacements frequently lead to overstressing of rigid supports. Consequently, ductile supports are recommended also for tunnels with low overburden. Experience shows that blocks have a potential for sudden brittle failure due to the accumulation of stresses during excavation advance. Using three dimensional displacement monitoring and advanced evaluation techniques a prediction of the rock mass structure around the excavation is possible even in such complex ground conditions as a tectonic melange. A detailed knowledge about the location, size, and shape of blocks, as well as the anisotropic matrix fabric during construction enable safe and economical tunnelling.

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References

BARTON N (1998) NMT support concepts for tunnels in weak rocks. In: Tunnels and Metropolises, Sao Paulo, Negro AJr, Feirreira AA (eds), Balkema, Rotterdam, pp 273-279

BARTON N, LIEN R, LUNDE J (1974) Engineering classification of rock masses for the design of tunnel support. Rock Mechanics 6(4): 189-236

BEER G (1999) BEFE user´s manual. Computer Software & Services International, Austria

BIENIAWSKI ZT (1989) Engineering rock mass classifications. Wiley, New York, 251 p

BUTTON EA, SCHUBERT W, RIEDMÜLLER G (2002) Shallow tunneling in a tectonic melange: rock mass characterization and data interpretation. In: Proc. NARMS-TAC 2002, Mining and Tunelling Innovation and Opportunity. July 7-10. Hammah R , Bawden W, Curran J, Telesnicki M (eds), Toronto Canada, Univ. Toronto Press, Toronto, vol 2: 1125-1132

DISSAUER J, LEITNER A, MITTELBACH H (2002) Tunnel Spital – Tunnelbau in schwierigen Verhältnissen.- Felsbau 20/1: 40 – 48

EBERL G (2002) Tunnel als wesentliche Teile sicherer und umweltfreundlicher Straßen:- Felsbau 20/1: 8 – 11

EINSTEIN HH (2000) Tunnels in Opalinus Clayshale—A review of Case Histories and New Developments. Tunnelling and Underground Space Technology, 15/1: 13-30

GORICKI A, SCHICK KJ, STEIDL A (2002) Quantification of the Geotechnical and Economic Risk in Tunneling. In: Probabilistics in Geotechnics: Technical and Economic Risk Estimation, Graz, Austria, Sept. 2002, Glueckauf, Essen, pp. 483-490

GROSSAUER K (2001) Tunnelling in heterogeneous ground- numerical investigations of stresses and displacements. Masters Thesis. Institute of Rock mechanics and Tunnelling. Graz University of Technology, Graz, 50 p

GROTENHUIS SM, PASSCHIER CW, BONS PD (2002) The influence of strain localisation the rotation behaviour of rigid objects in experimental shear zones. Journal of Structural Geology, 24: 485-499

HEIM N (2001) Geologic Documentation for the Spital Tunnel, Quartalsbericht Nr. 02/2001. Technisches Büro für Geologie und Geotechnik TBGG Dr. Norbert Heim, Vienna, Austria

KLIMA K, RIEDMÜLLER G, STATTEGGER K (1988) Statistical Analyis of Clay Mineral Assemblages in Fault Gouges. Clays and Clay Minerals, 36/3: 227-283

LINDQUIST ES (1994) The strength and deformation properties of melange. PhD thesis, Dept.of Civil Engineering, Univ. of California, Berkeley, 262 p

MANCKTELOW NS, ARBARET L, PENNACCHIONI G (2002) Experimental observation on the effect of interface slip on rotation and stabilisation of rigid particles in simple shear and a comparison with natural mylonites. Journal of Structural Geology, 24: 567-585

MANDAL N, CHAKRBORTY C, SAMANTA KS (2001) Control of the failure mode of brittle inclusions hosted in a ductile matrix. Journal of Structural Geology, 23: 51-66

MARINOS P, HOEK E (2000) GSI: A Geologically Friendly Tool for Rock Mass Strength Estimation. In: Geo Eng 2000, Proc. Int. Symp. Melbourne, Ervin MC (ed), CD

MEDLEY EW (1994a) The engineering characterization of melanges and similar block-in-matrix-rocks (bimrocks). PhD thesis, Dept. of Civil Engineering, Univ. of California, Berkeley, 387 p

MEDLEY EW (1994b) Using stereological methods to estimate the volumetric proportions of blocks in melanges and similar block-in-matrix-rocks (bimrocks). In: 7th International IAEG Congress, Lisbon, Portugal; Balkema, Rotterdam, pp.1031 – 1040

MEDLEY EW (1998) Confronting geological complexity: Working with melange bimrocks. In: 8th International IAEG Congress , Vancouver, Canada; Balkema, Rotterdam, pp. 227 – 233

MEDLEY EW, GOODMAN RE (1994) Estimating the block volumetric proportion of melanges and similar block-in-matrix-rocks (bimrocks). In: Proc. 1st North American Rock Mechanics Conference (NARMS), Austin, Texas; Balkema, Rotterdam; pp. 851 – 858

MOORE EM, TWISS JT (1995) Tectonics. Freeman, New York, 415 p

MORITZ BA (1999) A Ductile Support Method for Tunnels in Squeezing Rock. PhD thesis. Gruppe Geotechnik Graz, Riedmüller G, Schubert W, Semprich S (eds), Graz University of Technology, Graz, 5, 112 p

NEUBAUER F, GENSER J (1990) Architektur und Kinematik der östlichen Zentralalpen. Mitt. Naturwiss. Ver. Steiermark, 120: 203 – 219

PÜSTOW H, RIEDMÜLLER G, SCHUBERT W (2001) Tunnelling in a tectonic melange of high structural complexity. Felsbau 19/4: 34 – 42

RAYMOND, LA, TERRANOVA T (1984) Prologue: The melange problem – a review. Geol. Soc. Am. Special Paper 198:1-5

RIEDMÜLLER G (1978) Neoformations and Transformations of Clay Minerals in Tectonic Shear Zones. Tschermaks Mineralogische und Petrographische Mitteilungen, Springer, 25: 219-242

RIEDMÜLLER G, SCHUBERT W, GORICKI A, PÖLSLER P (2000) Investigation strategies for the design of the Semmering base tunnel. Felsbau, 18/4: 28 – 36

SCHUBERT W (1995) Dealing with Squeezing Conditions in Alpine Tunnels. Rock Mech. Rock Engng, 29(3): 145-153

SCHUBERT W, BUDIL A (1995) The Importance of Longitudinal Deformation in Tunnel Excavation. In: Proceedings 8th Int. Congress on Rock Mechanics (ISRM), Tokyo, Balkema, Rotterdam, pp 1411-1415

SCHUBERT W, GORICKI A, BUTTON, EA, RIEDMÜLLER G PÖLSLER P, STEINDORFER A, VANEK R (2001) Excavation and Support Determination for the Design and Construction of Tunnels. In: ISRM Reg. Symp. Eurock 2001, Espoo, Finland. Rock Mechanics a Challenge for Society, Särkkä P, Eloranta P (eds), Balkema, Rotterdam, pp 383 –388

SCHUBERT W, MORITZ BA, SELLNER P (2000) In: Tunnelling Methods in Squeezing Ground. In: Proceedings Geo Eng 2000, An International Conference on Geotechnical and Geological Engineering, Melbourne, Australia, pp 19-24

SCHUBERT W, RIEDMÜLLER G (2000a) Tunnelling in Fault Zones - State of the Art in Investigation and Construction. Felsbau 18/2: 7-15

SCHUBERT W, RIEDMÜLLER G (2000b) Tunnelling in Fault Zones - Innovative Approaches. In: Pacific Rocks 2000, Proc. Int. Congr. Seattle, Girard, Liebman, Breeds, Doe (eds) Balkema, Rotterdam, pp 113-124

SCHUBERT W, STEINDORFER A, BUTTON EA (2002) Displacement monitoring in tunnels- an overview. Felsbau 20/2: 15-23

SELLNER P (2000a) Prediction of displacements in tunneling. Ph.D thesis, Gruppe Geotechnik Graz, Riedmüller G, Schubert W, Semprich S (eds), Graz University of Technology, Graz, 9, 129 p

SELLNER P (2000b) Prediction of displacements in tunneling. In: Geo Eng 2000, Proc. Int. Symp. Melbourne, Ervin MC (ed), CD

STEINDORFER A (1997) Short term prediction of rock mass behaviour in tunnelling using advanced analysis of displacement monitoring data. PhD thesis. Gruppe Geotechnik Graz, Riedmüller G, Schubert W, Semprich S (eds), Graz University of Technology, Graz, 1, 111 p

VAVROVSKY GM, SCHUBERT P (1995) Advanced analyses of monitored displacements opens a new field to continuously understand and control the geotechnical behavior of tunnels. In: Proceedings 8th Int. Congress on Rock Mechanics (ISRM). Tokyo, Balkema, Rotterdam, pp 1416-1420

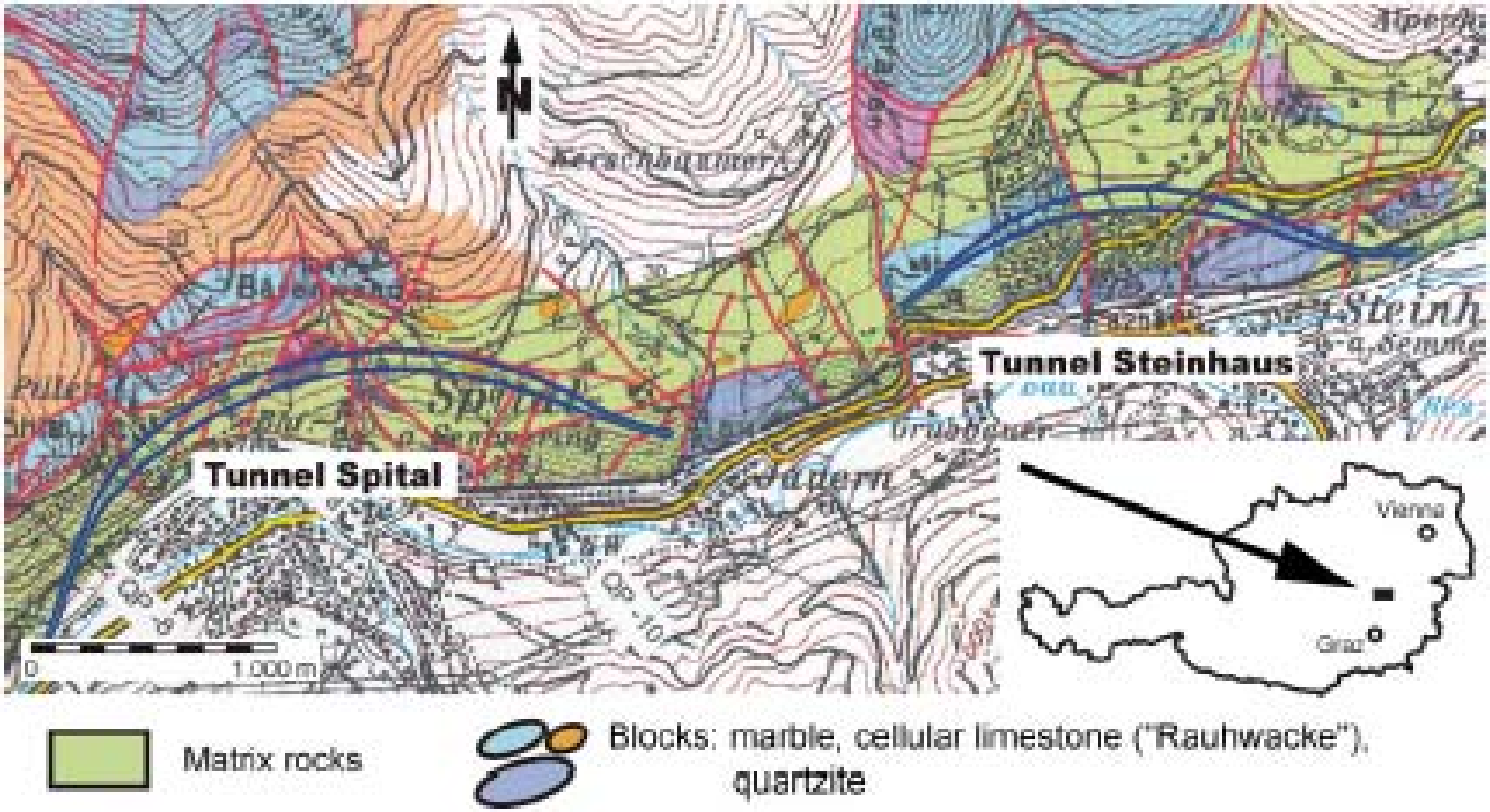


Figure 1. Site location and geology. The tunnel alignments are shown with dark blue, matrix rocks are undifferentiated phyllites, which surround blocks of marbles and rauhwacke (dark and light blue) and quartzite (orange). Individual faults are identified with red lines.

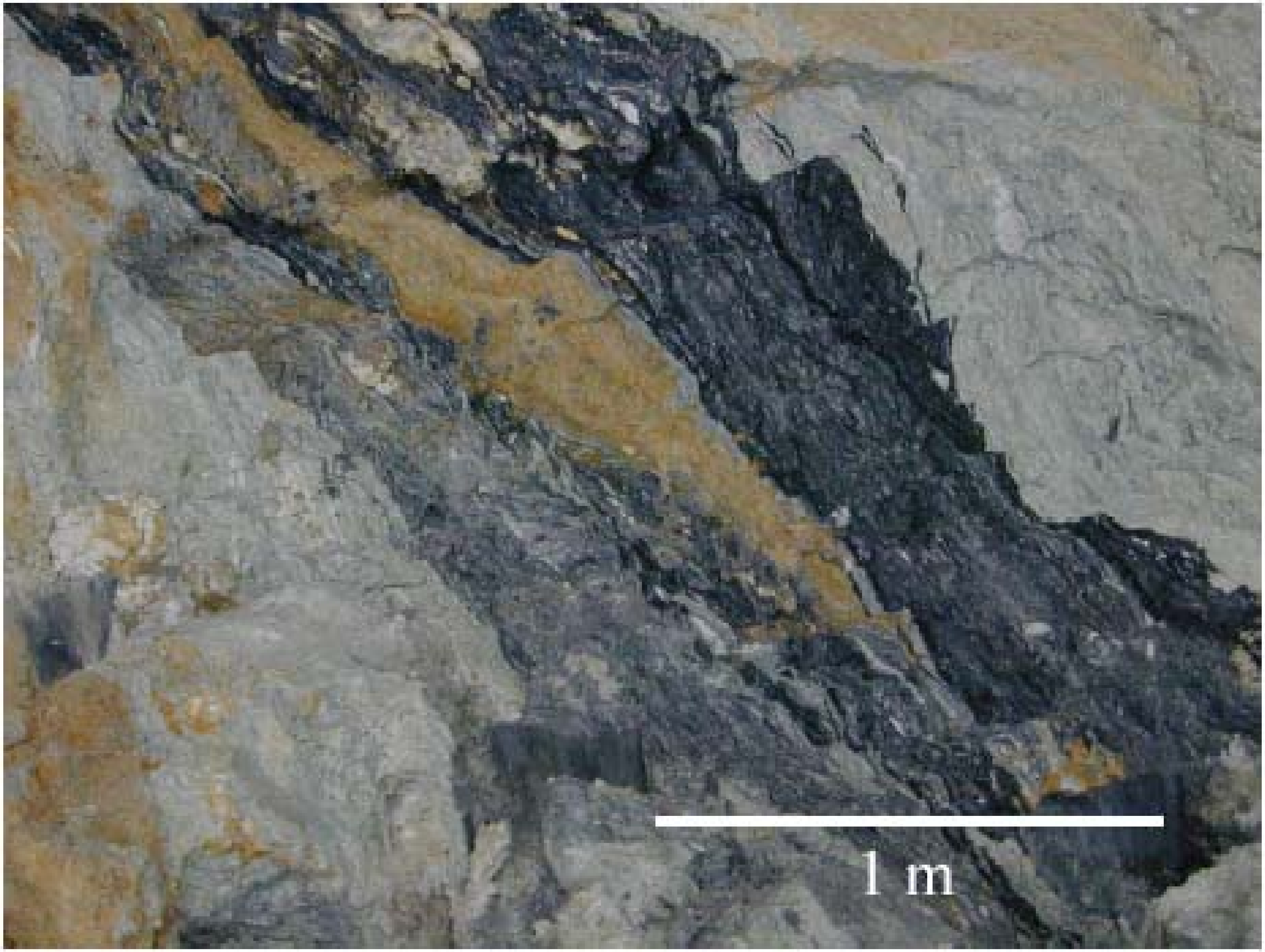


Figure 2. Small block of rauhwacke (cellular dolomite) surrounded by graphitic phyllite (black) and chlorite phyllite (grey)

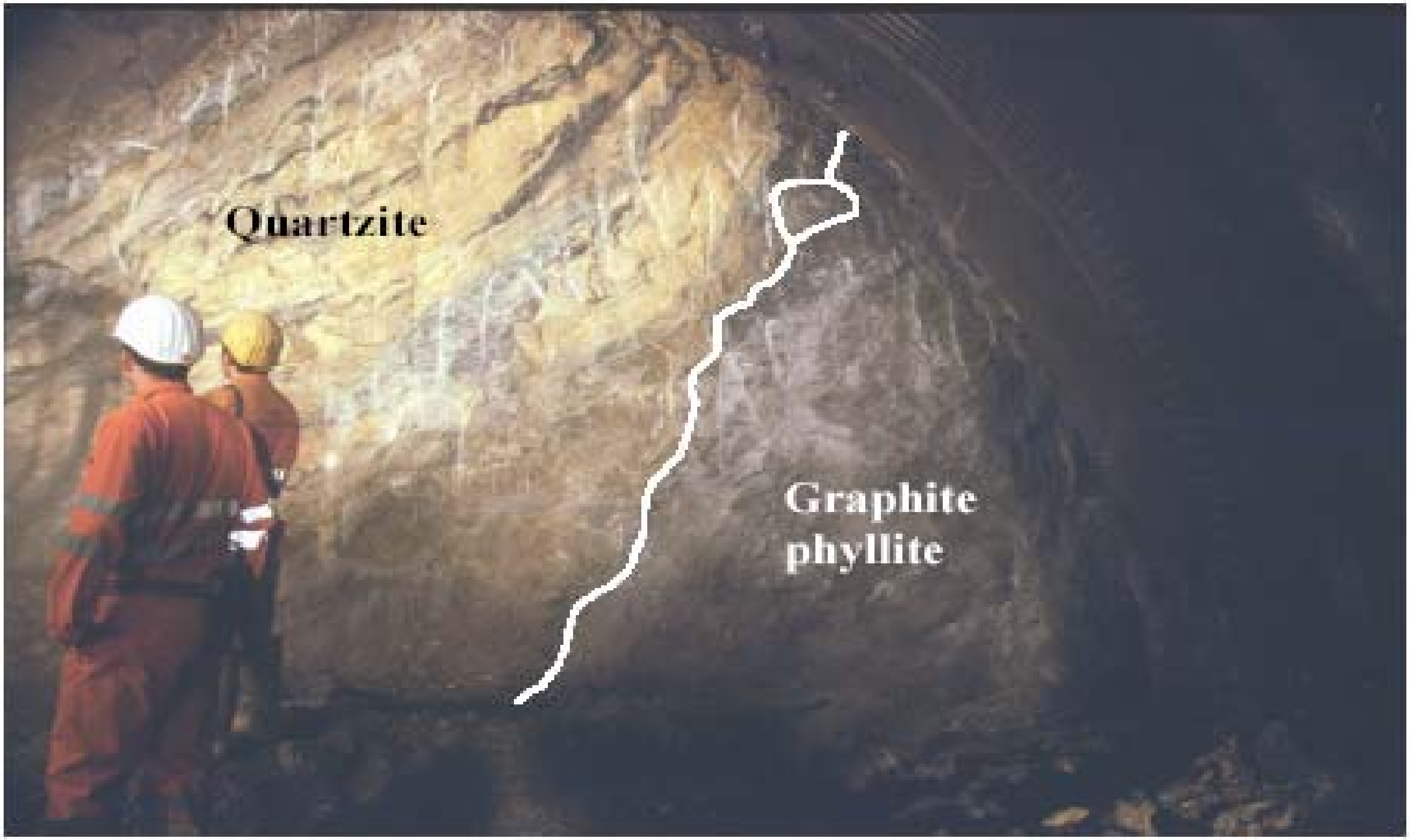
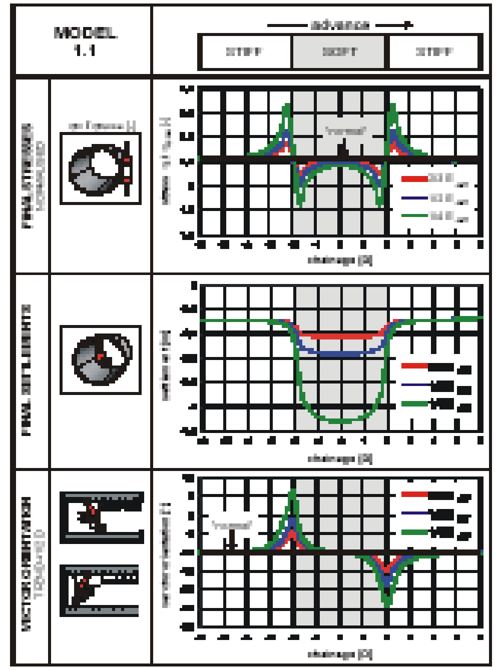
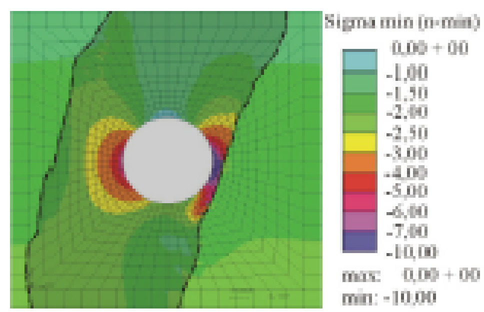


Figure 3. Large block of quartzite (orange) surrounded by graphitic phyllite (grey) encountered during the excavation of the Steinhaus tunnels south bore.

Figure 4a. The effect of tunneling through a soft zone with different stiffness ratio's on the stresses, displacements, and vector orientation. After (Grossauer 2001). 4b Stress concentration occurring in a block surrounding the tunnel excavation (After Püstow 2001)



4a



4b

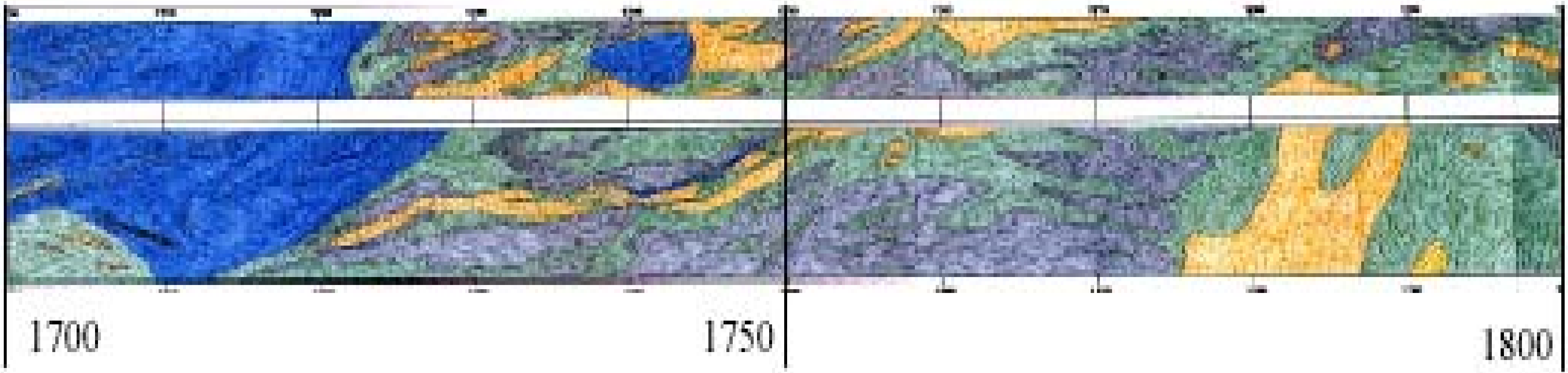


Figure 5. Documented geology of the Spital Tunnel south bore between stations 1700 and 1800. Upper portion is a longitudinal section and the lower portion is a plan view at the bottom of the top heading. Blue - marble, yellow - quartzite, green - chlorite phyllite, gray - undifferentiated phyllites.

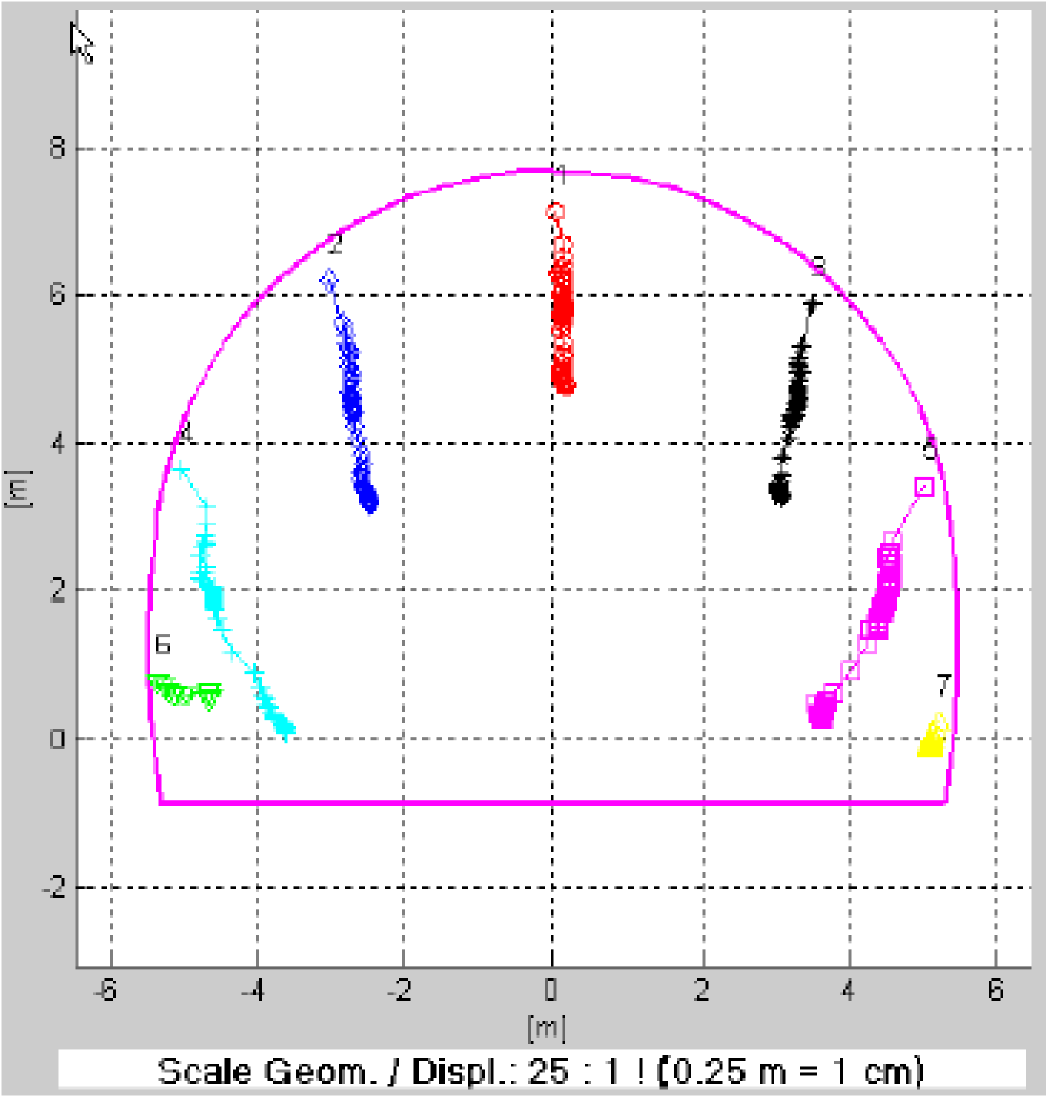


Figure 6. Monitored displacements in a matrix dominated rock mass, station 1769 south bore Spital tunnel. Displacements are magnified by 25.

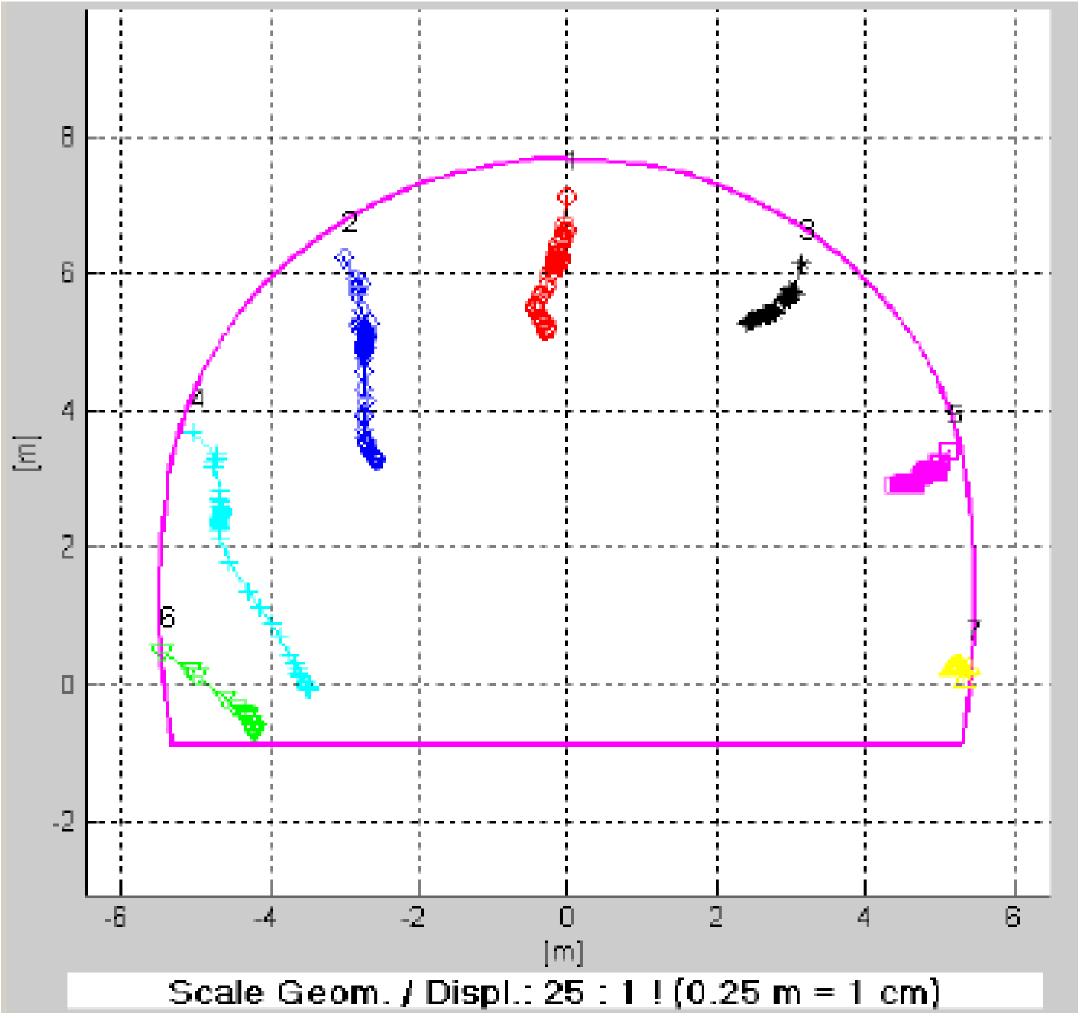


Figure 7. Monitored displacements in a block influenced rock mass, station 1779 south bore Spital tunnel. Displacements are magnified by 25.

Figure 8. Damage to the tunnel lining due to the anisotropic deformations between stations 1785 and 1800.

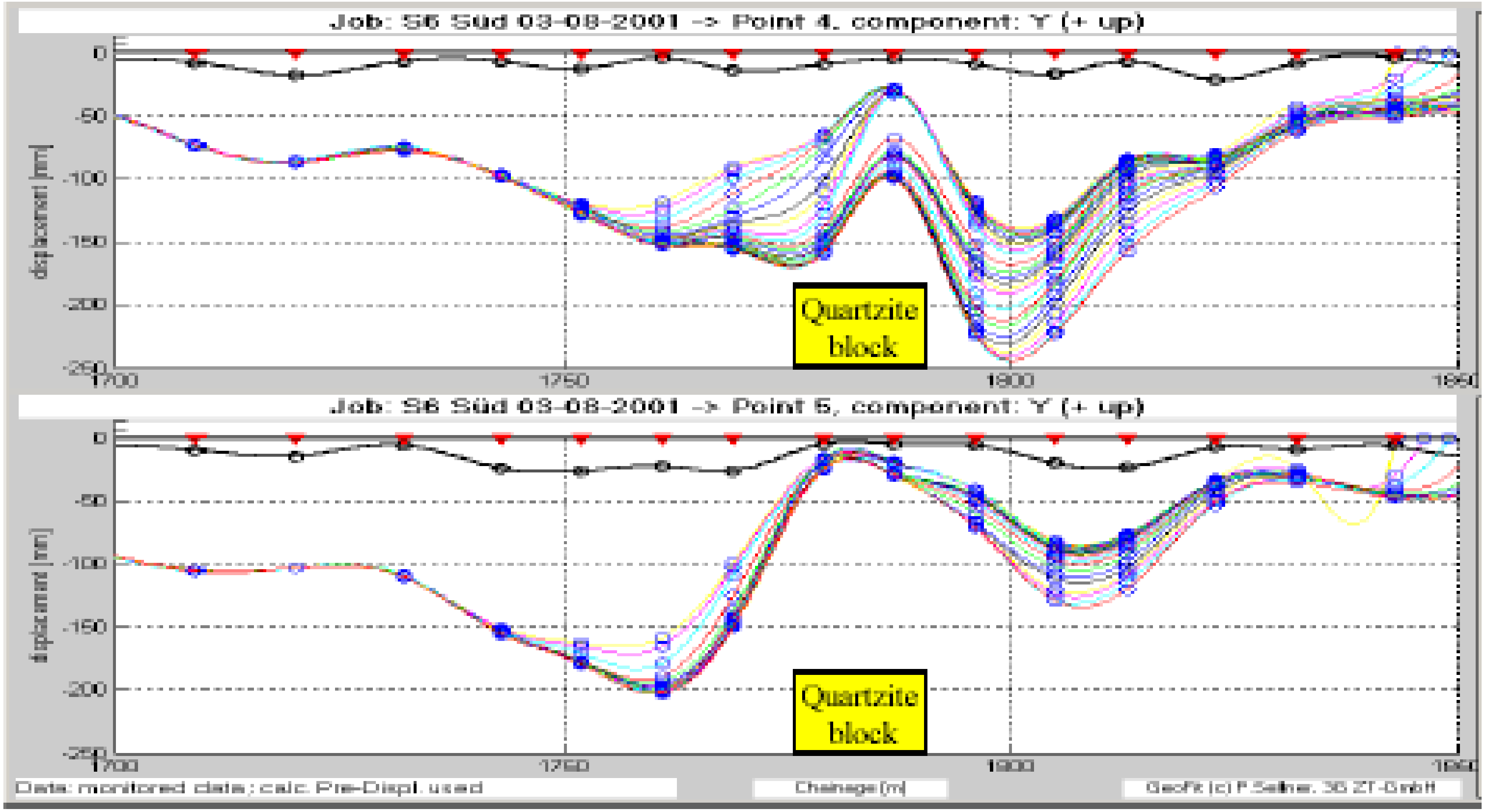


Figure 9. Deflection lines for points 4 and 5 showing the influence of the quartzite block located in the bench between stations 1771 and 1779 on the displacements.

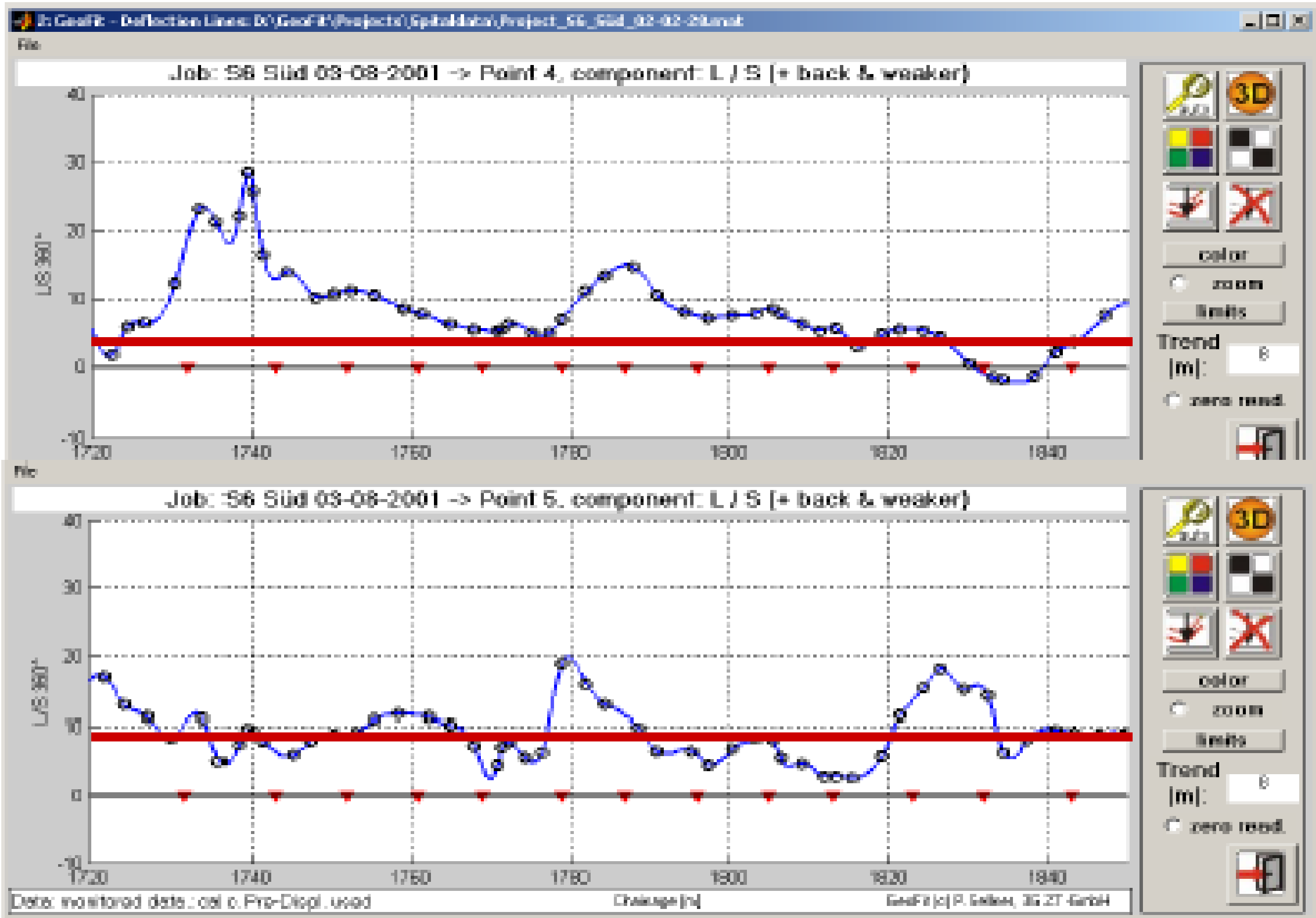


Figure 10. Comparison of the vector orientation plots for points 4 and 5 between stations 1720 and 1850. The "normal" orientation is approximately 8°-10°. The trend is developed 8 m behind the tunnel face.