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The Relevance of Brittle Fault Zones in Tunnel Construction – Lower Inn Valley Feeder Line North of the Brenner Base Tunnel, Tyrol, Austria

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Abstract

In tunnel engineering, zones of rock affected by brittle deformation cause problems. Frequently, they call for special tunnelling methods, which in turn lead to higher costs for the contractor. In some cases, due to incalculable safety risks or for economic reasons, further advance is impossible. Gaining knowledge about the appearance and the petrography of such fault zones and their geomechanical and hydrological properties at tunnel level is eminantly important.

The reconnaissance tunnels of the Feeder Line North of the Brenner Base Tunnel, cut across brittlely deformed competent and incompetent rock with extremely variable geomechanical characteristics, in the Lower Inn Valley, one of the largest fault zones in the Eastern Alps.

From the geomechanical point of view, brittlely deformed incompetent host rocks (e. g. phyllite, marl, shale, etc.), so called kakirite or fault gouge (HEITZMANN, 1985), form zones with soil-like characteristics. Such zones have a large squeezing potential and exhibit long-lasting plastic deformation which declines over time. Their hydrological properties are advantageous, as the presence of finely ground rocks, containing large amounts of phyllosilicates, results in a low permeability.

Brittlely deformed competent host rocks (e. g. granite, massive carbonate, quartzite, etc.) form nearly cohesionless zones, but are also termed kakirites. In this paper special attention is paid to brittle fault zones in carbonate rocks. Such zones have often undergone intensive diagenetic solution and precipitation processes and therefore represent a special type of kakirite. If filled with water, they constitute the most arduous zones during tunnel construction. If such a zone is unexpectedly hit, material and water will ingress within seconds. In this case, further advance is not possible without draining ahead of the tunnel face and/or improving the rock mass using injection methods.

This shows that different kinds of parent rock result in the varying geomechanical properties of fault zones. Using experiences from 8.56 km of tunnelling within the Lower Inn Valley Fault Zone the geology, structural geology and geomechanical characteristics of brittle fault rocks are described in this paper.

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1. Introduction

Brittle fault zones have great influence on underground construction projects, especially in the case of deep lying tunnels, where they cause serious problems, above all when they possess high permeability. At the surface these zones are often masked by scree and Quaternary sediments. Minor fault zones accompanying major fault zones show only little displacement and may have been overlooked in the course of mapping. Detailed mapping, at a scale of 1:2000 to 1:5000, structural as well as petrographic analysis and extensive hydrogeological investigations enable geologists to predict the geomechanical properties and groundwater conditions at tunnel level.

The Feeder Line North forms part of the Railway Project Munich – Verona (Fig. 1) and consists of several deep lying tunnels. It runs approximately 40 km sub-parallel to the Inn Valley, Tyrol, Austria, and obliquely crosses several faults which are part of the Lower Inn Valley Fault Zone. During construction of the Brixlegg-East and Vomp-East reconnaissance tunnels, different types of brittlely deformed rocks were encountered and led to serious tunnel engineering problems.

Apart from surface mapping, additional information was gained from drilled cores, which were extracted during an early phase of the project. The unfavourable outcrop situation, caused by a particularly thick and widespread Quaternary sediment cover, required the projection of geological structures and fault zones over large distances to the position of the proposed main tunnel lines. In order to obtain more detailed information on the geomechanical and hydrological conditions for the main tunnels due to be constructed between 2003 and 2008, excavation of the reconnaissance tunnels was carried out between 1998 and 2002. During excavation of these tunnels several different types of fault zones were encountered.

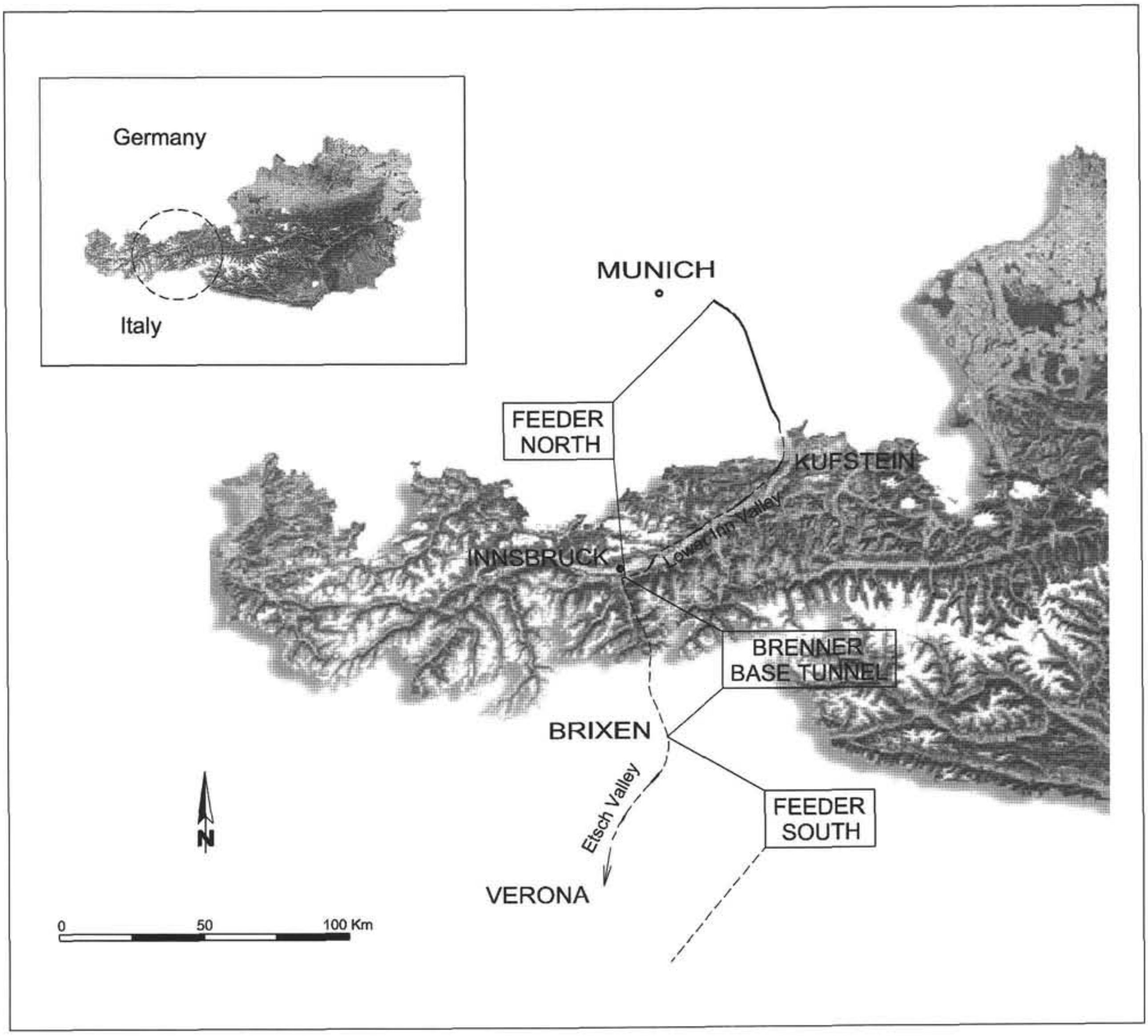


Fig. 1
The Railway Project Munich – Verona: The approximately 60 km long Brenner Base Tunnel crossing the Eastern Alps will connect Austria with Italy. The Feeder Line North runs parallel to the Inn Valley from Kufstein to Innsbruck, the Feeder Line South from Verona to Brixen runs along the Etsch Valley.

2. Geological and Tectonic Setting

Thick sequences of Permomesozoic sedimentary rocks outcrop along the Lower Inn Valley. They include a variety of formations consisting of siliciclastic sediments, evaporites and carbonates which transgress on the Paleozoic basement rocks of the Grauwacken Zone (GWZ)outcropping in the southern part of the Inn Valley. The Permomesozoic cover and GWZ form parts of the nappe stack of the Northern Calcareous Alps (NCA) with the two main tectonic units, the Bajuvarikum at the bottom and the Tirolikum on top (Fig. 2). The Inntal Nappe, Vomperbach Slice Complex and the Thaur, Hauskogel and Hohenegg Slices are part of the Tirolikum, the Lechtal Nappe is part of the Bajuvarikum.

Heteroaxial and polyphase folding and thrusting related to various Alpine orogenic phases produced complex structures, with locally important thickness reductions due to normal faulting in the Upper Cretaceous (Gosau Basins) and Tertiary (EISBACHER & BRANDNER, 1996). Continuous tectonic movements resulted in several backthrusts and out-of-sequence thrusts. The dominating structure now is the Lower Inn Valley Fault Zone which is one of the largest faults in the Eastern Alps (see also ORTNER and STINGL, 2001). Sinistral strike-slip along this fault of about 40 km (ORTNER et al., 1999) is kinematically linked to the Brenner Normal Fault of Miocene age (FÜGENSCHUH et al., 1997). The youngest structures in the Inn Valley area are NW striking, dextral strike-slip faults which cut the Lower Inn Valley Fault Zone (ORTNER et al., 1999).

3. Brittle Fault Zones

Deformation at shallow depths in the crust results in the formation of brittle fault zones. The main characteristics of this deformation process is the crushing of rocks and the reduction of grain size without mineralogical or chemical alteration taking place (HEITZMANN, 1985; BUERGI et al., 1999).

According to HIGGINS (1971) and HEITZMANN (1985), brittlely deformed rocks can be classified as kakirites, fault gouges or cataclasites.

The geomechanical and hydrological properties of such fault rocks (Fig. 3) are defined by three significant factors:

1. Rheology: depending on the host rock rheology, two groups of fault rocks occur:
   a) Kakirites, which consist of slightly cohesive material and possess low permeability are termed fault gouges. The term "local kakirite" (SCHNEIDER, 1997) is not used as it is a synonym for fault gouge. When host rocks of low compressive strength and with a low Young's Modulus, such as shales of the Raibl Group (NCA) or phyllites of the Wildschönau Formation (GWZ) are brittlely deformed, the result is fault rock

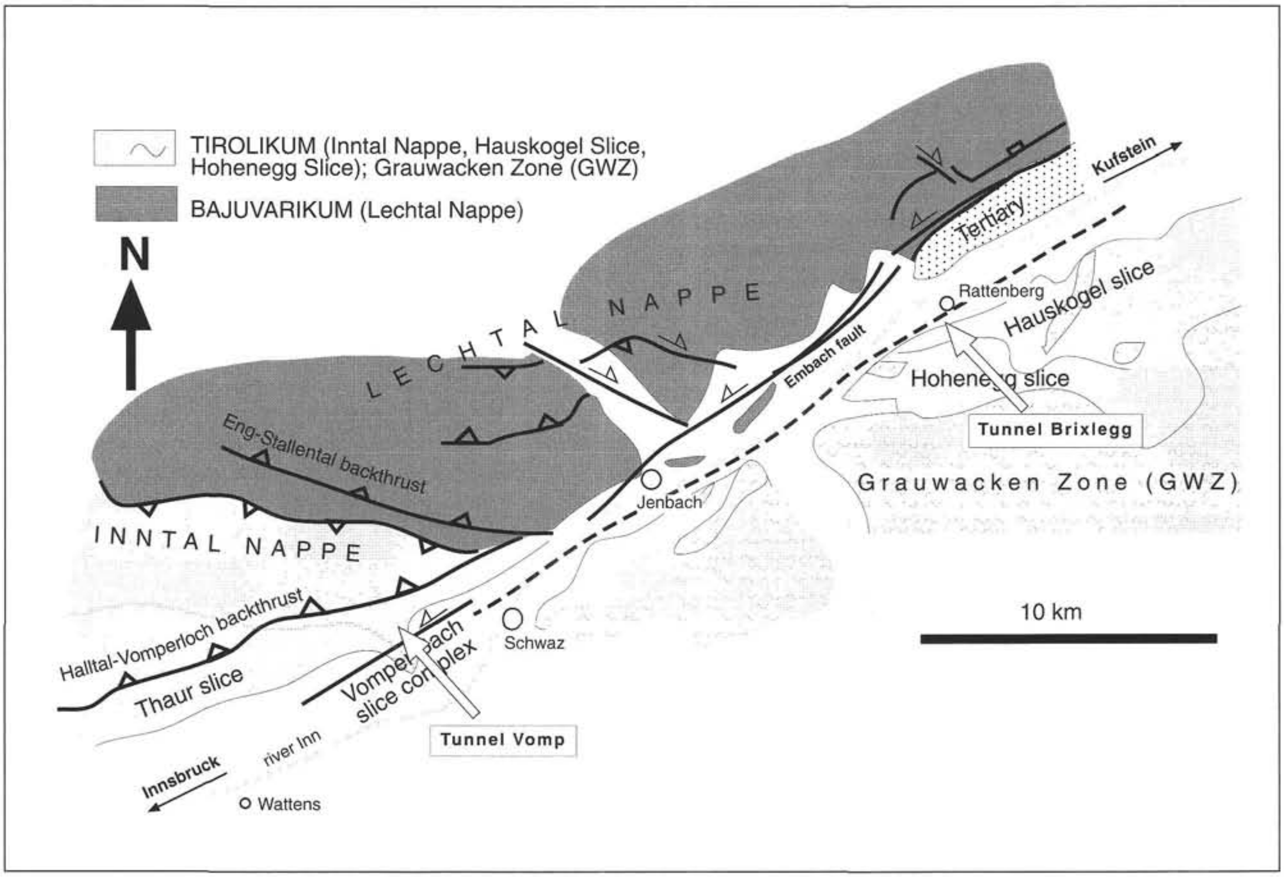


Fig. 2
Tectonic sketch map of the Lower Inn Valley area (BRANDNER et al., 1997). The Palaeozoic Grauwacken Zone (GWZ) is the Variscan basement of Permomesozoic sequences of the Inntal Nappe and several slices of the Tirolic Nappe unit – see text. The Oligocene to Miocene sedimentary sequence of the "Tertiary" is bounded by faults of the sinistral Inn Valley Fault Zone which has been active since the Oligocene.

	Characteristics					
Age of Faults		**Geomechanical**	**Hydrological**		**Geomechanical**	**Hydrological**
	Incompetent Rocks e.g. phyllite , marl, shale			**Competent Rocks** e.g. carbonate, granite, quartzite		
Young	Fault gouge zone – **Kakirite**			Fault breccia – **Kakirite**		
		Unconsolidated fault breccia with a cohesive soft rock characteristic; low compressive strength, low values of Young´s modulus	Impermeable character; Occasionally dripping water at tunnel face		Cohesionless, made up of sand- to gravel-like material, stones and blocks	Highly permeable zones; High potential of water ingress
		Squeezing rock character			Ingress of water saturated material	
Old	Fault gouge zone – **Kakirite**			Cataclasite/Cemented fault breccia		
		Properties do not change significantly compared to young fault zones due to a low permeability and therefore minor flow of cementing solutions	Impermeable character; Occasionally dripping water at tunnel face		Consolidated, cemented fault breccia – cementation is highly influenced by solvents, which permeate and precipitate; high compressive strength and high values of Young's modulus	Low permeability; Dripping water at tunnel face
		Squeezing rock characteristic			Properties like those of intact rock	

Fig. 3
Relationships between the geomechanical and hydrological properties of fault rocks, host rock, petrography and age of fault activity. Note the two types of kakirite classified according to the different lithology of the host rock, showing completely different geomechanical and hydrological characteristics.

with a high squeezing potential. For such extensively deformed areas the term "fault gouge zone" is proposed.

b) Kakirites consisting of cohesionless material and exhibiting high permeability are termed "fault breccias" (WISE et al., 1984 and BUERGI et al., 1999). They result from the crushing of competent rock high values of compressive strength and a high Young's modulus, e. g. rigid carbonates of the Wetterstein Formation, Raibl Group or Hauptdolomit. They constitute the most arduous zones in tunnel engineering because material from these zones can ingress within seconds when encountered, particularly when water-saturated.

With regard to tunnel engineering, both types of kakirites have soil-like characteristics but possess completely different geomechanical and hydrological properties. For engineering geology it is proposed to distinguish between "fault gouge", "fault gouge zone" and "fault breccia" and to emphasize their different properties, because they require differing tunnelling methods.

2. Age of fault activity:
The lithification status of fault rocks normally depends on the occurrence of the last faulting activity. In general, the older the fault rock is, the better the lithification. The rate of cementation is controlled by the permeability of the fault rock and amount of pore water circulation. Thus, older fault breccias and kakirites with an originally high porosity and permeability tend to be well cemented and lithified. Geomechanically, they have a rock quality similar to that of intact rocks and are termed "cataclasites", where the grade of cementation defines the geomechanical and hydrological characteristics.
However, in slightly cohesive fault rock with squeezing rock properties – fault gouge – the cementation rate is normally very slow. This is due to the low permeability within such zones and therefore there is no significant percolation of solutions which would precipitate cements. Recently formed fault breccias and kakirites frequently show only superficial or cloudy cementation but also dissolution caused by undersaturated pore waters. These fault rocks – fault breccias – are friable or cohesionless and thus comprise "problem zones" in engineering geology.

3. Depth of formation:
Brittlely deformed rocks formed at a depth of approximately 4 km, are cohesive with angular clasts (mm–m) in

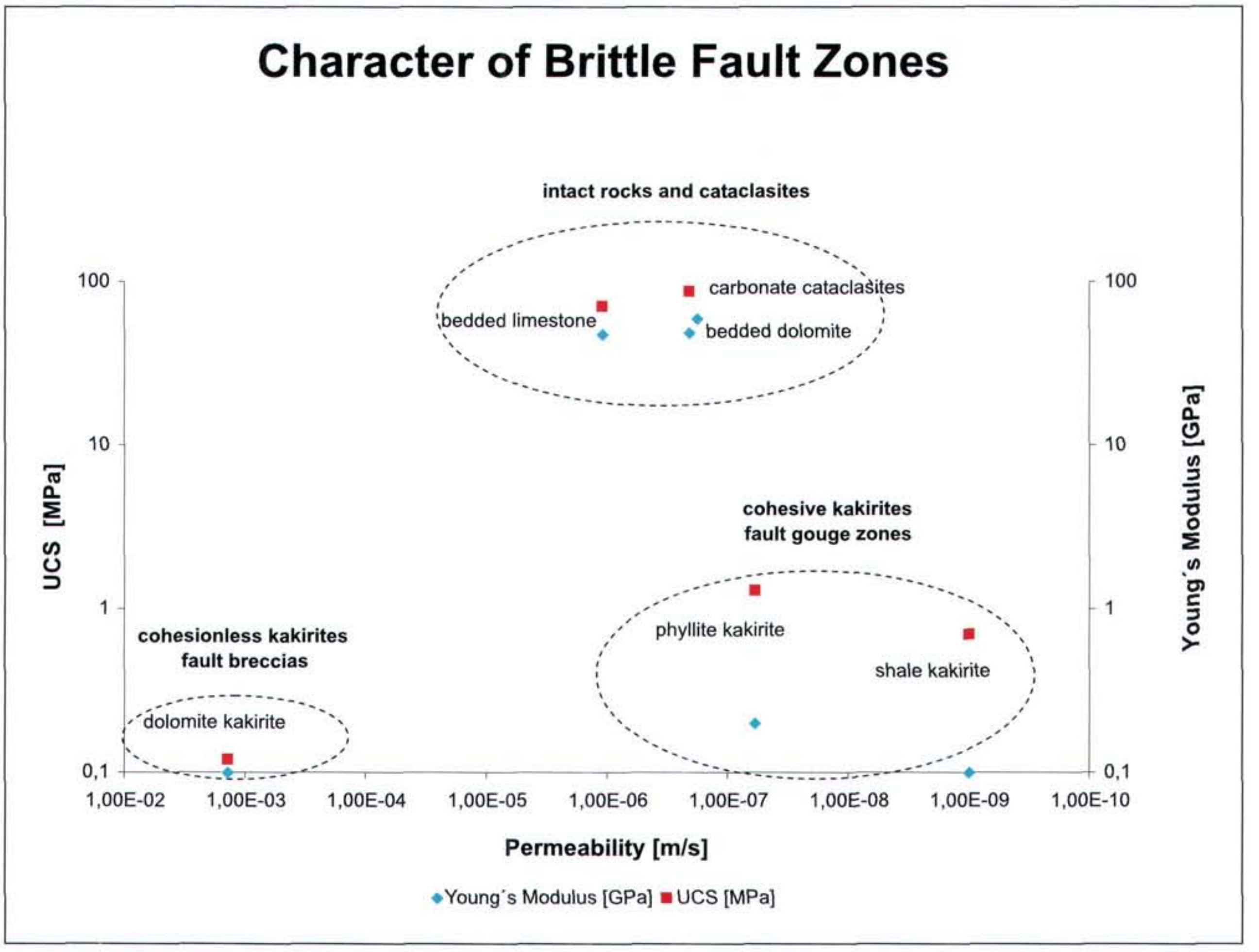


Fig. 4
Geomechanical and hydrological characterisation of the brittle fault zones along the Lower Inn Valley. The diagram shows the relationships between UCS (Uniaxial Compressive Strength), Young's Modulus, and permeability of different types of fault rocks as well as that of the intact rocks. Note that the rock quality of the carbonate cataclasites is similar to that of the intact rock and therefore has little to no geomechanical relevance in tunnel engineering.

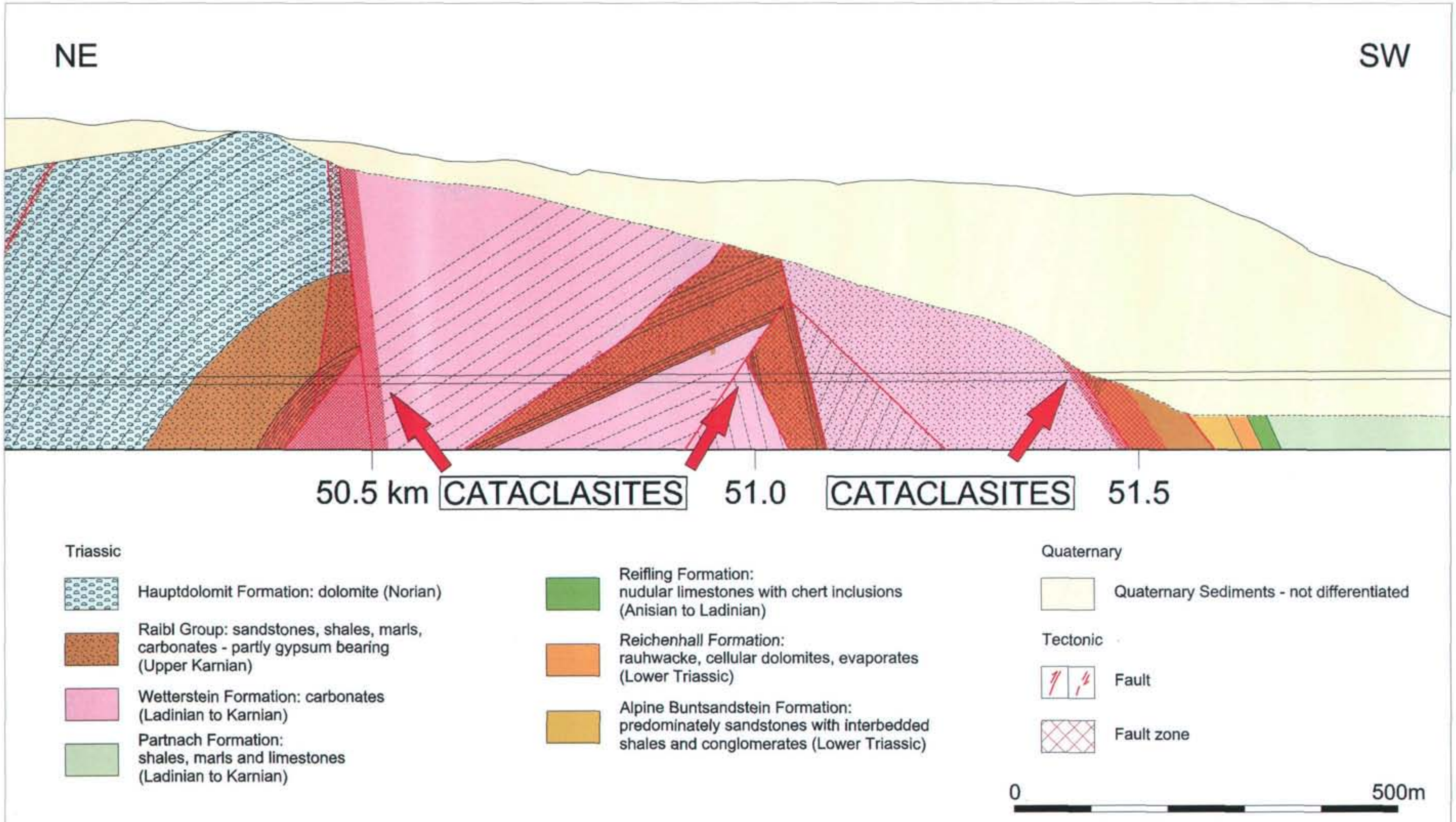


Fig. 5
Geological cross-section of the Vomp-East Reconnaissance Tunnel (ILF-GHH, 1998-2002 published with permission of BEG). Arrows show positions of the cataclasite zones.

a fine-grained matrix (SIBSON, 1977). HEITZMANN (1985) termed these fault rocks "cataclasites". Such rocks do not play a significant role in tunnel engineering.

3.1 Cataclasites encountered during tunneling in the Vomperbach Slice Complex

The Vomp-East Reconnaissance Tunnel penetrates the "Vomperbach Slice Complex" at the southern margin of the Inntal Nappe at km 51.44 (Fig. 2). Several cataclasite zones were encountered within the Wetterstein Formation. It is assumed that the faults have been reactivated several times producing cataclasites of different grain size (mm-m). All the fault rocks are well cemented or cohesive, showing no significant geomechanical deterioration. However, it has to be noted that in the Wetterstein Formation the processes of dissolution and precipitation are faster in the limestones than in the dolomites. Here the term "cataclasite" was extended to include the cemented fault breccias, which have similar geomechanical characteristics. The term „second

Table 1
Geological, geomechanical and hydrological characteristics of the encountered fault zones.

Geological Characterisation				Geotechnical and hydrological Characterisation			
Fault zone	Host Rock	Assumed Age of fault	Geological Setting	Description	UCS *) [MPa]	Young´s Modulus [GPa]	Permeability [m/s]
Cataclasite Vomp East km 51.44	Carbonates	Cretaceous to Miocene	Southern margin of the Inntal Nappe – Steeply inclined thrust faults due to an intensive shortening of the sequence - reactivated during Miocene strike slip faulting	Well cemented fault breccia – none to little geotechnical relevance. Occasionally increased water ingress due to additional fractures and joints.	101 +/-38	49 +/- 17	1.8x10E-07
Kakirite							
Fault gouge and fault gouge zones Brixlegg East km 29.94	Phyllite	Cretaceous to Miocene	Normal fault juxtaposing Wildschönau phyllitic rocks to carbonates and shales of the Partnach Formation	Unconsolidated fault rock with a cohesive soft rock property – strong and long lasting deformation - fault gouge frequently has an impermeable character	0.7+/-0.5 **)	0.1 to 0.24	2.0 x10E-08
Fault breccia Brixlegg East km 31.23	Gypsum bearing carbonates	Young or recent	Special type of diagenetically altered and karstified rocks within the Raibl Group, representing weak rock zones and thought to be fractured by younger activity along the Inn Valley Fault Zone.	Cohesionless material of sand- to gravel-size combined with water under high pressure representing a hazard zone – flushing out of material and water ingress. Highly permeable fault zones with large water supply under high pressure (6 bar)	none	none	1.4x10E-03

*) Uniaxial Compressive Strength

**) For the phyllites, no values are available; however, sheared shales of the Raibl Group represent shear zones with similar geotechnical characteristics, as seen from the deformation measurements.

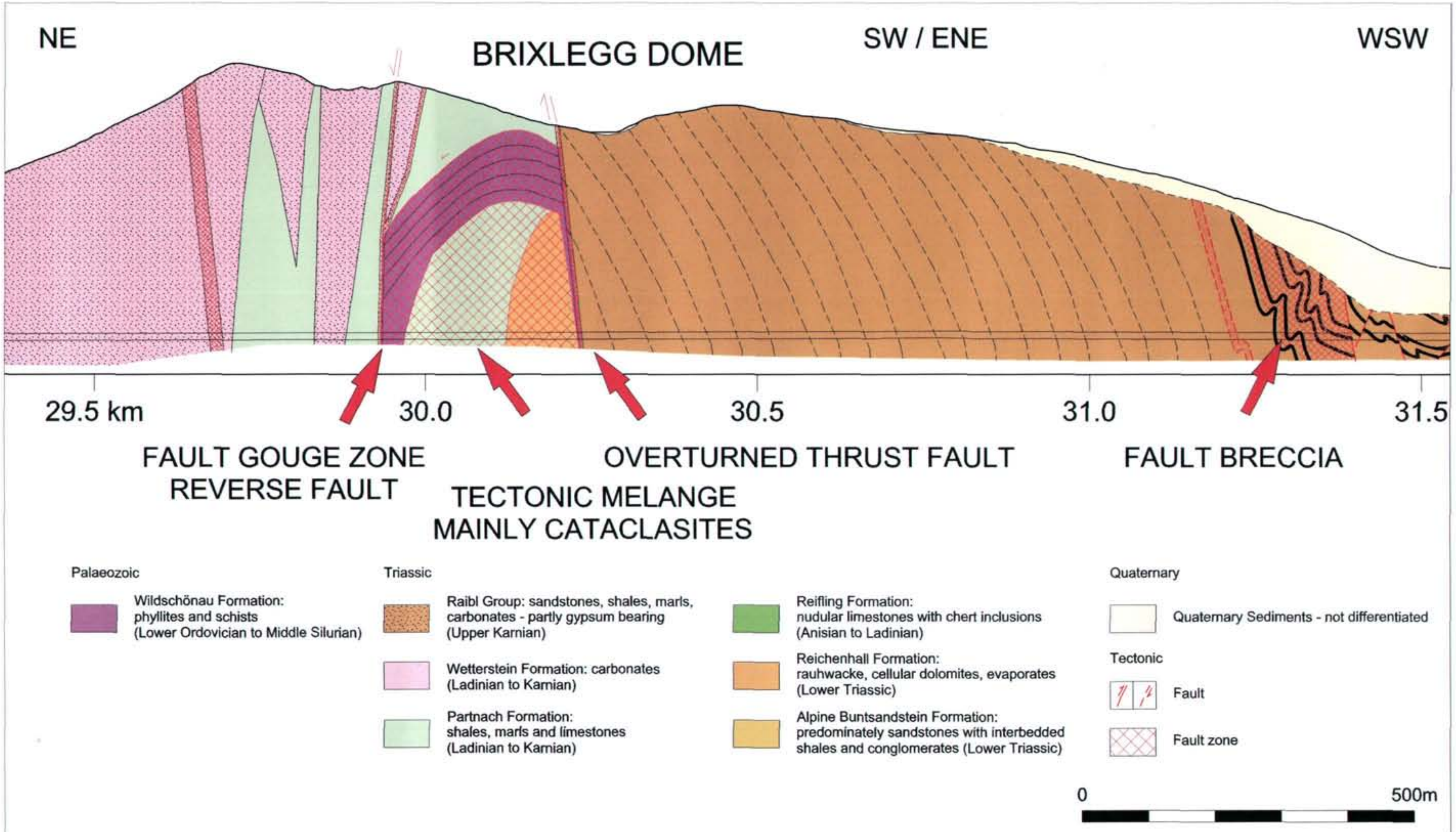


Fig. 6
Geological cross section of the Brixlegg-East Reconnaissance Tunnel (ILF-GHH, 1998-2002 published with permission of BEG).

cohesion" used by BUERGI et. al, 1999, is not as accurate, because it is not directly related to the fault zone formation.

Tests carried out in bore holes and on core samples from within the cataclasite zones in the laboratory revealed a compressive strength of between 63 and 139 MPa and a Young's Modulus of between 32 and 66 GPa. These values are close to or equal to those of undeformed rocks. Minor water influx with dripping water conditions was observed at the tunnel face, representing permeabilities between 1.8×10E-06 m/s and 6.2×10E-08m/s (Fig. 4, Fig. 5 and Table 1).

3.2 Kakirites encountered during tunneling in the Brixlegg area

In the region of Brixlegg, south of the Inn River, Paleozoic basement rocks of the GWZ and the transgressive Permian-Mesozoic cover sequence are exposed (Fig. 6). Due to large scale tectonic shortening, the bedding is now steeply inclined and in places overturned. Superimposed folding has caused the formation of the dominating Brixlegg Dome structure. Eoalpine and Mesoalpine folding and thrusting resulted in the development of the east- and westward plunging of the fold axis of the Brixlegg Dome. The steeply inclined stack of slices was overprinted in the Miocene by strike-slip faulting occurring along the Inn Valley Fault Zone which results in very complex geologic structures (see also ORTNER and REITER,1999).

The Brixlegg-East Reconnaissance Tunnel crosses these structures at an acute angle, encountering several kakirites within mostly reactivated fault zones. Here it is evident that the differing geomechanical properties depend strongly on host rock rheology.

3.2.1 Fault gouge and fault gouge zone

The fault zones described here are found in incompetent bulk rock which has undergone brittle deformation. Detailed investigations have revealed that these zones are rather complex and heterogeneous: Strongly deformed centimetre- to metre-wide zones (fault gouges) alternate irregularly with weakly deformed zones (fault breccias) of several meters thickness (Fig. 7). The thickness of the fault gouges can be directly related to the accomodated strain

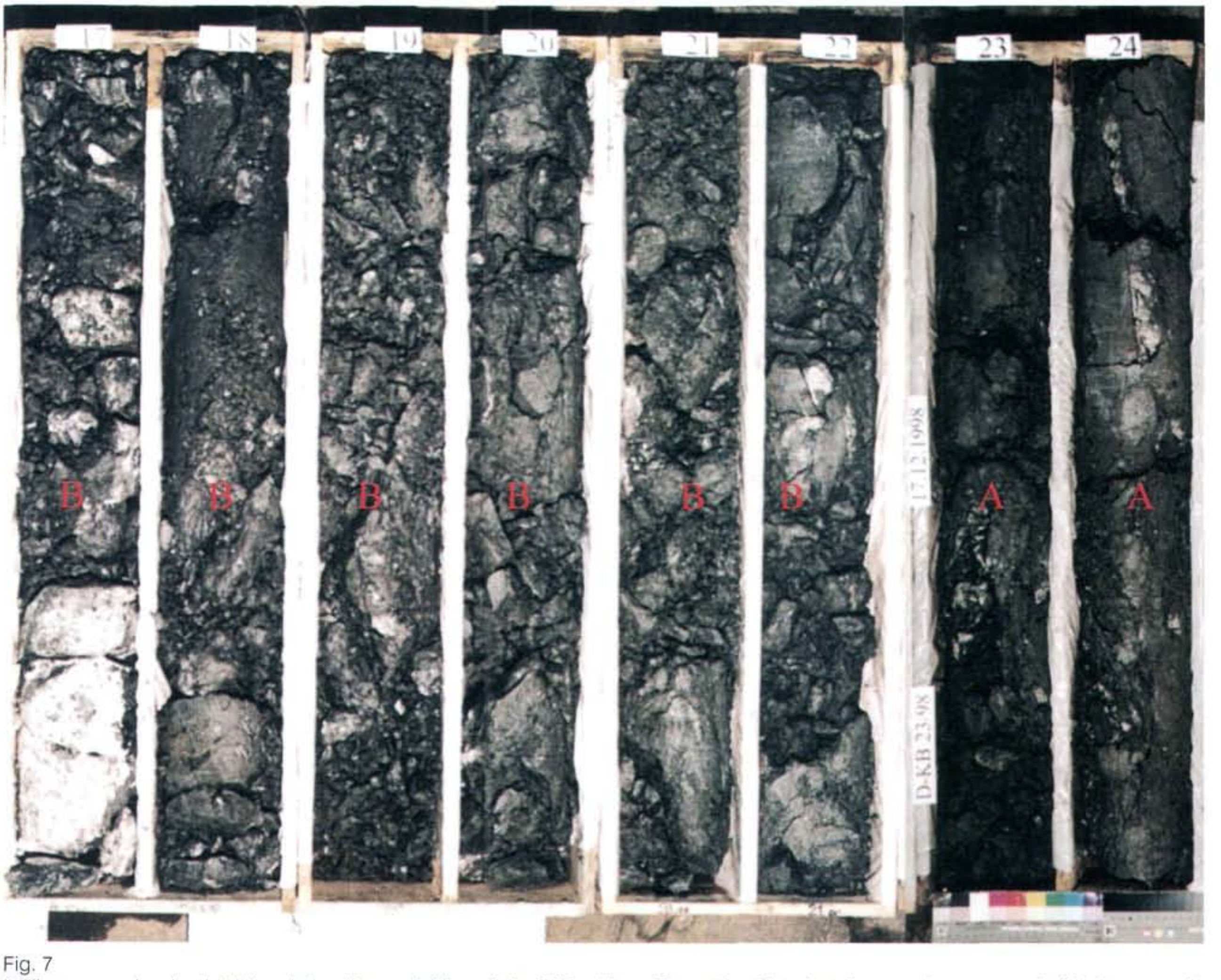
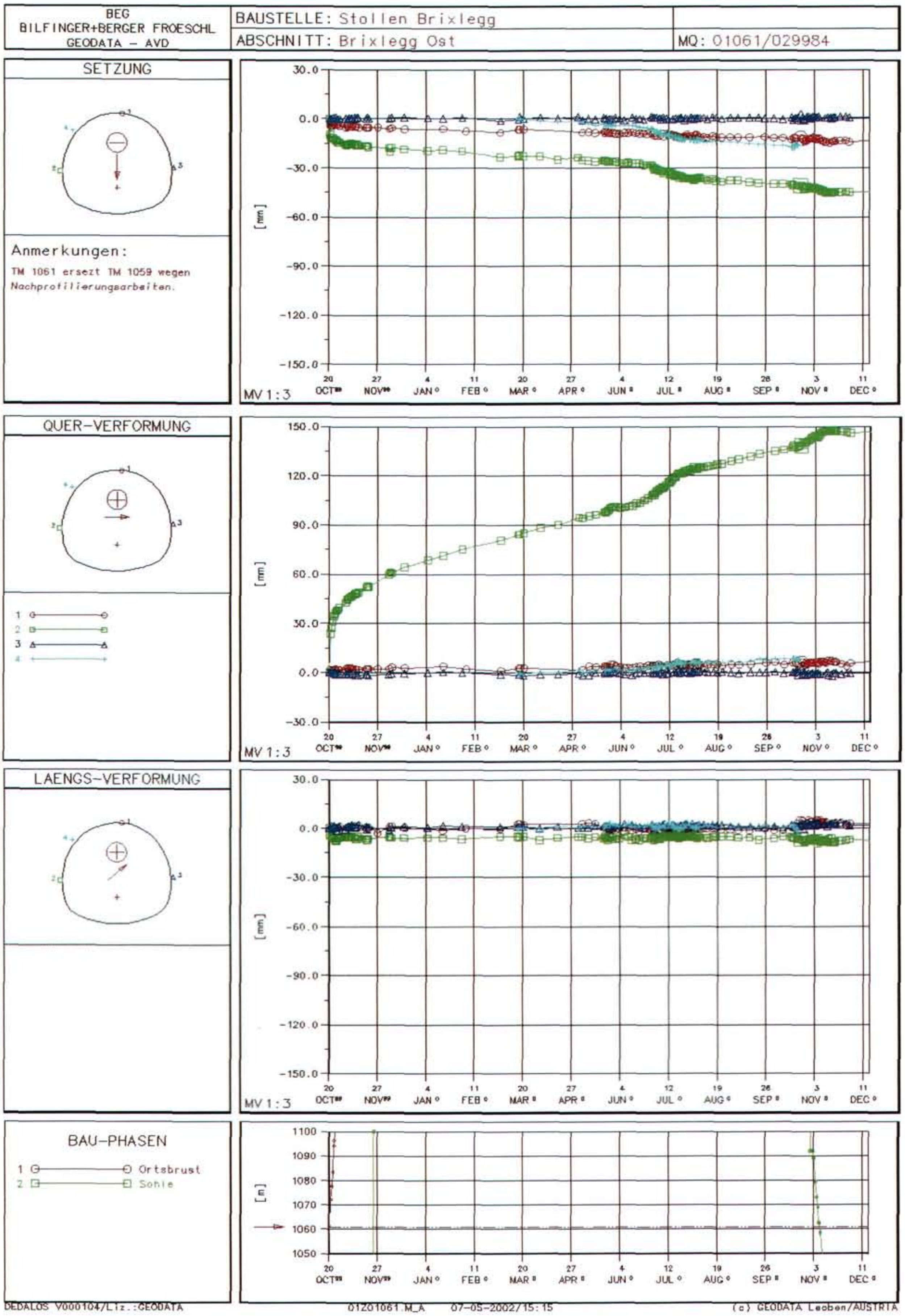


Fig. 7
Drilling cores showing kakirites derived from phyllites of the Wildschönau Formation. Note that the zone is composed of fault gouge (A) and fault breccia (B). In the fault gouge, due to large accomodated strain, no internal structures are visible. The neighbouring fault breccia does show the primary phyllitic structure intersected by a multitude of fault planes. The accommodated strain is much less in the latter zones.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(see SIBSON, 1977; SCHOLZ, 1987). Due to the whole fault zone having similar geomechanical characteristics the term "fault gouge zone" is proposed to describe the complete zone.

Strongly sheared phyllites of the Wildschönau Formation, in the Brixlegg-East Reconnaissance Tunnel at km 29.94, contain zones of cohesive soil-like material (fault gouge), which is typically kneadable by hand. In the weakly faulted zones (fault breccias) deformation is mainly – but not only – concentrated along the existing foliation, but also along shear planes, which cross the foliation obliquely. A main characteristic of the whole fault zone, including the fault gouges, is its squeezing potential whose magnitude relates to the amount of overburden. In the case of the Brixlegg-East Reconnaissance Tunnel the amount of overburden is 370 metres which leads to a relatively high squeezing potential (Fig. 8). Fault gouges displaying similar properties formed in strongly sheared marls at km 31.23 in the Brixlegg-East Reconnaissance Tunnel, and strongly sheared shales in the Vomp-East Reconnaissance Tunnel at km 50.44, occur within the Raibl Group. Bore hole tests in such fault gouges revealed a Young's Modulus ranging from 0.1 to 0.24 GPa which points to a high plasticity. The fault zones (fault gouges) have an impermeable character which is similar to that of the host rock. The permeability lies between $2.1 \times 10E\text{-}08$ and $6.0 \times 10E\text{-}08$ m/s and was determined using packer tests (Fig. 4 and Table 1).

3.2.2 Fault breccia

This special type of kakirite was encountered in the Brixlegg-East Reconnaissance Tunnel at km 31.23, along a steeply inclined, WNW striking fault zone. During drilling for an anchor hole in the southern tunnel wall, a major water ingress (25 l/s) occurred, resulting in the flushing out of sand- to gravel-sized dolomitic material (Fig. 9). For safety reasons, tun-

← Fig. 8
Squeezing rock properties as revealed by three-dimensional trigonometrical measurements (GEODATA, 2000). The asymmetry observed in the deformation results from the small angle between the fault zone and the tunnel axis. The fault zone was struck on the southern side (= left side) of the tunnel, whereas on the north side intact carbonates are situated.

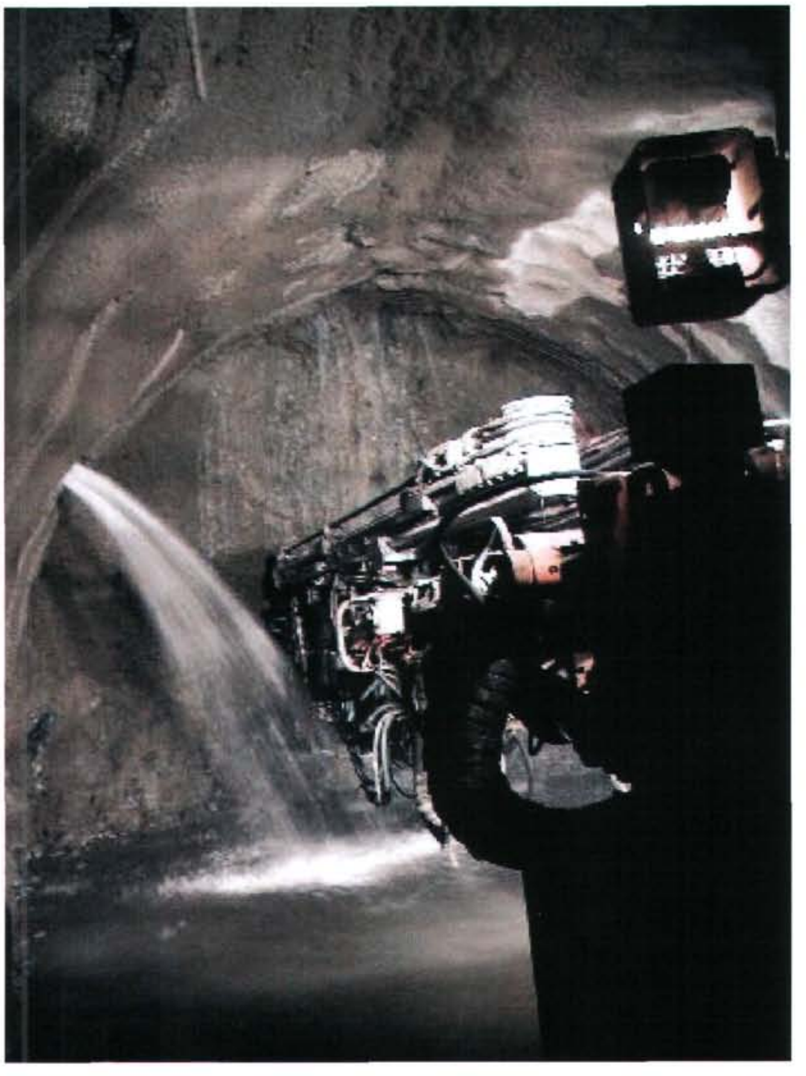

Fig. 9
A dramatic ingress of water (upper photograph) and sand- to gravel-sized dolomitic material (lower photograph), occured after the drilling of anchor boreholes tapped a cohesionless water saturated fault zone at km 31.23, Brixlegg-East Reconnaissance Tunnel.

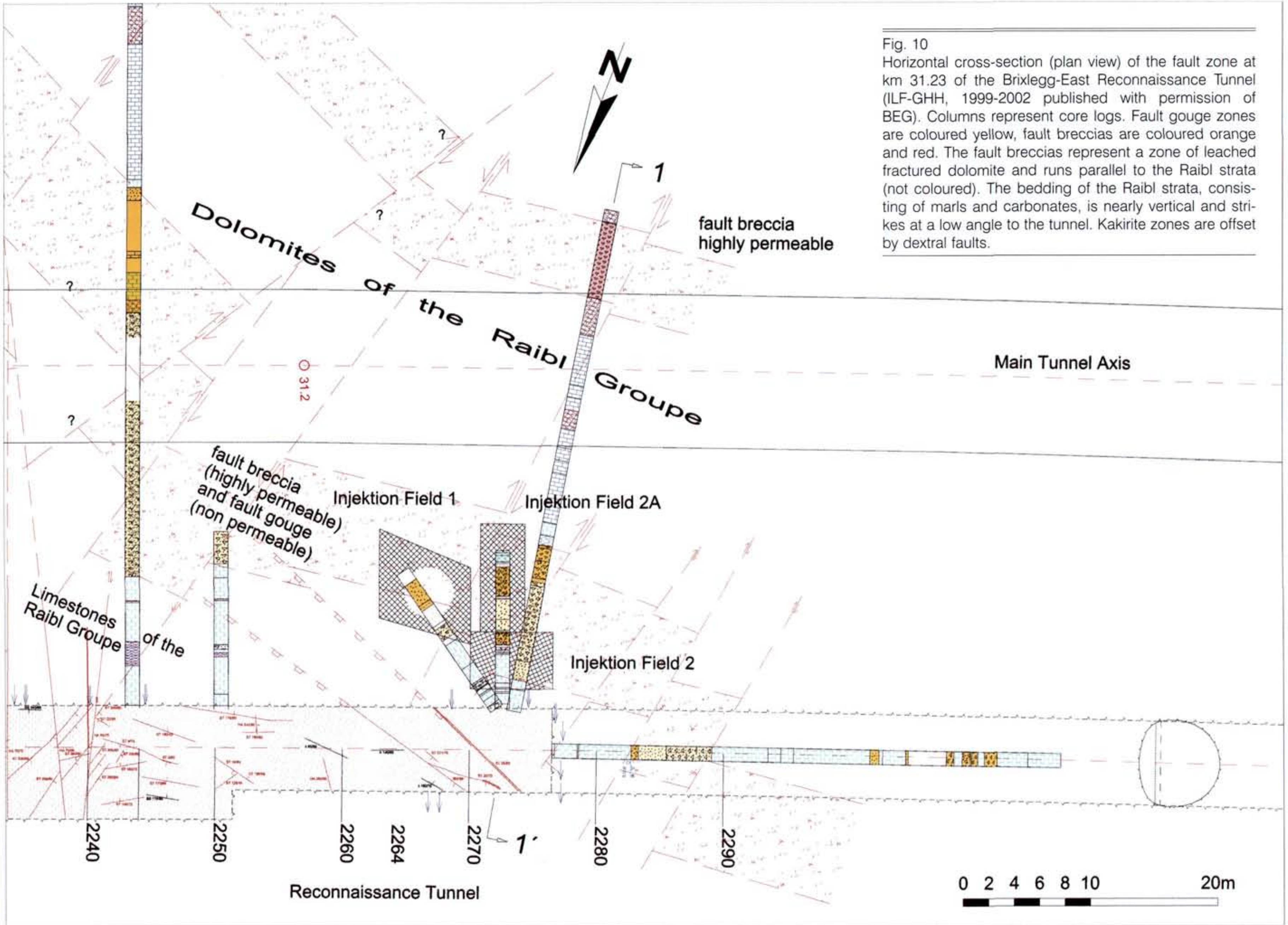

Fig. 10
Horizontal cross-section (plan view) of the fault zone at km 31.23 of the Brixlegg-East Reconnaissance Tunnel (ILF-GHH, 1999-2002 published with permission of BEG). Columns represent core logs. Fault gouge zones are coloured yellow, fault breccias are coloured orange and red. The fault breccias represent a zone of leached fractured dolomite and runs parallel to the Raibl strata (not coloured). The bedding of the Raibl strata, consisting of marls and carbonates, is nearly vertical and strikes at a low angle to the tunnel. Kakirite zones are offset by dextral faults.

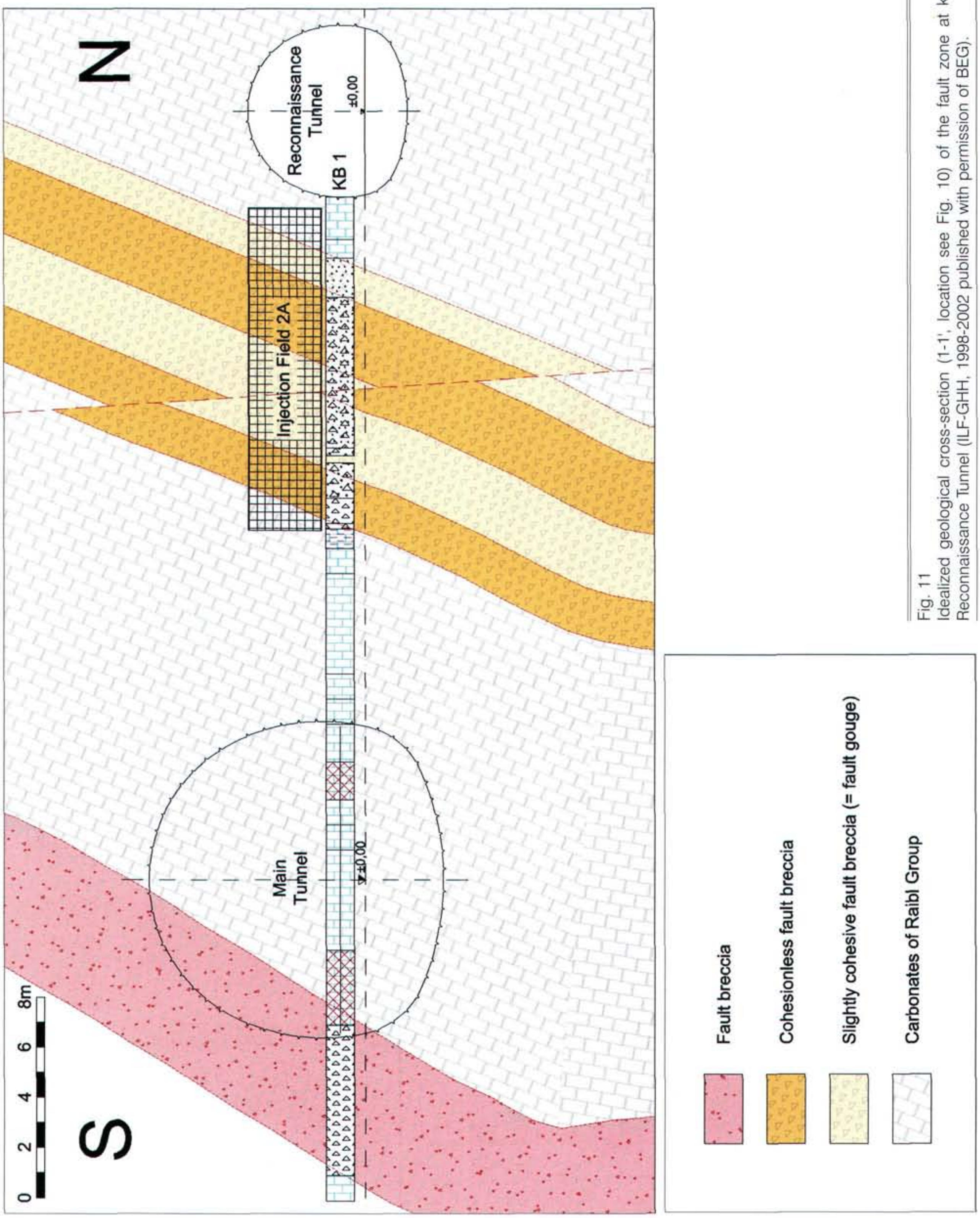

Fig. 11
Idealized geological cross-section (1-1', location see Fig. 10) of the fault zone at km 31.23, Brixlegg-East Reconnaissance Tunnel (ILF-GHH, 1998-2002 published with permission of BEG).

nelling was stopped immediately and an intensive investigation campaign was initiated. The results of the campaign follow (see also Fig. 10, Fig. 11 and Fig. 12).

- The genesis of the cohesionless fault rock – fault breccia – appears to be due to a complex process of multiple fault activity which also involves bedding-parallel leaching in the coarse grained calcareous dolomites of the Raibl Group. In this case, weakening of rocks was accomplished by diagenetic dedolomitisation by brines originating from evaporitic rocks below, migrating up through the fracture network (Fig. 13). Subsequent faulting and fracturing formed the cohesionless fault breccia. However, it is interesting to note that these faults display no notable displacements.
- The area where the fault breccia occurs has a complex structure resulting from superimposed folding and faulting events. Nearly impermeable brittlely deformed marls (fault gouges) adjoin highly permeable zones of sand- to gravel-sized dolomitic fault breccias in no specific manner. Numerous steeply inclined faults have led to a dextral offset of the strata and fault breccias.
- The diagenetically altered, karstified and fractured dolomites now form a nearly cohesionless material.
- The intensively sheared marls (SC-fabrics) show plastic material characteristics with a Young's Modulus of 0.1 to 0.24 GPa.
- Packer tests revealed a permeability of $1.4\times10E\text{-}03$ m/s in the water saturated fault breccias. Fault gouges, derived from marls, have a value of approximately $2.0\times10E\text{-}07$ m/s.
- The water pressure in the fault zone, which is part of an important sulphate-rich mineral water (900-1500 μS/cm) aquifer (POSCHER et al, 2002), is nearly 6 bar at tunnel level.

At the time of writing, it has not been possible to consolidate the whole rock mass using injection methods – while maintaining the high water pressure – to such an extent as to be able to resume tunnelling. While the highly permeable carbonate fault breccia can be fully cemented, the fault gouge zones show almost no penetration of injection material due to their low permeability (Fig. 12). Therefore, further tunnel advance will only be possible by reducing the water

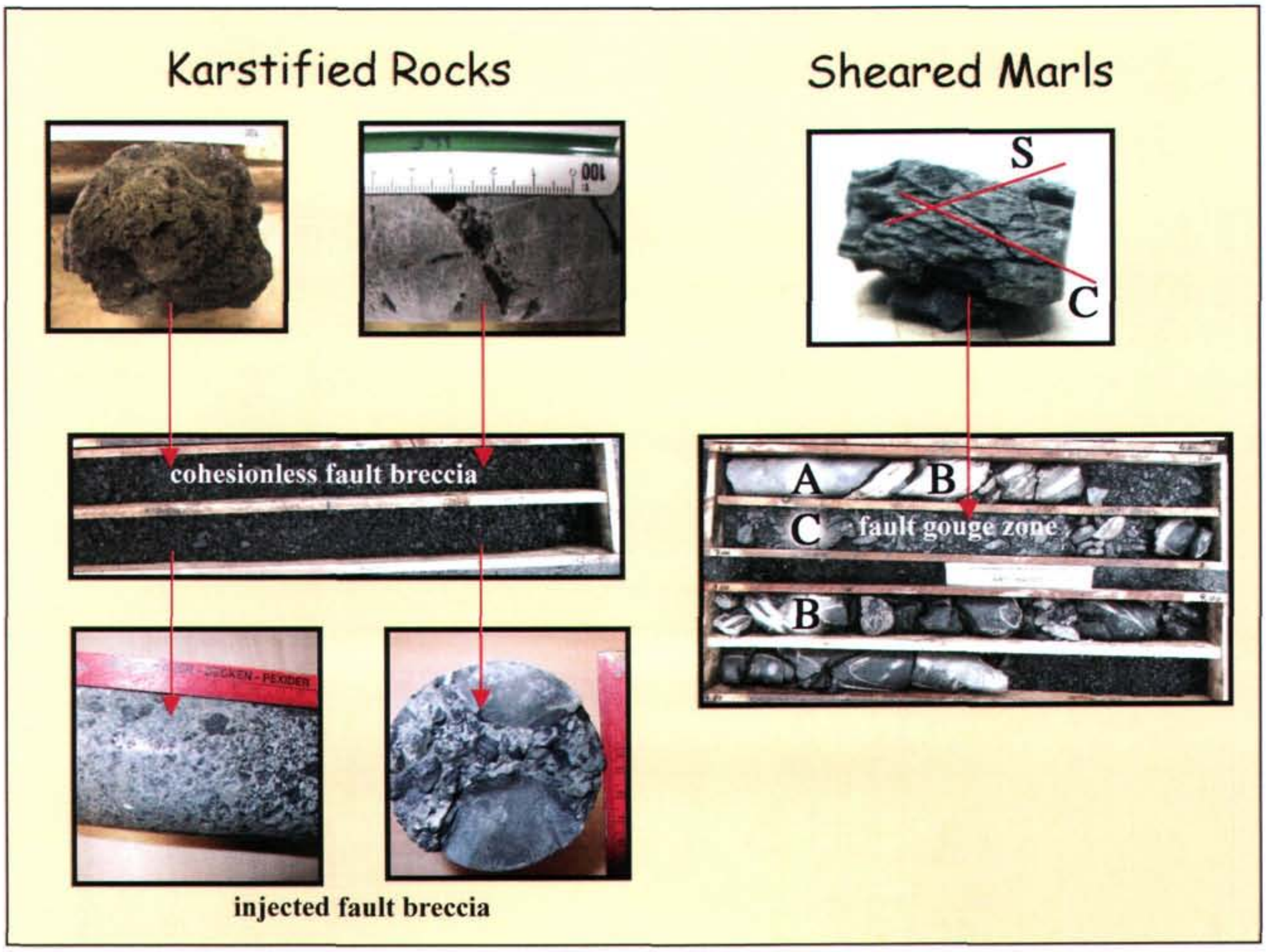

Fig. 12
Fault Analysis: The fault zone consists of irregularly alternating coarse grained dolomite, partly calcite and minor gypsum (left side) and strongly sheared marls (right side). Leaching of calcite and gypsum leads to partial karstification. The marls show SC-fabrics, which are presumed to be related to early movements during the Alpine orogeny. The fracturing of diagenetically altered karstified rocks is thought to have been produced by younger fault activity along the Lower Inn Valley Fault Zone. Injection trials, using high- grade cements to improve the rock mass showed good results in the cohesionless fault breccia (bottom left). However, no penetration occurred in the sheared marls (fault gouge – Zone C), due to poor permeability. Zone B, adjacent to the sheared marls (Zone C), shows the penetration of injection material along foliation and fractures. Zone A represents the intact rock.

pressure as well as using specific tunnelling methods, e.g. injections with grouts consisting of plastic resin, jet grouting etc., to improve the surrounding rock mass (see also REICHL et. al., 2002).

4. Conclusions and Preview

The geomechanical and hydrological properties of brittle fault zones are of utmost importance and can be decisive when considering the technical and economic feasibility of a tunnel project. The type of fault rock and corresponding geomechanical properties strongly depend on the host rock rheology, age of faulting activity and depth of formation. The examples described show that even small displacements along faults can produce kakirites, which constitute the most problematic zones in tunnelling projects.

Special attention should also be drawn to cloudy distributed, late diagenetic dolomitisation zones in massive carbonate rocks, which act as inherited zones of weakness during deformation events. High porosity and permeability caused by the formation of fractures and fissures enables dedolomitisation and leaching of carbonate rock, especially in areas where evaporitic brines are present. In combination with further deformation, cohesionless fault breccia consisting of sand- to gravel-sized dolomitic material form irregularly bounded, up to tens of metres across sized brittle fault zones.

With regard to future tunnel projects, e. g. the deep lying Brenner Base Tunnel, connecting Austria to Italy, it is recommended to specifically investigate brittle fault zones occurring in carbonate rocks. Fracturing of carbonate rocks not only causes fault breccias, but is moreover followed by circulation of pore water and a complex process of diagenetic alteration and leaching which can occur at any level within the shallow crust.

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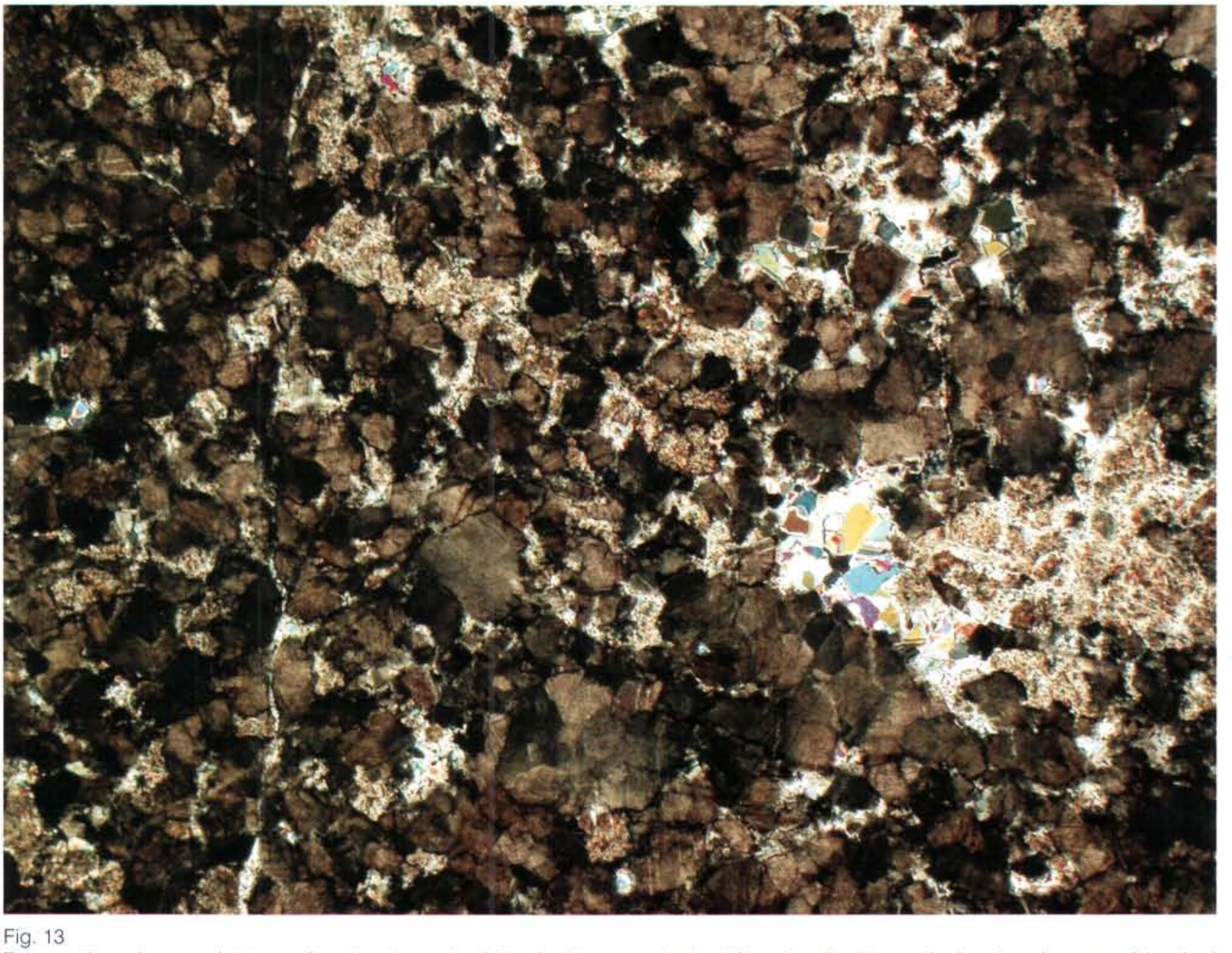

Fig. 13
Thin section of a special type of carbonate rock of the faulting area derived from locally diagenetically altered zones of leached cataclasites consisting of coarse grained crystalline dolomites from the Raibl Group. Note the patchy cementation by gypsum (varicoloured) in solution cavities after leaching of irregularly distributed calcite (= dedolomite) in the coarse grained frame of ferrogenous dolomite crystals. Crossed Nicols. Magnification: 6×.

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