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20th Tectonomechanics Colloquium

Conference Report

Von Siegfried W. Hermann[1]

On the following pages we present 18 abstracts and extended abstracts as well as three full articles that were presented as talks at the 19th and 20th "Tektonomechanik-Colloquium" (TmC) at the university of Graz. The 20st conference in this series was held on June 20th 2002 at the University of Graz and sparked the idea to publish the presentations from this meeting series in this forum.

The first meeting of TmC took place in June 1991 at Graz University of Technology, Department of Engineering Geology and Applied Mineralogy. That was the first get-together of a small group of physicists and geologists after the "Arbeitskreis Tektonomechanik" has been established under the leadership of G. Mandl. The definition of a geomechanical term for tectonic faults was the declared intention of that first meeting. There two presentations, (i) G. Mandl: "Wie entsteht eine tektonische Scherzone in der spröden Erdkruste?" and (ii) H.P. Rossmanith: "Bruchmechanische Aspekte tektonischer Schervorgänge" introduced into the theme of the earth's mechanics and earth's tectonics. As a result of vast discussions there the term tectonic fault was defined as: *"Tectonic faults are zones of concentrated shearing along which the adjacent rocks have been offset."* This definition was rather blanket and consequently TmC started as an open forum for the total field of earth sciences.

Over the following decade TmCs was convened two times a year, usually each spring and autumn. Organizing effort and technical assistance has been handled by M. Brandmayr, W. Unzog and H. Fritz during the first period and by S. Hermann since 1998. Invitation of participants was largely done by G. Mandl and E. Wallbrecher but also by G. Riedmüller and F. Lehner. In total, several hundred contributions on the theories as well as applied research of rock deformation in different levels of the earth's crust have been discussed. Since the goal of TmCs is fairly broad, the topic of the 20th TmC followed the formation of faults in the earth's crust at any scale.

TmC has established as an international conference. Well-known scientists from five continents presented fundamental information, detailed results and sometime speculative presumption. However, the proudly cherished speciality of TmC meetings are extended and fruitful discussions among an interdisciplinary audience. Every meeting was completed by field excursions to large quarries that impressive demonstrate eg. the Plattengneiss shear zone and deformed eclogites in the Koralm mountains as well as major strike slip faults within the Neogene of the Styrian extensional basin.

The current issue of the Mitteilungen des Naturwissenschaftlichen Vereins für Steiermark contains 18 abstracts and extended abstracts and three full articles of talks presented at 19th and 20th TmC. One article describes a method how to calculate the delay time for blasting in faulted rock (H.P. Rossmanith). This article lightens the importance of basic research for applied geosciences. The articles by E. Pueyo et al. and

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P. Bankwitz et al. have relevance for geological processes in the Eastern Alps and the territory of Styria respectively. The article by Pueyo & al. discusses the restoration of geological structures by use of paleomagnetic analysis. Such method was used to restore folded and multiphase deformed thrust belts among the Northern Calcareous Alps in upper Styria district. The article by P. Bankwitz et al. contributes to processes of mantle degassing along seismic active faults. Similar features might be observed at active faults separating the Eastern Alps from the Neogene Styrian basin.

Abstracts

Structural geological discontinuity analysis as a tool in engineering geological drill core and site investigation

Von Franz Josef BROSCH[1], Robert VANEK[2], Gerald PISCHINGER[2], Arnold STEIDL[2] & Richard OTTO[1]

In the course of site investigations (design process) for the approximately. 30 km long "Koralm" railway base tunnel (rock overburden up to 1700 m; Client: HL-AG, Austrian High-Speed Railway Company), among others the 3G ZT GesmbH Civil Engineers and the Institute of Engineering Geology & Applied Mineralogy of Graz University of Technology were involved in an engineering geological rock mass characterisation issue.

The basic idea was to make up the standard engineering geological drill core logging and documentation standards as well as to improve the 3-D tectonic rock mass model derived from remote sensing and field mapping results. This was done by adopting structural geology techniques for the interpretation of the rock mass deformational status in view of its geotechnical significance. To this end, each discontinuity encountered in selected drilled core sections and identified by acoustic bore hole televiewer (w/r to true orientation and location) was examined for their nature, surface markings, mode and relative directions of wall displacements, fillings and primary (in-depth) aperture. Some of the indicators (and structural arrays), used both in field mapping and in the KDA (Kinematic Discontinuity Analysis) on drilled cores will be displayed and discussed in this lecture.

The computed and via paleo-stress/strain analyses proceeded data of the observed kinematic markers led to a consistent brittle deformation tectonics model of actual prevailing (oblique) normal faulting and extensional jointing, accompanied by slip along the foliation planes. The analyses altogether rendered generally extensional deformation regimes during the most recent tectonic evolution of the investigated region, and predominantly oriented in an approximately E–W direction,. Indications of recent compressional brittle tectonics are generally rare and restricted to some planes of schistosity. Certain differences in the kinematics along the corridor can be stated, in that in the East the E–W-extension seems to prevail while in the central part additionally a N–S extension could be reconstructed. The relative age of both regimes is still open to discussion. The influence of the Lavanttal Fault zone on the kinematic indicators contents of the cores is vague. From field mapping, however there is some evidence of a dextral strike-slip strain regime. These (in parts still preliminary) results have shown to be consistent down to well below the present base of erosion and are for the larger part compatible with the actual local primary stress field, as it had been detected independently by hydrofrac methods.

In terms of actuo-geological and engineering geological interpretations, the results of the performed KDA favour a global extensional tectonic model for the investigated part of the Koralm and lead the geomechanical focus towards the consideration of potential unusually low confining pressures in depth, and associated anisotropic subsurface rock mass stress relief phenomena and water access to underground excavations.

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Stiffness controlled direct shear testing: Observed deformation styles

Von Edward Button[1] & Manfred Bluemel[1]
With 2 Figures

When testing rock samples to determine the strength for investigative purposes, whether it is for an engineering project or for more specific testing related to geological processes, reproducing and scaling the correct boundary conditions is always difficult. We would like to show the results of several direct shear tests performed on rock samples under stiffness controlled boundary conditions. By restricting the dilation the normal load increases depending on the chosen stiffness. By using an infinite stiffness zero normal dilation is allowed and the sample can be tested in "simple shear", we did not restrict the dilation in any direction except vertical for these tests. By specifying displacement boundary conditions and control modes we allow the sample to respond to the imposed strains. This allows the natural rock resistance to deformation be determined. Complex controls modes can be specified to mimic most deformation paths in two dimensions of strain. This type of testing is not common but may provide an interesting opportunity to study the effects of stain paths instead of stress paths on a rocks deformation and strength characteristics.

We have observed different failure modes and deformation mechanisms in samples depending on their local structures and competency. The deformation associated with weak faulted phyllites will be discussed as well as that of strong foliated quartzite (quartz dominated quartz phyllite).

The weak phyllites sheared perpendicular to the foliation deformed by localization of shear bands in weaker zones being deformed by stiffer regions protruding into the samples shear zone (Fig. 1). Interlayer slip and brittle folding were the dominating mechanisms. When the samples are sheared parallel to the foliation, foliation shear occurs as well as distributed interlayer slip, particle folding and gouging from stiffer inclusions depending on the local conditions.

In the hard samples sheared perpendicular to the foliation ridged body rotation and bending developed a bookshelf shearing mechanism which lead to tensile failures and the localization of a shear plane (Fig. 2). Shearing parallel to the foliation resulted in shearing along individual foliation planes with tensile cracks developing release points

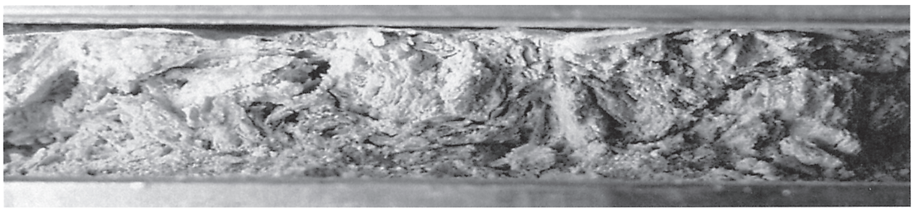

Fig. 1: Photograph of the weak phyllite sheared perpendicular to the foliation after 2 cm of displacement. The folding of the weaker layers driven by the stiffer components is visible, as well as other localized zones of deformation. The specimen is 8 cm long and 1.8 cm high. Shearing was dextral.

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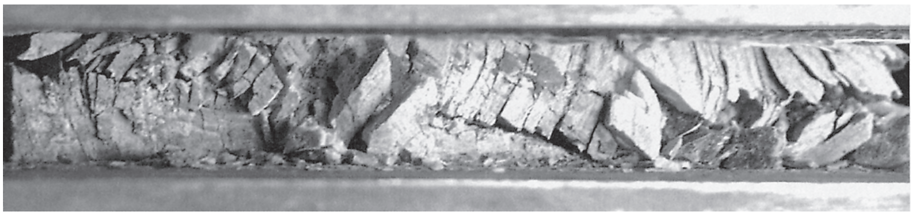

Fig. 2: Photograph of a hard quartz phyllite sheared perpendicular to the foliation. The "blocks" are separated by individual foliation planes (0.1 to 0.5 mm thick) that accommodated the original antithetic shearing while the quartz layers were bent leading to tensile failure and then block rotation. Note the elastic rebound of the layers at the right side of the photo indicating the original orientation of the foliation. Sample is 13 cm long 1.9 cm high. Shear direction was dextral.

allowing internal shear parallel dilation ultimately resulting in a "stepped" failure surfaces. These failure styles are observed at all scales from micro-scale processes to crustal deformation. The results of these tests allow the effect of different failure styles on the measured stress paths to be investigated. Ongoing investigations are continuing looking into the relationships between the constituents stiffness, shapes, cohesive strengths, and distributions on the deformational style and the results stresses.

Fracture mechanics of brittle material – an alternative approach based on a particle representation

Von Peter A. CUNDALL[1]

Numerical modelling of fracture in rock is difficult because the material is heterogeneous: single, "classical" cracks are rarely seen. Rather, a number of isolated microcracks develop and merge to form large-scale ruptures. In particular, the failure under uniaxial compressive stress is not well understood; there are different ideas about how apparent tensile cracks form and propagate when there is no macroscopic tension. The size effect in rock and concrete is also the subject of current research. Several attempts to model the material numerically as a collection of brittle springs, elastic grains, bonded particles or even molecules have been made. Superficially, the results of these simulations are encouraging: cracks are seen to form where expected. However surprisingly little effort has been made to establish an equivalence to established results in fracture mechanics. For example, none of the papers on numerical modelling of material with microstructure provides a way to determine the fracture toughness of the synthetic material. A microstructural model consisting of bonded disks is described, in which each bond break is regarded as a microcrack. The microcracks interact and link up, causing ultimate failure of the body being modelled. The synthetic material can be calibrated by performing simulated laboratory tests. Further, the fracture toughness can be derived explicitly for regular particle assemblies. The model gives rise to realistic fracture patterns and failure modes in simulations of boundary value problems. Examples are presented of failure around circular openings, as compared to field observations.

Perhaps more importantly, the bonded-particle model provides a conceptual picture of the fracture process that seems simpler than the ones usually given in textbooks on fracture mechanics. For example, new light is cast on the topic of size effect, and on classical results, such as that of Griffith (1920). Although tensile failure is the focus of the work described in the talk, some examples of shear failure are presented, in which the predominant micro-mechanism is that of tensile cracking. The macroscopic behaviour of such shear fractures may differ considerably from that assumed in the conceptual model of classical fracture mechanics.

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What exactly is a fault?

Von Terry ENGELDER[1], Benjamin F. HAITH[1] & Amgad YOUNES[2]

In addition to classic fault zones with complex internal structures, several other types of brittle structures exhibit shear displacement. These latter structures include veins with oblique fibers, offset joints, and hybrid shear fractures. This paper presents a case study for two structures that may not be faults according to some structural geologists: hybrid shear fractures and offset joints.

One model for the development of hybrid shear fractures is transitional-tensile fracture propagation, a process described as the in-plane propagation of a crack subject to a shear traction while held open by a tensile normal stress. Presumably, such propagation leads to a brittle structure that is the hybrid of a joint and a shear fracture. Crack-seal veins with oblique fibers are possible candidates. While these veins clearly show shear offset, this is not conclusive evidence that a shear traction was present at the time of initial crack propagation. Many recent structural geology textbooks use a parabolic Coulomb-Mohr failure envelope to explain the mechanics of transitional-tensile fracturing. However, the laboratory experiments cited as demonstrating transitional-tensile behaviour fail to produce the fracture orientation predicted by a parabolic failure envelope. Additional attempts at verification include field examples of conjugate joint sets with small acute angles, but these conjugate joints form neither simultaneously nor in the stress field required by the transitional-tensile model. Finally, linear elastic fracture mechanics provides strong theoretical grounds for rejecting the notion that individual cracks propagate in their own plane when subject to a shear traction. These observations suggest that transitional-tensile fracture propagation is unlikely to occur in homogeneous, isotropic rock, and that it is not explained by a parabolic Coulomb-Mohr failure envelope as several recent structural geology textbooks have suggested.

Some Alleghanian joints in black shales of the Geneseo and Middlesex Formations of the Catskill Delta complex, Finger Lakes district, NY, slipped horizontally up to 8 cm. Horizontal slip is measured by the offset of ENE-striking joints that cross cut these cross-fold joints. Alleghanian joints striking in the range 330° to 350° display a right-lateral sense of slip while joints striking in the range 004° to 010° slip in the left-lateral sense indicating that this joint spectrum acted as a conjugate set of slip surfaces. The average slip on the right lateral joints (1.9 cm) is greater than the average slip on the left-lateral joints (1.3 cm). The maximum horizontal stress (S_H) driving slip on the conjugate slip surfaces falls between 350° and 004° which encompasses the direction of S_H driving Alleghanian layer-parallel shortening as indicated by both disjunctive and pencil cleavage in the Finger Lakes district. This later-stage Alleghanian S_H subjects the right-lateral slip surfaces (i.e., joints) to a higher resolved shear stress on average than the left-lateral joints. A higher resolved shear stress is consistent with greater average slip on right-lateral slip surfaces. The offset of the ENE-striking joints indicates that a joint set predated the Alleghanian stress field. Consequently, we correlate the ENE set with veins of the same orientation in deeper rocks and hypothesize that both propagated in an Acadian stress field. From these data we conclude that both pre-Alleghanian and early Alleghanian joints survived as open cracks during later development of a penetrative fabric.

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An elastic-plastic model for the folding of pervasively fractured sedimentary rocks

Von Martin L. E. GUITON[1, 2, 3], William SASSI[1],
Yves M. LEROY[2] & Bertrand D. M. GAUTHIER[3]

An evaluation of the productivity of fractured hydrocarbon reservoirs requires the characterization of sub-seismic fracture systems in 3D. Here the current practice relies on a geostatistic extrapolation of well data with 3D seismic constraints (e.g., by Gaussian curvature analysis). In this lecture, a mechanical analysis is presented that should yield further physical constraints on fracture prediction by linking a given fracture set to a specific tectonic folding event.

First, typical discontinuities of interest are illustrated from a field study of Emsian fractured sandstones folded during Hercynian orogeny in the Southern Anti-Atlas of Morocco. As in many other field studies of comparable settings, two main sets of fractures can be distinguished, striking perpendicular and parallel to the local fold axis. These fractures present evidence of an opening mode at their onset. Indicators of slip reactivation on these sets in a late folding stage are associated with the development of a third set of fractures in shear. This complex history of opening and slip activation or reactivation is described with an elastic-plastic model based on multiple yield functions, each corresponding to a specific orientation of the discontinuities. The role of inherited and new fracture sets is illustrated by a 3D simulation of folding either due to buckling or diapirism.

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The lateral extrusion of the Eastern Alps: Did it happen? If yes, when did it happen?

Von Ewald HEJL[1]

Several geotectonic models dealing with Neogene tectonics of the Eastern Alps have postulated an eastward extrusion of the Central Alps towards the Pannonian basin. One main requirement of these models is a large-scale sinistral displacement along major faults at the southern margin of the Northern Calcareous Alps. Such late sinistral strike-slip has never been proven for the Salzach and Ennstal faults. The opposite seems to be true for the following reasons: (i) The drainage pattern of the Salzach and Enns fluvial systems in incompatible with a young sinistral displacement at the northern border of the Tauern window. (ii) The eastward prolongation of the Salzach fault is situated exactly to the N of the Mandling wedge. A hypothetic fault segment at the southern margin of the Mandling wedge – as has been postulated by the extrusion models – does not exist in nature. Therefore, the E-W trending Salzach and Enntal faults do not belong to one continuous fault system. (iii) The Tertiary of Wagrain (presumable lower Miocene) was subjected to dextral shear. A post-depositional sinistral displacement can be excluded. (iv) Extrusion tectonics should have caused counter clockwise rotation of individual segments of the Northern Calcareous Alps. Palaeomagnetic studies have demonstrated that just the opposite did occur. (v) A young dextral displacement along the Salzach-Mandling fault would be compatible with the arcuate structure of Weyer (so-called Weyerer Bögen) which would have been produced by E-W convergence resulting from opposite sense of movement along the Salzach-Mandling fault to the W (dextral) and the Mariazell-Puchberg and Trofaiach lines to the E (sinistral).

Consequently, any tectonic models which require a Neogene strike-slip along the northern border of the Tauern window seem to be wrong. A continuous SEMP line (Salzach-Ennstal-Mariazell-Puchberg) does not exist. If at all, the lateral extrusion of the Eastern Alps could only occur previous to the deposition of the Miocene sediments of Wagrain.

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Comparison between the Ultramafic Delitzsch Complex and the active magmatic evolution in the western part of the Eger Rift: Interaction between fracture tectonics, migration of magmatic fluids and the structure of the seismogenic crust

Von Horst KÄMPF[1]

We cannot observe the interaction between fracture tectonics, migration of magmatic fluids and the structure of the seismogenic crust directly, but we can study and compare sections of different examples of earthquake or palaeo-earthquake areas and so the key problems for modelling of the earthquake swarm processes can be analyzed (KÄMPF & al., 1991, 1992).

The comparison includes two examples, the Carbonatite – Ultramafic Lamprophyre Complex of Delitzsch, which is located 25 km north of Leipzig (CUL-Delitzsch Complex, SEIFERT & al. 2000) and the Magmatic Reservoir of the western part of the Eger Rift (MR-Western Eger-Rift, KÄMPF & al. 1999, WEINLICH & al. 1999).

The features and evolutionary trends of both magmatic complexes are:

- both complexes are located within the N–S trending Naab-Pritzwalk lineament (length: ~450 km, width ~60 km),
- extent of the magmatic reservoirs (diameter of the CUL-Delitzsch Complex: ~20 km; MR-Western Eger-Rift: ~60 km in diameter),
- timespan of magmatic activity (CUL-Delitzsch Complex: Upper Cretaceous: ~110–70 Ma; MR-Western Eger Rift ~15 Ma – active),
- magma types in both examples are CO_2 enriched mafic to ultramafic continental magmas (CUL-Delitzsch Complex: dolomite and calcite carbonatite, alnöite, aillikite; MR-Western Eger-Rift: nephelinite, ijolite, CO_2 degassing at the surface),
- the position of the magma reservoir in both examples is the Upper mantle,
- the position of the magma chamber is different in both examples (CUL-Delitzsch Complex: Upper crust; MR-Western Eger-Rift: Subcontinental upper mantle, ? lower crust),
- partial intrusions, volcanoes and CO_2 plumes at the surface (CUL-Delitzsch Complex: Serbitz, Storkwitz, Torna; MR-Western Eger-Rift: Komurni Hurka, Zelezna Hurka, Prdhorny Vrch/scorias and volcanoes, Cheb Basin, Marianske Lazne, Karlovy Vary/CO_2 plumes),
- magma or fluid transport (CUL-Delitzsch Complex: diatremes of dolomite carbonatite magmatic breccia, dykes and fissures of carbonatite, alnöite and aillikite; MR-Western Eger Rift: dykes of nephelinite and ijolite, CO_2 transport in fault zones).

The origin, type and transport of magmas and the extent of the magmatic reservoir in both examples seems to be comparable. The position of the magma chamber and magma-crust interaction is different. The magma chamber of the CUL-Delitzsch Complex is located in the upper crust (magmatic to subvolcanic environment), while the

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position of the magma chamber of the MR-Western Eger Rift is subcrustal mantle to lower crust (magmatic environment). Consequently the coupling between fluid migration and fracturing (rheology of the seismogenic continental crust) seems to be different in both examples: volcanic (magmatic overpressure) induced earthquake swarms, which has a high explosive component (CUL-Delitzsch Complex) and fluid (overpressure CO_2) induced earthquake swarms, which has a low explosive component (MR-Western Eger Rift).

For future search of a model of earthquake swarm processes we have to investigate active sections, which are opposite in the explosive component of the earthquake swarm mechanism.

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Cauchy versus Gauss: a new approach to stress and deformation

Von Falk KOENEMANN[1]

Up to now, the understanding of stress is based on the ideas developed by Euler between 1740–1776, refined by Cauchy in 1821 and 1827. In this view, Newton's mechanics is adapted to help in the understanding of continuum mechanics. Newton's theory applies to the mechanics of discrete bodies in free space. Cauchy's approach to stress is thought to prove the applicability of Newton's physics to the mechanics of solids, but it ignores the constraints supplied by the Gauss divergence theorem in particular, and the theory of potentials in general Elastic deformation is to be understood as work done upon a system in the sense of the First Law of Thermodynamics, hence elastic deformation represents a change of state. This is not apparent from the Euler-Cauchy approach which suffers from other imperfections as well. Therefore a new approach is required.

The new approach is in principle an adaptation of the discrete mechanics theory of Newton in which forces act upon a body of finite size. Contrary to the Euler-Cauchy theory, stress is understood as the elastic potential, i.e. work done per unit mass upon a system of solid in the sense of the First Law, and its spatial properties are represented by a force vector field. Starting with a thermodynamic system in an unloaded standard state, three groups of forces must be considered in order to consider work done upon the system: (1) forces exerted by the surrounding upon the system, (2) forces exerted by the system upon the surrounding, (3) forces that bond the system and the surrounding. Forces of group 1 are controlled by the exterior, forces of group 2 represent the material properties, and group 3 show up in considering the equilibrium conditions: they are observed in cases that are potentially dis-equilibrium cases which cannot occur within a solid as long as no bonds are broken. For example, stretching a body requires that the surrounding is bonded to the system; hence there are the external stretching forces (1), the system forces (2) counteracting (contracting) and balancing those of (1), and the bonding forces (3) without which an interaction of (1) and (2) is impossible. Bonding forces (3) reach zero at solid-freespace interfaces.

The new approach delivers the same results for plane pure shear deformation as the Euler-Cauchy approach, but it also delivers substantially better results for simple shear. It correctly predicts (a) the orientations of S- and C-planes and the general kinematics of SC-fabric including the correct orientation of non-rotating eigen directions; (b) the correct orientation of dilational joints in shear zones; (c) the correct orientation of the maximum stress orientation along transform faults, especially that observed along the San Andreas Fault; (d) the correct energetics: experiments show that elastic simple shear requires 10% more work than elastic pure shear, but plastic simple shear requires 30% less work than plastic pure shear, and the new approach predicts both the existence of the inversion and the correct relative magnitude; (e) the orientation of conjugate joints in 3D. Furthermore, the approach permits the identification of an instability located at the reversible-irreversible transition which causes the stressed state to collapse into one of two possible energetic configurations which have opposite skew. This instability causes the Y-direction in plane deformation to be instable. It is believed to be the cause for the existence of conjugate joint sets in brittle deformation, of sheath folding in extensive plastic deformation, and of turbulence in low-coherence viscous flow.

The new approach is a proper field theory in the mathematical sense. It does not require cumbersome auxiliary methods (FEM) for modeling, but can be used straightforwardly using Fourier series methods: the boundary conditions are thereby modeled such that one single solution exists for the entire region of interest, and for any point within that region the equations can then be solved. An example is worked out for a body under vertical compression with freedom to expand into freespace horizontally.

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Microstructural constraints on the kinematics of fault propagation folds and the mechanics of kink bands

Von Bertrand MAILLOT[1], D. BUIL[1] & Yves M. LEROY[2]

In external zones of mountain belts or accretionary prisms the superficial sedimentary cover commonly undergoes large horizontal displacements. The resulting thrusting of the cover follows various kinematic paths. The first part of this lecture covers a number of case studies from the NE Pyrenees, France, that will illustrate an approach developed at Cergy-Pontoise to relate the gross kinematics of large scale folds to small-scale observations. In addition to classical micro-tectonics strain markers, the orientation, the spatial gradients and the chronology relative to the folding of the diffuse small strain history can be determined by measuring the anisotropy of the magnetic susceptibility of centimetric-scale rock samples. These tools provide strain data that allow us to discriminate between the following global kinematic models: a combination of fault-bend and fault-propagation kinematics for the Lagrasse fold, and a trishear fault propagation kinematics for the Oupia anticline.

Further constraints on the micro-mechanisms in these low strain rate-, low temperature-, low pressure regimes could be established through the complementary approach of mechanical modelling. In the second part of this lecture we present a mechanical model of kink bands at the extremities of a ramp, which are a widely observed feature of thrust related folding and a feature common to all purely kinematic models. For a power-law creep rheology, the assumption made in these kinematic models that the sedimentary layers keep their thickness constant during folding is shown to require a dissipation about 10% above the minimum and this in turn predicts a thickening of about 15% of the hanging wall above the ramp (values weakly sensitive to the power law exponent). However, the occurrence of kink bands, i.e., the localisation of deformation into a narrow simple shear zone, imply the presence of a destabilizing mechanism in the rheology which is rarely accounted for. Flexural slip between creeping layers is shown to be a suitable destabilizing micromechanism. The construction of the stress field in the band allows us to predict the possible orientation of micro-fractures that can be compared with orientations measured in the field or on analogue models.

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Characteristic scales of fault roughness due to frictional damage in lignite

Von Martin NAVARRO[1] & Horst J. NEUGEBAUER[1]

The analysis of fracture roughness provides a multi-scale description of fracture surfaces and has become an important tool for the numerical modelling of mechanical and hydraulical fracture properties. Many fracture and fault surfaces show a scale invariant (fractal) roughness. Unfortunately, it is difficult to decide whether exceptions from scale invariance are random or systematical only by considering the scaling of roughness. Characteristic scales can only be identified by relating scaling properties to specific fracturing processes visible in the field or laboratory. If this is possible, roughness analysis provides an additional view on the fracturing or faulting process. We have analyzed the roughness of normal faults in lignite perpendicularly to slip direction over a scale range of 3 to more than 4 orders of magnitude. Hurst exponents vary between 0.6 and 0.9 indicating a deficient self-affine (scale invariant) scaling. Self-affinity is essentially disturbed by an increased roughness of the hanging wall. Instead, we find a characteristic scale of roughness which is dependent on fault offset. Field observations support that these phenomena attribute to a detachment of lignite from damage zones which develop due to the friction of rough fault surfaces.

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Fluid induced seismicity: pore pressure diffusion versus nonlinear permeability

Von Horst J. NEUGEBAUER[1]

Fluid injection experiments have been carried out at the KTB drill-hole in the last century. Our presentation refers to the first experiment at a crustal depth level of 9 kilometer. 200 cubic meter fluid have been injected over a time interval of 35 hours. The response of the crustal rocks reached 400 microearthquakes with a maximum magnitude of 1.2. The localisations of the hypocenters comprise a volume of about 1.5 by 3.0 km. This is a reasonable indication that fluids have a controlling influence to seismicity. The space-time distribution of the foci reveal a sudden onset of seismicity at about 0.5 km distance from the injection point up to 18 hours. After that time the distance of hypocenters increased to a range of 1.0 km with a tendency of decay. The maximum magnitude event occured at 18 hours after the onset of injection at a distance of 1.5 km. The experiment provides a rather suitable study for the determination of the dynamical process responsible for the occurence of seismicity; because we have access to both the input and the systems response. Thus we discuss two possible mechanisms for the development of the fluid-pressure and rock-stress system. Beside pore-pressure diffusion a nonlinear flow in faulted rocks is compard with the experimental data. The field variables have been quantified by independent model calculations.

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Physical analogue modelling: The role of physical model experiments in a numerical computerized world

Von Dick. A. NIEWLAND[1]

Rapidly increasing computer power, ever-faster computers and seemingly unlimited hard disc capacities for even the smallest computers have given a tremendous boost to the use of computers. The believe in what can be achieved with numerical models is very firm and is justified by the development of increasingly better modelling results with numerical tools. Even 3D numerical models are appearing. As a result it is a widespread believe that 'everything can be modelled with a computer'.

However, numerical models still have their limitations, some of which are not likely to be solved in the near future. The most fundamental shortcoming is the fact that computer models run on the basis of algorithms, which in turn are an expression of our current state of knowledge. Secondly, all models must simplify the real world, which is the focus of the model; it is simply not possible to incorporate all aspects of the real world in a model.

Physical models have the same limitations, in principle, as computer models, however, they are different and this is where the strength of physical modelling comes into play. Physical modelling has developed tremendously over the past twenty years or so. New techniques and new materials emerged, in part building on the developments in computer power. It is the integration of these two approaches, which results in a powerful synergy. The most important and fundamental difference between numerical and physical models is, that numerical models need algorithms, whereas physical models are exclusively run on the basis of the laws of physics. This makes physical models very 'pure' analogues of natural processes and geometries. Naturally, also physical models have their limitations, the most critical is the true scaling of the model. The choice of modelling materials and strain-rates is of fundamental importance to scientifically correct modelling. It is often forgotten that this same problem also occurs in numerical models, especially finite element models struggle with the element size.

New techniques, new materials and integration of physical and numerical models are a powerful way of working which has a long and healthy future ahead.

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Geotechnical impact of brittle faults

Von Gunther RIEDMÜLLER[1]

Tunnelling through brittle fault zones requires special considerations during all phases of a tunnel project from design to construction. The geotechnical problems during construction relate primarily to the substantial heterogeneity of fault zones in terms of strength properties of the rock mass.

Geotechnical aspects of fault characterisation and problems of investigating a tunnel in a fault zone are discussed. It is demonstrated that a technical and economical optimization of construction can only be achieved by a flexible contractual set up which allows for modifications of the construction method. In this context it is emphasised that, based on a continuous evaluation of geological and geotechnical monitoring data, the predicted geological model is adjusted to the actual conditions. Based on the updated model, excavation and support is adjusted accordingly. The principal geotechnical difficulties and adequate counter measures during excavation problems related to tunnelling in brittle faults and the development of advanced support technology are demonstrated by case studies.

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Virtual sections trough porphyroclast systems

Von Frank SCHOBEL[1]
With 2 Figures

Porphyroclast systems are widely accepted as reliable shear sense indicators in natural shear zones. There exists a huge amount of literature concerning their description and about methods to find the shear sense by the use of their asymmetry. Porphyroclast systems are assemblages composed of a rigid core which in surrounded by a rim of recrystallised core material, called the mantle. The core and the mantel are embedded in a matrix formed by considerably smaller crystals. The distortions of the mantle material in the surrounding flow, described as wings and tails, are used to classify the systems using greek letters appropriate in shape to the geometry of the distortions: d, s, q and f geometries. The asymmetry of the distortions is used to describe the sense of shear.

Despite the knowledge accumulated, it is not always easy to evaluate the asymmetry of natural porphyroclast systems in terms of sense of shear. One problem is that the available data are mainly restricted to a two dimensional approach. Currently it is recommended to search for shear sense indicators in sections that contain the stretching lineation and that are normal to the foliation. This recommendation is derived from the more easy to handle monoclinic geometry of currently used shear zone models. The limitation of this assumption was highlighted in several studies of the last years, studies that showed that monoclinic shear zones are only end members of a much larger spectrum of possible geometries. Triclinic or even more complex flow geometries should be very wide spread. The main characteristic of such flows is that the vorticity vector, neither shows a perpendicular or parallel orientation with respect to the observed stretching lineation, nor it is obligatory included into the foliation. So, the first step for characterising triclinic flows is to find the orientation of the vorticity vector. Aiming to solve this problem, we propose a method using the 3D-geometry of natural porphyroclast systems.

Methodology

Asymmetries in natural fabrics are induced by the simple shear component of the flow. The sense of shear is fixed relative to the shear zone boundary by the orientation of the vorticity vector. It is well known that the sense of shear recorded in different oriented sections through the same shear zone may be even opposite. For example, for the transport direction "top to the north" of a nappe, viewed on outcrops of the detachment shear zone exposed to the east, porphyroclast systems will exhibit a clockwise rotation, whereas viewed on exposures oriented to the west, the asymmetries will infer an anticlockwise rotation. We noticed that for a three-dimensional porphyroclast system, the asymmetry description is a question of perspective view.

In Fig. 1a an extruded "asymmetric" S-shaped object is embedded into a transparent block (the sample) with the frontal view in E-W direction of the sample coordinate system. Viewed from the west, the object shows an S-asymmetry, viewed from east the mirrored object outline shows a Z-asymmetry, whereas viewed from upside down, from north or from south the object shows only the thickness of the extrusion without any asymmetry at all. Starting from the periphery of the stereographic projection, the asymmetry "tightness" decreases systematically until it completely disappears into the

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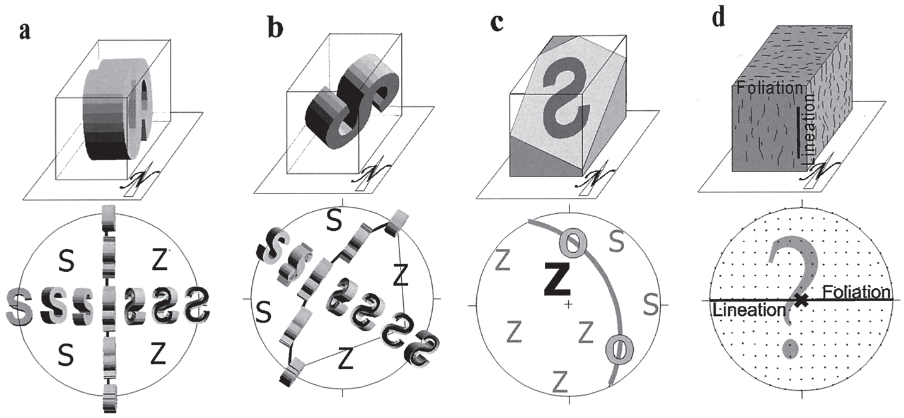

Fig. 1: Finding the orientation of the symmetry elements of an object.

vertical view. The occurrence of the S- and of the Z-asymmetries is delimitated by a plane of view directions that show no asymmetries, we called it the plane of symmetry. The corresponding normal to the plane of symmetry is called the asymmetry axes and corresponds to the frontal view to the object. Figure 1b shows views of the same object in a tilted an rotated position relative to the sample coordinate system. Strictly from geometric point of view, it would be only two views requested that exhibit no asymmetry to construct the above defined symmetry elements. Figure 1c shows a situation where an object is embedded into an opaque material. A section through the sample with a steeply NNW plunging normal cuts the object. The Z-shaped asymmetry is noted into the stereographic projection of the sample coordinate system in the point representing the sectional normal. A sufficient amount of randomly distributed virtual sections through the sample are needed to find at least two section with no asymmetry, sections that are requested to construct the symmetry plane. One possibility is to choose these sections according to Braun's distributions used in manual counting nets. A systematic approach implying a sufficient number of sections with different orientations will constrain the orientation of the asymmetry axes. A similar procedure may be used to geological samples containing a porphyroclast (Fig. 1d). The asymmetry axes of a porphyroclast system is supposed to record the rotation axes of the clast in the flow, which consequently also should represent the vorticity vector of the shear zone.

The approach described above suggests an independent method for finding the porphyroclast rotation axes. It is necessary to produce equal distributed sections through the gravity centre of the porphyroclast. The evaluation of the asymmetry of these sections will provide information that are requested to constrain the symmetry elements of the porphyroclast systems.

Criteria for asymmetry definition

For the morphological description of porphyroclast systems, a particular terminology is established. We will highlighten some aspects related to symmetry concepts. One of the typical features of d-shaped porphyroclast systems is that they show a point symmetry relative to the centre of symmetry. The centre of symmetry is supposed to be also the centre of gravity of the clast, through which the rotation axes of the clast should pass through. This feature is currently described as asymmetry. s-shaped porphyroclast systems show also asymmetries that may be characterised by point symmetries. s-clasts don't show a sharp angled embayment of the mantle or even no embayment at all, there cases may occur exhibiting mirror symmetries. In these particular cases, due to the higher occurring symmetry, the determination of the sectional shear sense may be problematic. q- And f-shaped porphyroclast systems exhibit a higher, orthorhombic symmetry, consisting of two perpendicular arranged mirror symmetries, with the mirror axes intersecting in the centre of gravity of the core. Orthorhombic symmetries are currently interpreted as indicators for sectional non-rotational behaviour or for coaxial deformation.

Clast3D Program

Three dimensional visualizations and multiple crosscutting sections through a virtual geological sample are possible due to techniques developed for medical purposes, the computer tomography CT. A virtual sample model is produced by stacking images one over the other in a three dimensional array. We obtained these images with an eroding and scanning technique.

The IDL language provides powerful tools for processing and visualisation data, permitting the modification of the IDL routine source codes for own purposes. On the basis of the IDL Slicer3 routine, which gives the frame work for CT data processing, we developed the Clast3D routine, which creates and evaluates the required virtual sections through the porphyroclast systems.

After creating the voxel array, the coordinates of the virtual rigid core gravity centre have to be fixed. This is made on the user interface by iterative shift of the centre coordinates until a best fit in three orthogonal sections is achieved. For eliminating perspective view errors, the normal to the section is rotated parallel to the virtual view-point, perpendicular to the screen. After the production of the sections (Fig. 2), their sectional symmetry is evaluated. The data are stored into a ASCI-file that is further processed with a Mathematica notebook, in order to calculate the symmetry elements, to effectuate the coordinate transformation from the sample into the geographic coordinate system and to visualize the calculations into a common stereographic projection. It is also possible to find the orientation of the axis of the rigid core, assuming an ellipsoidal shape.

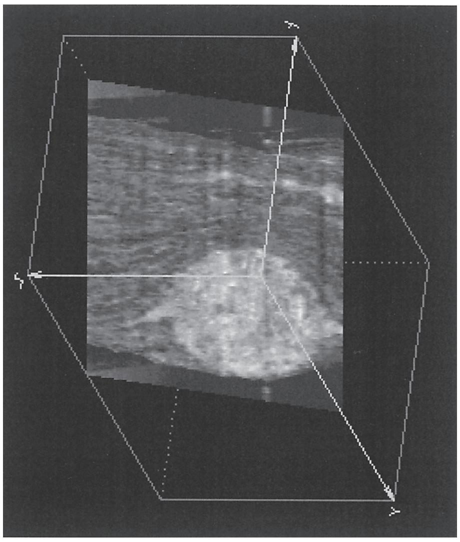

Fig. 2: Virtual section trough a porphyroclast point symmetry, d-clast, dextral sectional shear sense.

Capturing the influence of principal stress axes – rotation with the multilaminate model

Von Hartmut SCHULLER[1], Christoph WILTAFSKY[1] & Helmut F. SCHWEIGER[1]

Within the framework of the finite element method Multilaminate models can be applied in the field of numerical simulations in geotechnical engineering for capturing effects of strain localisation, e.g. the development of shear bands during tunnel excavation.

Another advantage of Multilaminate models if compared to most constitutive models formulated in terms of stress invariants is the ability to account for rotation of the principal stress axes. Most engineering works, such as excavations, the loading of foundations or construction of embankments, result in complicated stress paths in the ground including principal stress axes rotation. This principal stress rotation can significantly influence the soil behaviour as demonstrated by experimental evidence (e.g. ARTHUR & al. 1980).

In Multilaminate models the constitutive relations are formulated independently on a number of so-called contact planes within each integration point. The global behaviour of the integration point is obtained by an integration of the contribution of each plane. In the formulation presented here a non-associated flow rule was applied. As a yield criterion the well known Mohr-Coulomb failure criterion was enhanced by a mobilised friction angle for deviatoric hardening.

The potential of the Multilaminate model to respond to changes in principal stress axes under a constant mean stress is demonstrated by comparing results of numerical simulations of various stress paths to results of analyses obtained with a standard Mohr-Coulomb formulation and an invariant formulation that incorporates deviatoric hardening. Further insight into the processes of activation and deactivation of various contact planes within the Multilaminate framework is presented for a stress axes rotation under constant mean stress (SCHWEIGER & SCHULLER 2000).

The constitutive model was further enhanced by including a "cap" yield surface for volumetric hardening into the formulation. Thus, laboratory tests analysing the response of clay samples to principal stress axes rotation under a constant mean stress can be matched with the numerical simulation.

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Experimental deformation of wet fault gouge

Von Chris J. Spiers[1] & B. Bos[1]

Despite the widely perceived importance of pressure solution and phyllosilicates in determining fault rheology in the brittle-ductile transition, there have been few experimental studies of their combined influence on fault constitutive behaviour under appropriate laboratory conditions. To address this, we have performed high strain, rotary shear experiments on experimental faults containing brine-saturated mixtures of halite and kaolinite (or muscovite) to simulate fault gouge. The experiments were done under room temperature conditions where pressure solution and cataclasis are known to dominate over dislocation creep in halite, thus modeling the brittle-ductile transition. We explored the effects of sliding velocity, effective normal stress, clay content, and shear strains of up to ~1000 on fault strength and microstructural development. All runs showed an initial peak strength, followed by strain weakening towards a steady state residual strength, the weakening being particularly marked at low sliding velocities. At high slip velocities, the experiments showed frictional, nearly rate independent behaviour. At low sliding velocities, the steady state data showed frictional-viscous behaviour, with the shear strength depending on both normal stress and shear strain rate. In contrast, purely frictional (i.e. normal stress dependent and shear strain rate insensitive) behaviour was observed when an inert pore fluid (silicone oil instead of brine) or an inert solid (quartz instead of halite) was used, and when using monomineralic halite and kaolinite gouges. This demonstrates that the frictional-viscous behaviour was caused by combined effects of pressure solution and phyllosilicates. In addition, the strain weakening seen in the phyllosilicate-bearing samples was associated with a transition from dominantly frictional behaviour, at shear strains up to 5–10, to dominantly rate sensitive sliding at higher strains. This was accompanied by a change from a cataclastic microstructure to a mylonitic one characterised by elongate halite clasts in a fine grained, foliated halite-phyllosilicate matrix. We infer that strain weakening and the transition from rate insensitive to rate sensitive slip was caused by brittle grain size reduction giving way, as the foliation developed, to sliding along the phyllosilicate-rich foliation planes with accommodation by pressure solution and by cataclasis/dilatation at the higher sliding velocities. These conclusions are strongly supported by microphysical modelling. If similar pressure solution accommodated behaviour occurs in natural phyllosilicate-rich fault zones, our model predicts that such zones will be much weaker than expected from traditional brittle-plastic strength envelopes. In addition, our mylonitic microstructures, which strongly resemble natural mylonites, suggest that cataclasis and pressure solution may play a much more important role in strain weakening and the microstructural evolution of mylonitic rocks than generally thought. Our results raise serious questions regarding the reliability of mylonitic microstructures as rheology indicators, as well as regarding the use of monomineralic flow laws for modeling crustal dynamics.

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Fault dependent drainage system in the area of the Sickerkopf valley thrust

Von Elmar STROBL[1] & Peter RAMSPACHER[1]

During the heading of the pilot tunnel Kaponig, which is driven through rock sequences of the Obere Schieferhülle of the Tauern window a large amount of water inflow has been encountered when passing a large fault system. A great number of hydrogeological investigations has been carried out in order to find an answer to the question of the origin of the infiltrating water and finally to get information regarding the drainage system.

Isotopic composition as well as hydrochemical composition of the infiltrating water clearly show a recharge area which is situated in very high elevations reaching almost to the top of the Sickerkopf mountain. The mapping of this region shows deep reaching loosening of the host rock (carbonatic schists, phyllites and quarzites) caused by a postglacial valley thrust. Practically all the surface water infiltrates into open faults which are outcropping in the upper part of the valley thrust. These are acting as preferential flow paths leading the water through a drainage system which is extending deeper than the recent surface of the Möll valley.

The heading of the pilot tunnel was passing this fault system, causing huge water inflow into the tunnel. As a consequence a few springs situated in a distance of about 2 km to the north, close to the border of the valley thrust became dry.

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Secondary deformation patterns near fault tips: comparison between fracture mechanics theory and some outcrop observations

Von Emanuel J. M. Willemse[1,2]

Sliding along a pre-existing flaw or fault can result in the formation of tensile cracks where stresses concentrate near the tips. These tensile cracks are referred to as wing cracks and are generally oriented oblique to the pre-existing flaw. Linear elastic fracture mechanics (LEFM) has been used in previous studies of this important deformation mechanism to establish a relationship between the kink angle and the ratio of normal to shear loading on the flaw. Recent work has shown that cohesive-end-zone (CEZ) flaw models may form a better approximation for faults than LEFM under some conditions or for some materials. We present analytical solutions for CEZ flaws and find that the relationship between kink angle and load differs significantly from that for LEFM flaws. Furthermore, the remote flaw-parallel normal stress may significantly reduce or increase the kink angle especially for CEZ flaws with large end-zones. Based on these findings, multiple interpretations can be given for some measured kink angles. In some materials solution surfaces may form at the tip of the sliding flaw. By considering the angle between wing cracks and solution surfaces, it is possible to determine whether the LEFM or CEZ model is more appropriate, and thus provide a better constrained interpretation of the boundary conditions that accompanied sliding. For CEZ flaws, the stress state in the cohesive-end-zone is nearly homogeneous, which could promote formation of arrays of opening mode cracks and solution surfaces that together form a shear zone. The CEZ flaw model can explain some patterns commonly observed near outcropping faults that can not be accounted for with the LEFM model.

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