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Geology of the Slovene Part of the Karavanke Road Tunnel

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Osnovna geološka karta SFRJ 1:100 000
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Slovenia
Austria
Karavanke
Road Tunnel
Upper Carboniferous
Permian
Triassic
Tectonic Structure

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Geologie der slowenischen Strecke des Karawanken-Straßentunnels

Zusammenfassung

Während des Baues des Karawanken-Straßentunnels in den Jahren 1986 bis 1989 wurden die sich bietenden Möglichkeiten genutzt, detailierte geologische Studien im Bereich des Südabschnitts der Westkarawanken durchzuführen. Die Trasse des Straßentunnels verläuft etwas westlich des Eisenbahntunnels, dessen geologische Verhältnisse von TELLER (1914) dokumentiert wurden. Beide Tunnel queren die südlichen Karawanken, die im Norden von der Periadriatischen Naht begrenzt werden und im Süden von der Save-Störungszone.

Die Vortriebsarbeiten wurden durchgehend geologisch dokumentiert, wobei die Untersuchungen geologische Kartierung, systematische Probenahme, hydrogeologische Beobachtungen, Konvergenz-, Methangas- sowie sporadische Gesteinstemperatur-Messungen umfaßten. Gleichzeitig wurde eine geologische Detailkarte 1:5000 des überlagernden Geländeabschnittes angefertigt.

Der slowenische Abschnitt des Straßentunnels durchteuft folgende lithostratigraphische Einheiten: 0–315 m Hangschutt und Moränenmaterial, 315–911 m Werfener Schichten, 911–1098 m Grödener Schichten mit tektonisch eingeschuppten Zwischenlagen von Bellerophon-Schichten, 1098–1703 m Grödener Schichten und Tarviser Breccie, 1703-2610m klastische Gesteine und Karbonate des Oberkarbon-Unterperm, 2610–2654 m dunkelgrauen kieseligen Dolomit, 2654–2767 m Werfener Schichten, 2767–2830 m Anisdolomit, 2830–2851 m Uggowitzer Breccie, 2851–3258 m Schlerndolomit und von 3258–3436 m (Staatsgrenze) terrigene Raibler Schichten.

Sowohl der Straßen- als auch der Eisenbahntunnel durchqueren fünf Ost-West streichende tektonische Einheiten (Text-Fig.1), die im Bereich der beiden Tunnel einerseits von der NW–SE verlaufenden subvertikalen Mlinca-Störung durchschnitten werden sowie von der NE–SW ausgerichteten steilstehenden und zylindrisch geformten Hrušenski-Störung. Beide Störungen repräsentieren Strike-slip faults; dies gilt auch für die Koschuta- und Gratschenitzen-Störung auf der österreichischen Seite.

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Geologija slovenskega dela Karavanškega cestnega predora

Povzetek

Med gradnjo cestnega predora skozi Karavanke, v letih 1986 do 1989, so imeli geologi izredno priložnost, da podrobno proučijo zahodni del gorske verige južnih Karavank. Cestni predor se začenja dobrih dvesto metrov zahodneje od železniškega, ki so ga zgradili pred 95 leti in ga je dobro opisal TELLER (1914).

Oba predora sekata južne Karavanke, ki so na tem območju omejene s periadriatskim šivom na severu in s savskim prelomom na jugu.

Med napredovanjem smo predor stalno podrobno kartirali, sistematično vzorčevali kamnine, opazovali hidrogeološke razmere, merili konvergence, koncentracije metana in občasno temperaturo kamnine. Istočasno smo izdelali novo geološko karto površine v merilu 1:5000.

Na slovenski strani je predor presekal naslednje litostratigrafske enote: 0–315 m pobočni grušč in moreno, 315–911 m werfensko formacijo, 911–1098 m grödensko formacijo s tektonskimi vložki belerofonske formacije, 1098–1703 m grödensko formacijo in trbiško brečo, 1703–2610 m zgornjekarbonske-spodnjepermske klastite in karbonate, 2610–2654 m temnosiv silificirani dolomit, 2654–2767 m werfensko formacijo, 2767–2830 m anizični dolomit, 2830–2851 m ukovško brečo, 2851–3258 m schlernski dolomit in 3258–3436 m (državna meja) rabeljske terigene plasti.

Cestni in železniški predor sekata pet tektonskih enot. Te enote imajo obliko pasov, ki potekajo v smeri vzhod- zahod, in jih na območju cestnega in železniškega predora presekata navpični mlinški prelom – ta teče od severozahoda proti jugovzhodu – in strmi hrušenski prelom, ki ima smer severovzhod- jugozahod, njegova prelomna ploskev pa je cilindrično povita. Oba preloma sta zmična. Tudi Košutin in gračeniški prelom na avstrijski strani sta zmična.

Abstract

During the Karavanke road tunnel excavation – from 1986 to 1989 – geologists had an excellent opportunity for a detailed investigation of the western part of the southern Karavanke zone. The road tunnel runs near and to the west of the railway tunnel. The geology of the railway tunnel was well documented by TELLER (1914). Both tunnels cross the southern Karavanke Mountains, which border on the Periadriatic lineament in the north and the Sava fault in the south.

The excavation was continuously documented by detailed geological mapping, systematic rock sampling, hydrogeological observations, convergence measurements, methane measurements and by sporadic rock temperature measurements. At the same time a new surface geological map at a scale of 1: 5000 was made.

The Slovene side of the tunnel intersects the following lithostratigraphic units: 0– 315 m slope debris and moraine, 315–911 m Werfen Formation, 911–1098 m Gröden Formation with tectonical intercalations of the Bellerophon Formation, 1098–1703 m Gröden formation and Trbiž/Tarvis breccia, 1703–2610 m Upper Carboniferous- Lower Permian clastic rocks and carbonates, 2610–2654 m dark grey silicified dolomite, 2654–2767 m Werfen Formation, 2767–2830 m Anisian dolomite, 2830–2851 m Ukve/Uggowitz breccia, 2851–3258 m Schlern dolomite and 3258–3436 m (state boundary) the Rabelj/Raibl terrigenous beds.

The road and the railway tunnels traverse five tectonical units (Text-Fig. 1). These units have a shape of E–W trending belts, intersected at the place of the road and railway tunnels by the NW–SE oriented subvertical Mlinca fault and the NE–SW oriented steep, cylindrically shaped Hrušenski fault. Both are strike-slip faults. The Košuta/Koschuta fault and the Gratschenitzen/Gračenica fault on the Austrian side are also of a strike slip character.

1. Introduction

The Karavanke chain has the specific morphologic structure of a narrow, long, parallel range of ridges, oriented in the east-west direction, beginning to the east of Tarvisio in Italy and ending at Slovenske Konjice in the north-east of Slovenia. In two sections they are curved in the northwest-southeast direction.

The geological structure of the Karavanke is also specific. By their origin they are closely connected to the Periadriatic lineament. This is a wide subvertical fault zone of regional importance, along which a large strike-slip movement occurred (TOLLMANN,1986). That movement influenced the shape of the tectonic units of the Karavanke shaping narrow long belts, bordering on subvertical or steep fault zones. Litostratigraphic units of the same age, but far apart at the time of their formation, were sometimes brought together by a horizontal displacement.

The Karavanke range is divided by the Periadriatic lineament into the Northern and the Southern Karavanke chains. The Northern Karavanke chain belongs to the Eastern Alps, while the Southern Karavanke are a part of the Southern Alps. The road and the railway tunnels intersect the whole Southern Karavanke range – from the Periadriatic lineament to the Sava fault (Text-Fig. 1). During the excavation of the road tunnel continuous geological observation gave us an excellent opportunity to improve our knowledge about their geological structure. It also gave useful information for the hydrogeological investigation of this border area (BRENČIČ et al., 1995).

2. Geological investigations

2.1. Regional geological investigations

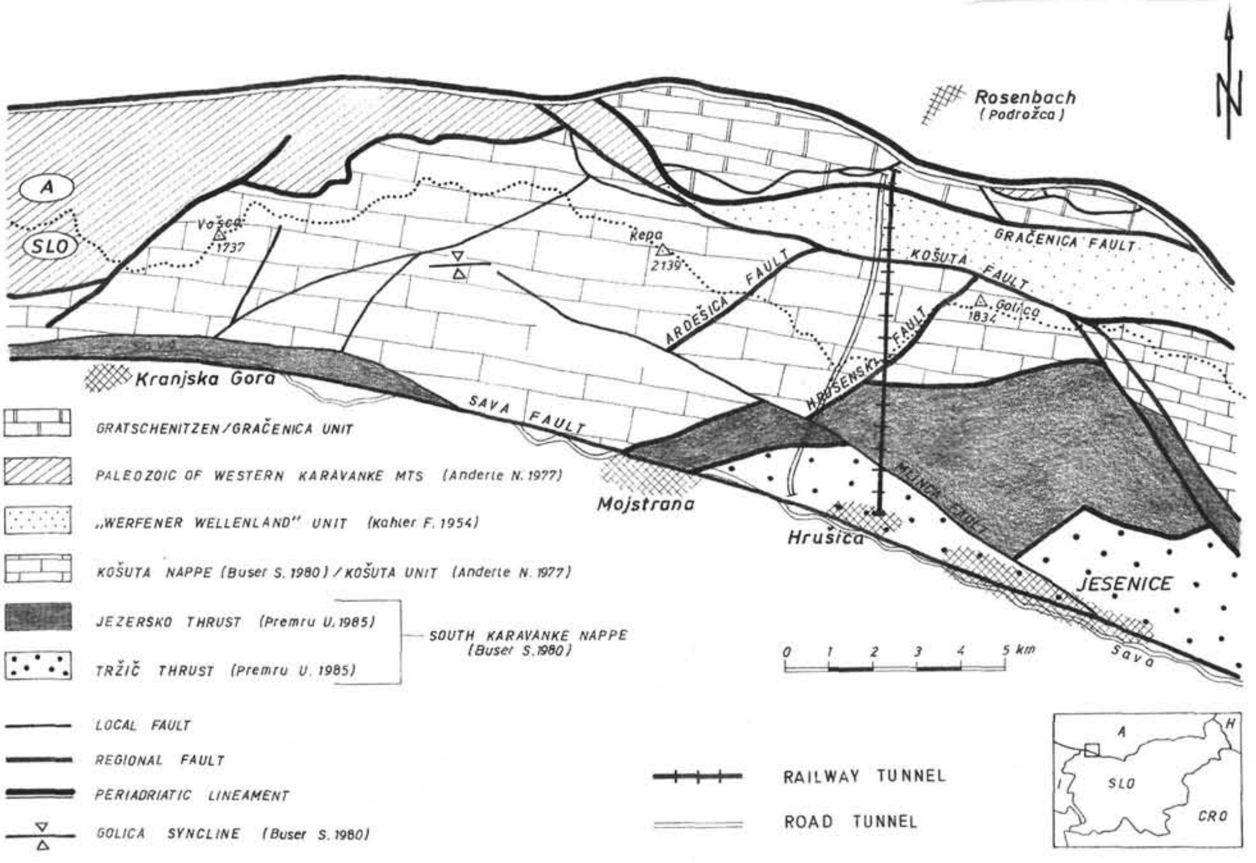
The first geological maps of the area were made by PETERS and LIPOLD (1854 and 1855).

A detailed geological investigation of the area was started in 1891 by the k. k. Geological Survey in order to find possible locations for a railway tunnel through the Karavanke. This tunnel was planned as part of the railway connecting Carinthia with Trieste/Trst on the Adriatic coast. The work began by preparing the geological map sheets Villach-Klagenfurt and Radmannsdorf at a scale of 1: 75 000 (TELLER, 1914). For the geological mapping of the Karavanke Friedrich Teller was responsible. He was also involved in the geological data collection at the beginning of the railway tunnel excavation. He made prognostic geological cross-section based on the field data collection from the 15th to the 20th January 1902 (TELLER, 1902); later on, during the excavations a rather different geological situation was established.

TELLER's observations were published in a special monograph on the geology of the Karavanke railway tunnel, including also geological map of the Karavanke from Stol/Hochstuhl to Srednji vrh at a scale of 1: 75 000.

These data were used by VETTERS in 1933 to complete the sheet Radmannsdorf, which also includes a part of the Karavanke. It remained unpublished.

In 1954 the Werfen Formation between Belca and Hrušica was mapped because of gypsum and anhydrite deposits exploration (NOSAN, 1954).



Text–Fig. 1.
Tectonic sketch-map of the surroundings of the Karavanke road- and railway tunnels.

The western part of the Southern Karavanke was mapped in 1963 (RAMOVŠ et al., 1964) and a manuscript geological map, scale 1:10 000, was accomplished. One of the most important results of this mapping was a detailed micropaleontological determination of the age of the limestone lenses, embedded in Upper Carboniferous-Lower Permian clastic rocks.

The investigated region was also mapped for the basic geological map of Yugoslavia 1:100 000-sheets Celovec (Klagenfurt) (BUSER and CAJHEN, 1979; BUSER, 1980) and Beljak in Ponteba (JURKOVŠEK, 1987a; JURKOVŠEK et al., 1987b). Together with the textbooks for these sheets they are the most complex presentation of the geology on the Slovene side of the Karavanke.

A compilation geological map of the area between the Koren/Wurzen pass and Golica/Kahlkogel was made for the team to study hydrogeological conditions of this border region (BRENČIČ et al., 1995). This was the first joint Slovene-Austrian geological map of this part of the Karavanke after the TELLER's one.

2.2. Geological investigations relevant to the road tunnel excavation

In 1964 22 possible locations for the Karavanke road tunnel were prepared by the Slovene side (SKULJ in MIKOŠ ed., 1991). The final location was determined by Yugoslav-Austrian commission established in 1974 (SKULJ in MIKOŠ ed., 1991). The geological investigation followed.

In Slovenia the following investigations were done: surface geological mapping at a scale of 1: 5 000; surface hydrogeological mapping at a scale of 1: 5 000; geophysical investigations – geoelectric and seismic – on the surface and in four deep boreholes (KT-1, KT-3, K-J, K-JA), three of them to the level of the tunnel; five shallow bore holes at the southern entrance of the tunnel; petrologic,micropaleontologic and roentgen investigations of the core samples from KT-3 and K-J.

The Austrians didn't need to do such an extensive investigation because of a simpler geological structure on their side of the Karavanke, well documented in the nearby railway tunnel, which runs 200 meters to the east (Text-Fig. 4). Geological and hydrogeological maps at a scale of 1: 10 000 were prepared (KERN, 1980) and one deep drill hole was made in the place where a ventilation shaft was planned.

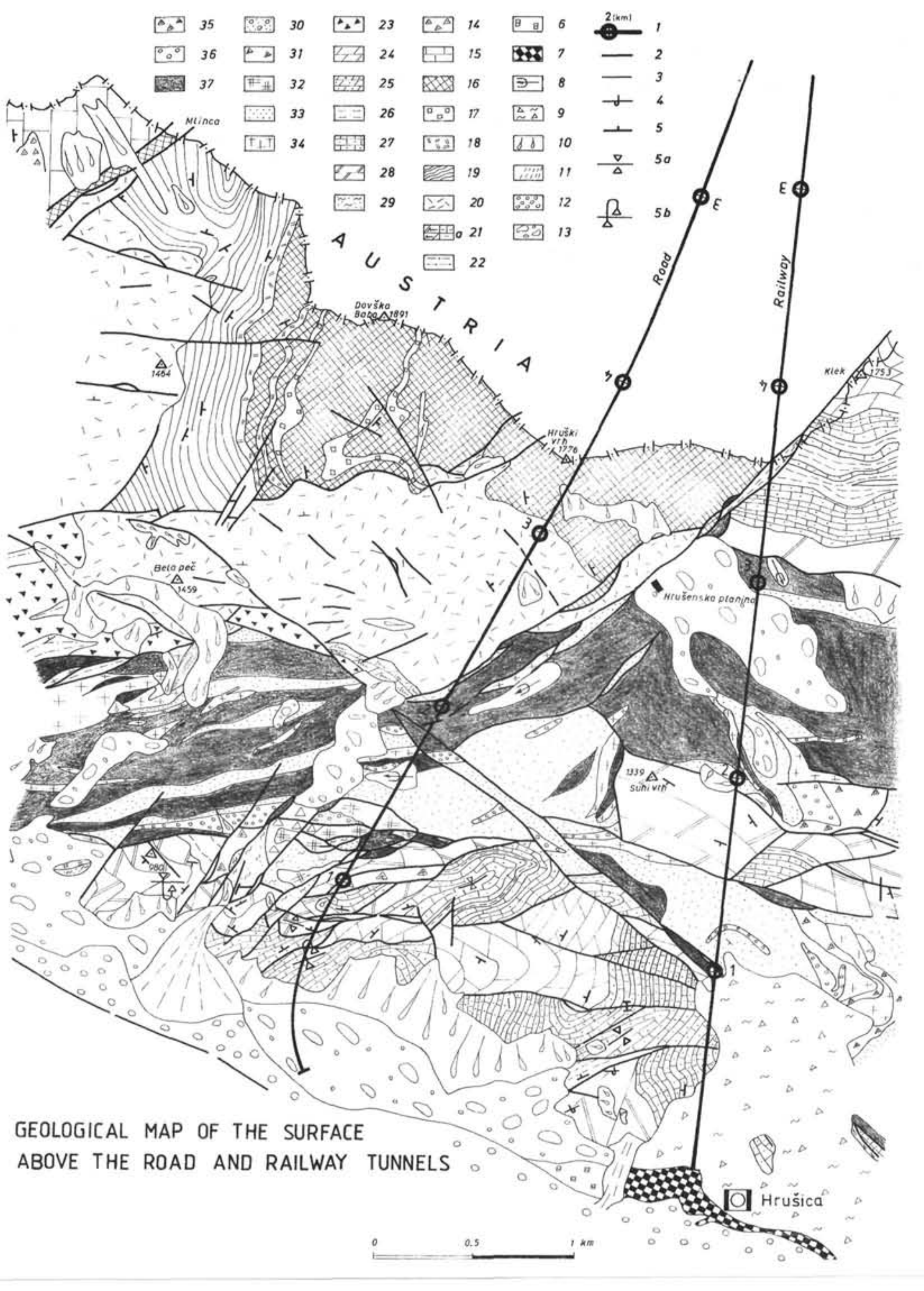
Slovene and Austrian investigations were shown on the prognostic cross section at a scale of 1:5 000, made by DROBNE and PREMRU (Slovenia) and by HERZOG (Austria) in 1979.

Compared to the real situation this cross-section shows some difference, especially on the Slovene side (BUDKOVIČ in MIKOŠ ed., 1991). This is due to improper use of the geoelectrical investigations (KUŠČER & BUDKOVIČ, 1989).

3. Geological observations during the road tunnel excavation

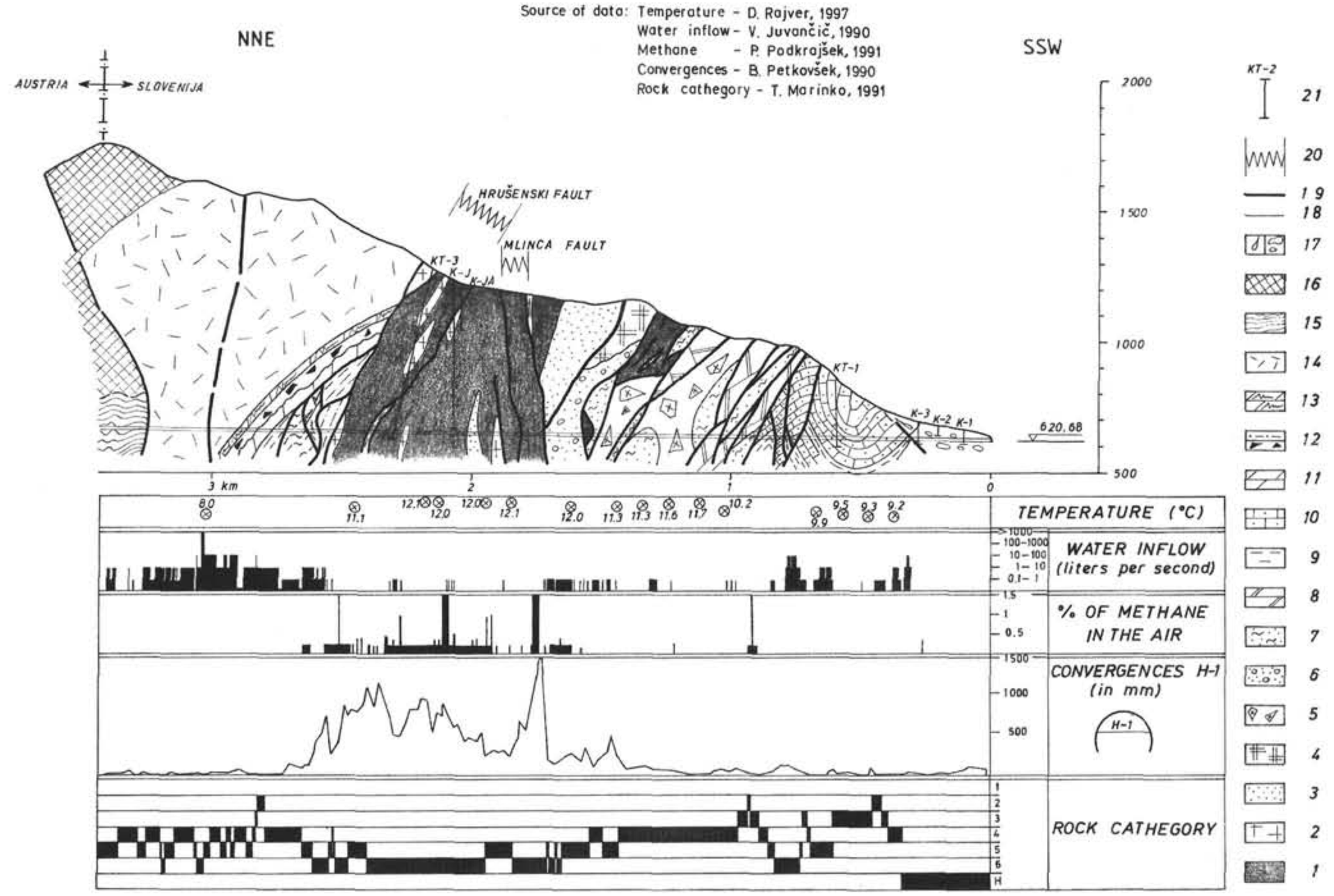
3.1. Technology of the geological data collection during the tunnel excavation

The tunnel excavation started on the 12th August 1986 on the Slovene side.



Text–Fig. 2.

Legend for the geological map of the surface above the road and railway tunnels: 1 – Road and railway tunnel, 2 – Fault, 3 – Geological boundary, 4 – Inverse bedding, 5 – Normal bedding, 5a – Syncline, 5b – Inverse syncline, 6 – Sanitary landfill, 7 – Tailings from the railway tunnel; **Quaternary:** 8 – Landslide, 9 – Debris from weathered Palaeozoic clastites, 10 – Slope debris, 11 – Alluvial fan, 12 – Terrace gravel, 13 – Moraine, 14 – Slope breccia; 15 – **Dachstein limestone:** Grey, thick bedded limestone and dolomite; **Formations of Klek/Hahnkogel unit:** Bača dolomite – Klek/Hahnkogel formation sequence (dark grey to black mudstone, marl, marly limestone, limestone, dolomite, dolomite with chert, limestone with chert), 17 – Mass flow breccia with limestone and dolomite components in Baba/Frauenkogel formation (after LEIN et al., 1995), 18 – Light grey, sparry dolomite in the hanging wall of Rabelj/Raibl terrigenous beds; 19 – **Rabelj/Raibl terrigenous beds:** Dark grey bedded limestone, marly limestone, dolomite; **Schlern dolomite:** 20 – White to light grey, massive, sparry dolomite, 21 – Grey bedded dolomite with chert; **Ukve/Uggowitz breccia:** 22 – Red, green and grey marl, siltstone and calcarenite, 23 – Variegated and grey carbonate breccia; **Anisian dolomite:** 24 – Grey thick to medium bedded dolomite; **Werfen formation:** 25 – Grey, thin bedded dolomite, 26 – Red to green micaceous dolomite and marl, gypsum bearing, 27 – Reddish oolitic limestone, thin bedded; **Bellerophon formation:** 28 – Grey, thick bedded dolomite, sometimes gypsum bearing; **Gröden formation:** 29 – Red shistose shale, siltstone, sandstone and conglomerate, 30 – Grey sandstone, conglomerate and breccia; **Tribiž/Tarvis breccia:** 31 – Red limestone breccia; **Trogkofel limestone:** 32 – Reddish and grey massive limestone; **Upper-Carboniferous – Lower Permian clastic rocks with limestone lenses:** 33 – Grey quartz sandstone, 34 – Dark grey to black massive limestone, 35 – Dark grey limestone breccia, 36 – Grey quartz conglomerate, 37 – Black schistose shale.



Text–Fig. 3.
Geological cross-section of the Karavanke road tunnel – Slovenian part: Upper Carboniferous – Lower Permian clastic rocks with limestone lenses: 1 – Black schistose shale, 2 – Dark grey to black massive limestone, 3 – Grey quartz sandstone; **Trogkofel limestone:** 4 – Reddish and grey massive limestone; **Trbiž/Tarvis breccia:** 5 – Red limestone breccia; **Gröden formation:** 6 – Grey sandstone, conglomerate and breccia, 7 – Red schistose shale, siltstone, sandstone and conglomerate; **Bellerophon formation:** 8 – Grey, thick bedded dolomite, at places gypsum bearing; **Werfen formation:** 9 – Red to green micaceous dolomite and marl, gypsum bearing, 10 – Grey to reddish oolitic limestone, thin bedded; **Anisian Dolomite:** 11 – Grey to brownish medium bedded dolomite; **Ukve/Uggowitz breccia:** 12 – Variegated and grey carbonate breccia; red, green and grey marl, siltstone and calcarenite; **Schlern dolomite:** 13 – Grey bedded dolomite with chert, 14 – Light grey massive sparry dolomite; **Rabelj/Raibl terrigene beds:** 15 – Dark grey bedded limestone, marly limestone and dolomite; **Formations of Klek/Hahnkogel unit:** 16 – Dark grey to black mudstone, marl, marly limestone, limestone, dolomite, dolomite with chert, limestone with chert, mass flow breccia – not differentiated succession from Bača dolomite to Klek/Hahnkogel formation (after Lein et al., 1995); **Quaternary:** 17 – Slope debris, moraine, 18 – Normal geological boundary, 19 – Fault plane, 20 – Fault zone, 21 – Surface borehole.

The continuous collection of geological data on the Slovene side began at 315 meters, when the tunnel entered solid rock. It included: mapping of the tunnel face on a special form (scale 1: 100) after every blast; taking photos of the face after every blast; taking samples of all types of rock at the tunnel face – more than 500 samples were collected, 204 samples were investigated; hydrogeological and engineering geological observations at the face; observation of the rock debris derived from the percussion drill holes at the tunnel face every 25 meters of advance to detect water or methane bearing zones.

For the construction purposes we were continuously updating the tunnel cross section at a scale of 1:1000. Along with the cross section also convergencies data were shown to establish their connection with geological structure. This documentation was currently used by the excavating personal to plan additional supporting measures.

The preexisting surface geological map proved insufficient for a reliable prediction of the most important contact zones (the contact between nonpermeable Palaeozoic and water bearing Triassic rocks). Additional surface mapping had to be done to solve this problem (Text-Fig. 2).

All the data were used to make a real geological cross section of the tunnel (Text-Fig. 3). The systematical collection of geological data was successful. We detected potentially dangerous zones, and thus contributed to a safer excavation process.

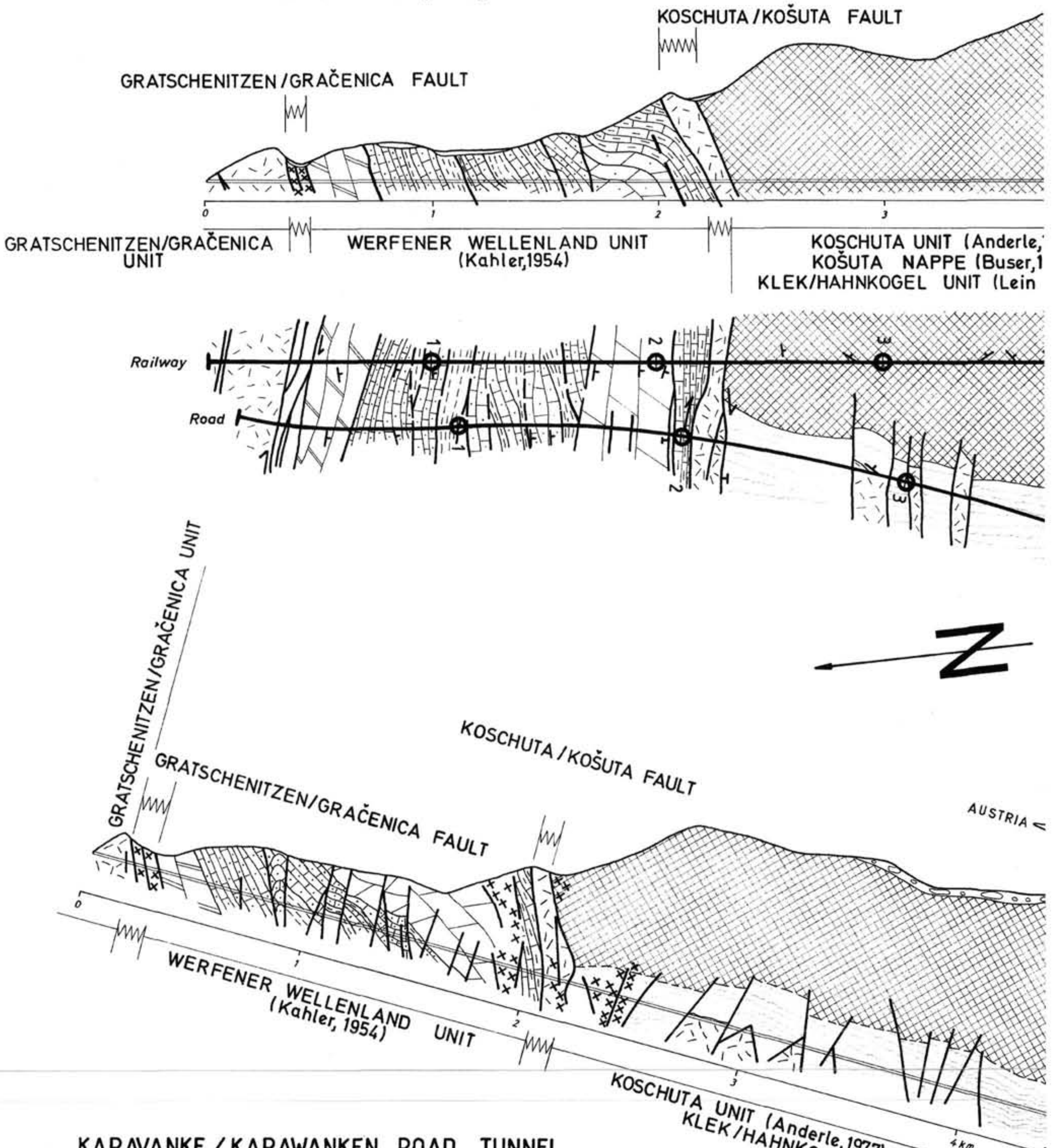
Detailed lithological and stratigraphical description of lithostratigraphic units in this part of the Karavanke is given by Ogorelec et al. (1999).

3.2. Geological situation in the Slovene part of the Karavanke road tunnel (west tube)

Section 0–315 m. Slope debris and moraine

In this section no continuous geological observation was performed, so it isn't sufficiently documented. From the shal-

KARAVANKE / KARAWANKEN RAILWAY TUNNEL
(Modified after F. Teller, 1914)



KARAVANKE / KARAWANKEN ROAD TUNNEL

TUNNEL DATA :

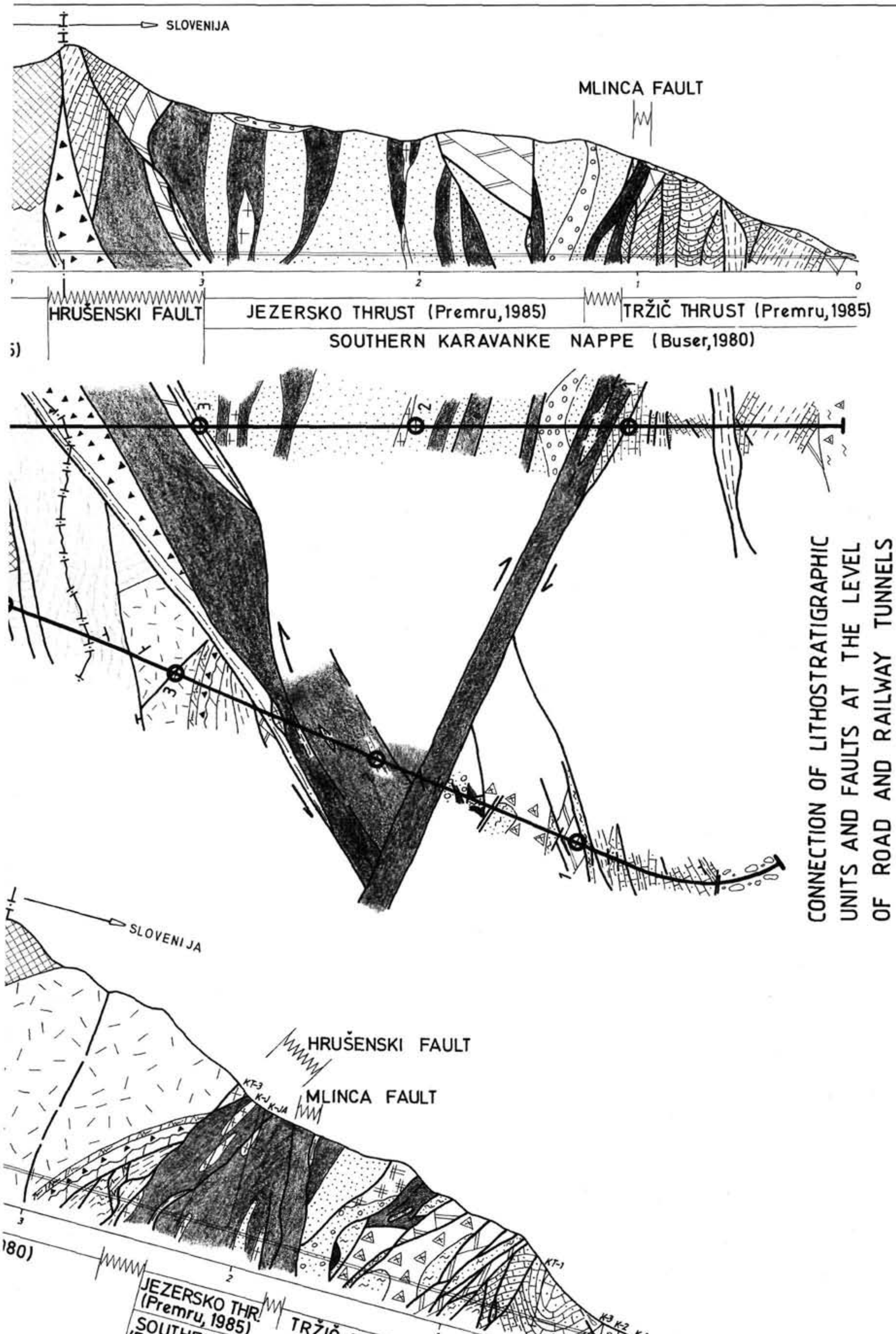
SLOVENIAN SIDE AFTER T. Budkovič, 1991

AUSTRIAN SIDE AFTER P. Müler, D. Jesinger, 1995

The legend is given on figs. 2 and 3

SURFACE DATA :

SLOVENIAN SIDE - SURFACE GEOLOGICAL MAPPING in scale 1:5000, T. Budkovič, 1988-91



Text-Fig. 4:
Explanatory text see Text-Fig. 2, 3.

low bore holes at the southern entrance (5 bore holes) it can be concluded that up to 250 m the tunnel goes through light grey moraine with larger blocks of limestone and dolomite (DROBNE et al., 1979). Between 250 and 315 m reddish slope debris with clayey silt intercalations dominates. At the contact with the Werfen Formation the slope debris is lithified. Methane,which probably originates from tectonic intercalations of Upper Palaeozoic clastites along the Sava fault ,was indicated at 264 m.

Section 315–911. Werfen Formation

The boundary plane to the slope debris is a young fault (Plate 1, Fig. 1). Between 315 and 332 m grey, thin to medium bedded dolomite prevails, followed up to 356 m by red, yellow and blue grey laminated marl. Red laminae are gradually passing into yellow and then into blue grey (Plate 1, Fig. 2). This marl is characteristical for the lower part of the Werfen Formation (DOLENEC et al., 1981). From 356 to 440 m the tunnel intersects dark grey bedded micritic limestone and sparitic dolomite. Between 440 and 605 m bedded dolomitized oolitic limestone of grey, dark grey, brownish and reddish colour dominates. It is followed by partly bedded, partly massive, white, brownish grey and greyish red dolomite (605 to 674 m).

From 674 to 705 m the tunnel passes through greyish red micritic dolomite with gypsum veinlets. Bedded dolomitized limestone and dolomite were intersected from 705 to 775 m. At 775 m, for the second time, the tunnel intersected a short sequence of variegated marl and dolomite. The same rock occurs again between 775 and 782 m. It is followed by bedded, grey and dark grey micritic dolomite; dark grey mudstone with light coloured gypsum up to 848 m. From 848 to 908 m the tunnel intersected miccaceous micritic dolomite with gypsum and anhydrite. The Werfen Formation ends with dark grey dolomite, containing nests and lenses of anhydrite. At the 900 m location a high level of methane – 1,9 % was detected in the air.

The rock sequence between 356 and 674 m forms a syncline. Its southern flank dips to the northwest. The Werfen Formation sequence is intersected by two steep fault systems. The NW–SE fault system has fault zones, up to ten meters wide, ending at E–W directed faults. In some places along these faults, small folds with axes oriented parallel to the fault plane occur. The E–W fault system has narrow fault zones. The most intensive deformed rocks of the Werfen Formation are those containing gypsum and anhydrite (Plate 1, Fig. 3). At 746 m water influx increased rapidly up to 150 l/s (LOČNIŠKAR in MIKOŠ, ed., 1991). Water eroded tectonized rock and created caverns above the tunnel. Rock blocks, which were falling on the tunnel support lining, damaged it. To reinforce the loosened rock, caverns were injected (MADER in MIKOŠ, ed., 1991). The water from this source is rich in sulphate, because it penetrates through gypsum and anhydrite bearing beds. To determine a connection between the tunnel water and the Presušnik torrent above the tunnel, a trace experiment was done. An inflow from the Presušnik was not confirmed.

Section 911–1098 m. Gröden Formation with tectonic intercalations of Bellerophon Formation

To the north of a subvertical, E–W oriented fault at 911 m the Gröden Formation with tectonical intercalations of grey, thick bedded dolomite occurs (Plate 1, Fig. 4). This dolomite belongs to the Bellerophon Formation, also occurring on the surface above the tunnel as tectonic lenses (Text-Fig. 2, Text-Fig. 3). The Gröden Formation consists of red sandstone and siltstone with developed schistosity.

The tectonic dolomite lenses are E–W oriented and dip at a high angle to the north. They are intersected by NE–SW faults, filled with tectonized red mudstone from the Gröden Formation.

No water occurred along this section.

Section 1098–1703 m. Gröden Formation and Trbiž/Tarvisio breccia with tectonical intercalations of Upper Carboniferous- Lower Permian clastic rocks

From 1098 to 1148 m red mudstone with developed shistosity was intersected. To the north, from 1148 to 1301 m, red quartz- carbonate breccia, red schistose quartz sandstone and mudstone dominate. Coarse grained clastic rocks form up to some meters thick sedimentary lenses in fine grained ones (Plate 1, Fig. 5). From 1301 to 1475 m red, fine grained clastic rocks prevail. Red schistose mudstone and lightly grey quartz breccia interfinger from 1475 to 1570 m. Red mudstone prevails. The interfingering is of sedimentary origin. Between 1570 and 1703 m a grey and red clastic rock sequence was intersected. Heterogenous and quartz grey breccia clastic rocks dominate over the red. Grey breccia also includes large blocks of dark grey limestone, which can have a volume of more than one cubic meter. In three places between 1453 and 1621 m tectonical intercalations of black Upper- Carboniferous- Lower Permian clastic and carbonate rocks occur (strongly tectonized black mudstone with blocks of massive and bedded limestone) (Plate 1, Fig. 6).

The tectonic belt with the Gröden Formation and Trbiž/Tarvis breccia trends in the E–W direction. The beds are in subvertical to inverse position. The oldest part of this succsession consists of grey, coarse grained clastic rocks. On the surface above the tunnel they are deposited on an erosional unconformity, developed on Trogkofel limestone (Text-Fig. 2). Trogkofel limestone doesn't reach the tunnel level, because it is cut along the fault (Text-Fig. 3). At 1450 m greater deformations of the tunnel tube occurred in the intensively tectonized red mudstone (PETKOVŠEK, 1990).

From the hydrogeological point of view this section is mostly impermeable. Water appeared only as drop water.

Section 1703–2610 m. Upper Carboniferous- Lower Permian clastic rocks with limestone lenses and tectonical inclusions – Gröden and Werfen Formations, Ukve/Uggowitz breccia with marl

At 1703 m the tunnel entered into the Mlinca fault zone, where Upper Carboniferous – Lower Permian clastic rocks with limestone lenses begin. From 1703 to 1824 m black, completely tectonized shale dominates. It disintegrates along schistiosity planes into small flat pieces. The schistosity planes are smooth because of an intensive tectonic movement. The tectonized shale is transformed into fault gauge in some places. At 1733 m an anthracite lense, crushed in dust, was found. The tectonical lenses of the Gröden Formation, especially of grey sandstone and conglomerate were crushed as well (Plate 2, Fig. 1). In the Mlinca fault there were the greatest convergences of the tunnel tube, detected

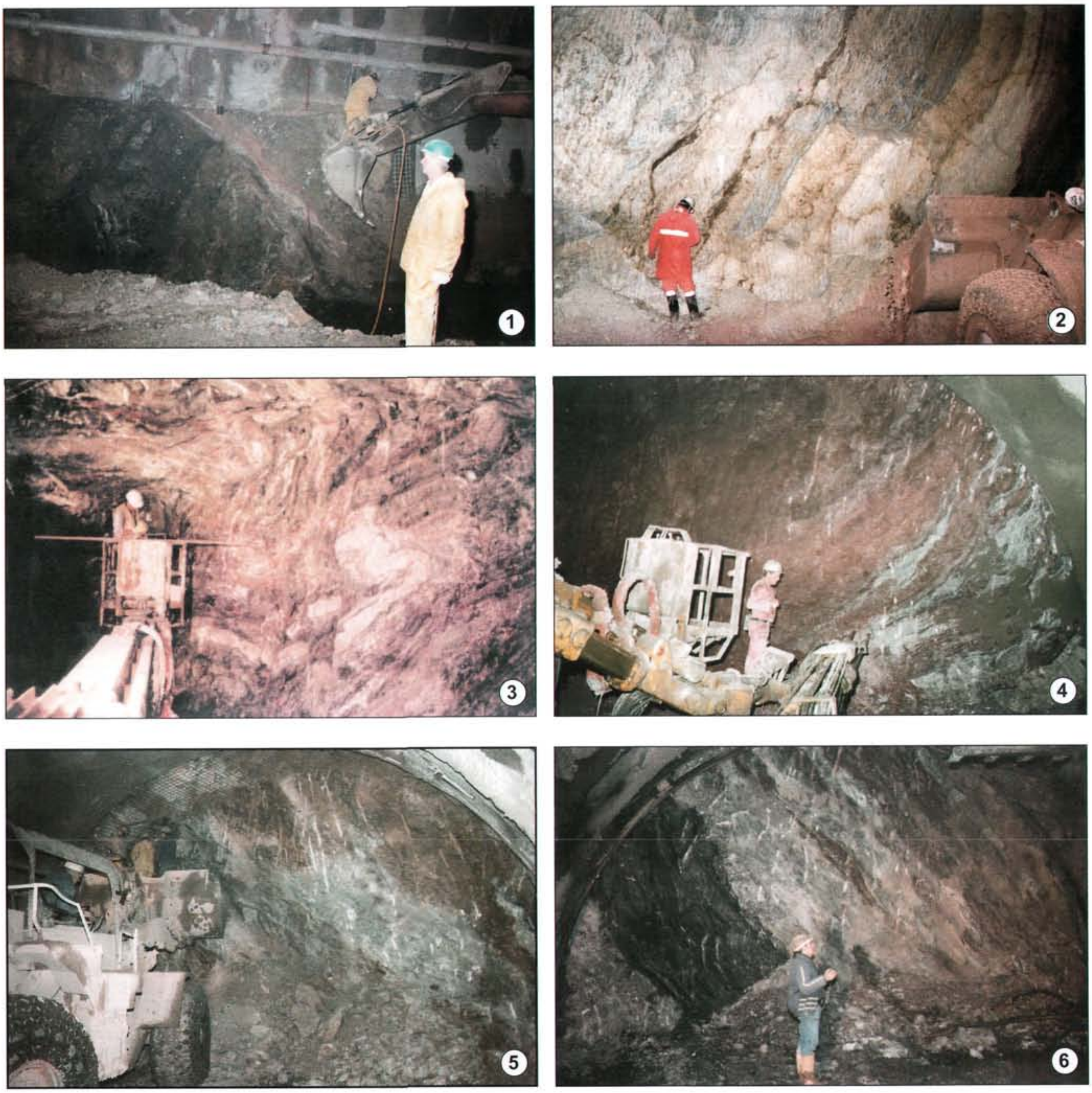


Plate 1

Fig. 1: Tectonic contact between slope debris and Werfen formation at 315 m.
Fig. 2: Variegated marl of Werfen formation (336 m).
Fig. 3: Folded Werfen formation with gypsum (890 m).
Fig. 4: Tectonic inclusions of Bellerophon formation in red siltstone of Gröden formation (1030 m).
Fig. 5: Sedimentary lenses of Trbiž/Tarvis breccia in red sandstone of Gröden formation (1567 m).
Fig. 6: Tectonic lense of black Upper Carboniferous-Lower Permian clastic rocks in Gröden formation (1604 m).

nowhere else along the whole tunnel (Text-Fig. 3). In this zone- at 1725 m – the highest methane concentrations in the air were detected (Text-Fig. 3).

Between 1824 and 1902 m the tunnel went through a relatively little tectonized succession of black carbonate clay shale, black limestone and grey sandstone (Plate 2, Fig 2). In some places in fine grained sandstone ripple marks were visible. Along this short undisturbed section the beds dip to the northwest.

From 1902 to 2610 m the tunnel crossed extremly tectonized dark grey to black clastic and carbonate rocks of Upper Carboniferous- Lower Permian age. The sandstone is folded into small folds. Black shale shows very close spaced schistosity planes with a smooth surface. Along them the rock disintegrates into very thin sheets. Schistose black shale forms up to some ten meters wide zones. Between them there are less tectonized parts of black limestone, grey sandstone and conglomerate. Limestone lenses are the most common. We suppose that they were sedimented as beds and were later disintegrated by tectonic processes. Thirteen greater lenses were intersected (Text-Fig. 3). They were composed of dark grey to black, mostly massive limestone with white calcite veinlets. Many of them contained crinoid fragments. At 2300 m a massive limestone lens was intersected. Highly mineralized water, smelling of H2S was springing out of it (MALI in MIKOŠ ed., 1991). The investigations of the samples from the deep bore holes KT-3 and K-J told us that limestone lenses could be of the Upper Carboniferous or the Lower Permian age (KOCHANSKY-DEVIDE in DROBNE et al., 1979). We believe that an exact age determination of each single limestone lens would not lead to a better understanding of tectonic structure, while we found the tunnel section from 1703 to 2610 m to be completely tectonized along the Mlinca and the Hrušenski faults.

In the tectonic zones of the Mlinca and the Hrušenski fault inclusions of younger rocks were found (Text-Figs. 3, 4). In the Mlinca fault zone, Gröden Formation tectonic intercalations are embedded. In Hrušenski fault zone there are several inclusions of younger rocks. Bigger tectonic lenses of the Werfen Formation – red and green sericite siltstone, light grey dolomite and white to reddish dolomite- were determined between 2386 to 2402 m; between 2422 to 2427 m, at 2450 m (Plate 2, Fig. 3) and between 2487 to 2494 m. In the section from 2562 to 2610 m grey, dark grey and reddish marl with thin calcarenite beds and lenses of variegated Ukve/Uggowitz breccia occurred. Those rocks were mixed with belts of strongly tectonized black shale.

The whole section from 1703 to 2610 m can be considered as a tectonic zone. From 1902 m on, almost all the tectonic elements - schistosity planes, fault planes, tectonic lenses - are oriented in the SW–NE direction and have a very steep position parallel to the Hrušenski fault.

The whole section is water impermeable with the exception of some limestone lenses with confined highly mineralized water.

Along the whole section high methane concentrations were detected. There were also very high tunnel deformations, requiring special support measures (PETKOVŠEK in MIKOŠ ed., 1991).

Section 2610–2654 m. Dark grey silicified dolomite

After the NE–SW oriented subvertical fault plane the tunnel entered dark grey, silicified and tectonically partly crushed dolomite. A similar dolomite, stratigraphically positioned below Schlern dolomite, was also observed on the surface above the tunnel. This dolomite forms a tectonic lense along the Hrušenski fault.

Hydrogeological conditions changed abruptly at the Palaeozoic clastites- Triassic carbonates boundary. This change was predicted by Kuščer and Budkovič, when the tunnel advanced to 2300 m in August 1988 (KUŠČER & BUDKOVIČ, 1989). Later it was indicated by a horizontal percussive borehole from the tunnel face at 2565 m. The water pressure in the borehole was estimated to be more than 50 bars, because of a very high overburden (Text-Fig. 3). Along the whole dolomite section water was dropping and springing.

Section 2654–2767 m. Werfen Formation

The silicified dolomite and the Werfen Formation are separated by a fault plane, dipping 40° to the south. The Werfen Formation succesion begins with temporarily laminated sandstone, which occurres up to 2681 m. From 2681 to 2725 m dark grey to reddish limestone and siltstone with purple gypsum lenses follow. Dark grey tectonized marl and bedded limestone occur from 2725 to 2736 m, followed by dark grey dolomite and grey, green and red marl, up to 2767 m.

Along the whole section the beds are dipping to the northeast. Fold axes, cleavage planes and faults follow the NE–SW direction.

Due to partly impermeable rock, water inflow along this section was low (from 0, 01 to 1,0 l/s) (Text-Fig. 3).

Section 2767–2830 m. Anisian dolomite

The boundary to the Werfen Formation is a fault plane.The Anisian dolomite is thin bedded, grey to brownish, with stylolites. It's age is not proved by fossils, but only estimated by its lithostratigraphic position.

Tectonically this section is not much disturbed. The beds are in normal position, dipping 50–70° to the northeast.

The water inflow at the face area varied from 1–10 l/s.

Section 2830–2851 m. Ukve/Uggowitz breccia

Fine grained conglomeratic dolomite breccia of grey colour is deposited on an erosional unconformity, developed in the Anisian dolomite. The beds have normal position and are dipping 50–70° to the north. The water inflow at the face area was from 1–10 l/s.

Section 2851–3258 m. Schlern dolomite

The Schlern dolomite is separated from Ukve/Uggowitz breccia by a fault plane, which dips 45° to the northeast. Up to 2865 m, the succesion is composed of grey bedded dolomite with grey, siltstone laminae. Between 2865 and 2893 m dark grey, sometimes laminated dolomite prevails. At 2893 m it changes into light grey and massive, sparry dolomite, which often gradually changes into dolomitized limestone. Sometimes it includes intercalations of dark grey dolomite (Plate 2, Fig. 4).

From 3030 to 3040 m, the dolomite succesion includes up to 30 cm thick green–grey clayey layers. Their contacts with the dolomite are oxidized, brown coloured. The dolomite is intensively fractured along the NW–SE and the E–W subvertical faults. The widest subvertical NW–SE oriented fault zone occurres from 3030 to 3040 m.

It is filled with fault gauge. During the tunnel excavation process it proved to be very dangerous. It was detected by percussive drilling from the tunnel face at 3010 m, when the water at high pressure began to splash out of the drill hole. When the tunnel face advanced to 3028 m, a massive water irruption happened (ČREPINŠEK in MIKOŠ ed., 1991). Within ten metres behind the face, the tunnel was completely filled with mylonite debris (Plate 2, Fig. 5). The tunnel excavation stopped for six weeks. A parallel » by pass » tunnel was built along the collapsed tunnel section. The paralell tunnel made further work possible during the time the collapsed tunnel section was being sanated. Now the » by pass « tunnel is used for the captage of the water from the fault zone. This water is bottled under the name » Juliana «. The second steep fault zone in the SE–NW direction was crossed at 3180 m. It was also filled with mylonite debris, but it caused no technical problems.

Plate 2

Fig. 1: Mlinca fault. Black fault gouge includes crushed lenses of coarser clastic rocks (1740 m).
Fig. 2: Upper Carboniferous-Lower Permian clastic rocks with carbonate beds. Sequence of black schistose shale, sandstone and limestone. Left side of the face is tectonically crushed (1900 m).
Fig. 3: Tectonic inclusion of Werfen Formation in black Upper Carboniferous – Lower Permian schistose shale (2452 m).
Fig. 4: Schlern dolomite – light grey, massive, grainy dolomite, with dark grey coloured intercalations (3041 m – »by pass« gallery).
Fig. 5: Water inrush area. Ten meters of the tunnel tube were filled with debris of Schlern dolomite (3028 m).
Fig. 6: Rabelj/Raibl terrigenous beds – dark grey limestone, marly limestone and dolomite (3260 m).

The Schlern dolomite was the most dangerous aquifer intersected by the road tunnel. It is very porous because of intensive tectonisation. The primary water pressure on the tunnel level was more than 50 bars. Along the whole section there were numerous springs. The biggest one was in the place of the water irruption. A very favourable circumstance for the tunnel progression was the fact that the Schlern dolomite was not in direct contact with the Upper Carboniferous–Lower Permian clastic rocks. If it were, the water irruption would be far more dangerous (KUŠČER & BUDKOVIČ, 1989).

Section 3258–3436 m (state boundary). Rabelj/Raibl terrigenous beds

The Rabelj/Raibl terrigenous beds are separated from the Schlern dolomite by several meters of the fault zone, with a steep inclination to the north. It is filled with dark grey fault gauge.

The successive Rabelj/Raibl terrigenous beds (LEIN et al., 1995) are composed of dark grey bedded limestone, marly limestone, marl and dolomite. The whole succesion is intersected by white calcite veinlets (Plate 2, Fig. 6).

With a few exceptions that are NW–SE and NE–SW oriented,the faults in this section mainly go in E–W direction. Fault related folds of about one meter breadth are visible along the fault at 3436 m.

There was no spring water along this section; only at 3436 m high mineralized water of green colour was dropping.

4. Positions of road and railway tunnels in regional geological structure

The surface geological mapping at a scale of 1:5000 made me realize extreme complexity of the geology of this region (Text-Fig. 2).

The main tectonical units are E–W trending belts, intersected by several NE–SW and NW–SE oriented steep faults. Going from the south to the north, road and railway tunnels intersect the following tectonical units (Text-Figs. 1 and 4):

Tržič thrust (PREMRU, 1985), named after Tržič, a town to the east of the investigated area, is composed of Upper Palaeozoic and Lower to Middle Triassic rocks. Both tunnels cross the folded Werfen Formation and the Bellerophon Formation. The folds go for several ten metres, and are sometimes turned over. Their axes are mainly E–W oriented. The folds are intersected by reverse faults, dipping steep to the north. The northern part of the Tržič thrust is composed mainly of the Gröden Formation, Trbiž/Tarvis breccia and Trogkofel limestone (observed only on the surface). The southern boundary of this structure is the Sava fault. The northern boundary is a reverse fault, dipping at 60° to the north. The tectonical inclusions of Upper Carboniferous-Lower Permian clastic rocks and carbonates in the Gröden Formation near the reverse fault agree with Premru's hypothesis of this fault to be a former thrust plane.

The Tržič thrust is cut by subvertical Mlinca fault (NW–SE oriented) of a strike-slip character with horizontal displacement of SW tectonical block for one km to the NW (Text-Figs. 2 and 4). Because of the displacement along the Mlinca fault, the Gröden Formation and Trbiž/Tarvis breccia in the railway tunnel are missing.

The Jezersko thrust (PREMRU, 1985) is named after Jezersko, a region to the east of the investigated area. This tectonic unit is mainly composed of Upper Palaeozoic clastic rocks: black slate, dark grey to grey sandstone, grey quartz conglomerate and carbonates: dark grey to black massive and bedded limestone. A full 2500 m of the railway tunnel is situated in the Jezersko thrust. Upper Palaeozoic rocks in this tunnel are represented mainly by grey sandstone, schistose black slate, quartz conglomerate and black limestone. The road tunnel sector of the Jezersko thrust is shorter- only 900 meters. The prevailing rock along it is schistose black slate with minor tectonic lenses of sandstone, limestone and conglomerate. In the Palaeozoic clastic sequence of the Hrušenski fault zone, also parts of the Bellerophon Formation and the Werfen Formation, Ukve /Uggowitz breccia and dark grey to grey marl with about one decimeter of calcarenite beds are embedded. In the railway tunnel they were intersected at 3008 m, and in the road tunnel between 2386 and 2610 m. Above the railway tunnel there is a 500 m wide elongated block of the Bellerophon Formation and Werfen Formation (Text-Figs. 2 and 4), which does not reach the railway tunnel level.

The boundary to Košuta nappe/Koschuta unit is the NE–SW oriented steep fault with a cylinder shaped fault plane. It dips to the southeast in the railway tunnel and to the northwest in the road tunnel. Along this cylinder shaped plane Ukve/Uggowitz breccia and red, green, grey and dark grey marl with limestone beds occur. TELLER (1914) misnamed these rocks as Trbiž/Tarvis breccia and Gröden Formation because of their similarity.

Košuta nappe (BUSER, 1980)/**Koschuta unit** (ANDERLE, 1977) is named after the Košuta/Koschuta ridge at the east of the investigated area. Because the Hrušenski fault intersects the Košuta nappe/Koschuta unit diagonally, the railway tunnel enters younger lithostratigraphic units (the Rabelj/Raibl terrigenous beds, Bača dolomite- KRYSTYN et al., 1994), while the road tunnel intersects the whole succesion from Werfen Formation, Ukve/Uggowitz breccia, Schlern dolomite (BUDKOVIČ, 1991) and the Rabelj/Raibl terrigenous beds (LEIN et al., 1995). Crossing the Rabelj/Raibl terrigenous beds, it cuts three horsts of Schlern dolomite, wrongly identified by LEIN et al. (1995) as Conzen dolomite. The Košuta nappe/Koschuta unit ends at the Košuta/ Koschuta fault, which is a more than ten kilometre long and about one hundred meter wide belt of Schlern dolomite, embedded along the fault zone.

The "Werfener Wellenland" unit (KAHLER, 1954) is situated between the Košuta/Koschuta fault and the Gratschenitzen/Gračenica fault. It consists of a succession of younger Palaeozoic and older Mesozoic beds beginning with the Bellerophon Formation and ending with dark grey bedded limestone, belonging to Buchenstein beds. The unit is folded and intersected by E–W oriented faults, dipping steep to the south. The northern boundary of it is the Gratschenitzen/Gračenica fault. The fault zone dips to the south and is more than one hundred meters wide.

The Gratschenitzen/Gračenica unit is a tectonic block between the Gratschenitzen/Gračenica fault and the Periadriatic lineament. It is mainly composed of Schlern dolomite. The Košuta/Koschuta unit and the Gratschenitzen/ Gračenica unit are separated by the Gratschenitzen/ Gračenica fault, along which are embedded also lenses of Palaeozoic rocks.

5. Conclusion and discussion

A continuous geological observation gave us a new insight and some quite interesting new facts about the geology of the Karavanke range. It can be summarized as follows:

– The contact plane between the slope debris with moraine and the Werfen Formation is a young fault plane.It can be considered as a proof of relatively young tectonic activity along the Sava fault.

– The Werfen Formation from 315–911 m is folded and intersected by several E–W and NE–SW oriented faults.

– The Gröden Formation and Bellerophon Formation from 911 to 1098 m are tectonically interfingering.

– The Gröden Formation and Trbiž/Tarvis breccia from 1098 to 1703 m show an inverse position.

– The succession of the Upper Carboniferous- Lower

Permian clastic rocks and carbonates is completely tectonised. It also includes tectonic lenses of younger rocks of the Upper Permian and Triassic ages.

– From 1703 to 1824 m the tunnel intersects the NW–SE oriented subvertical Mlinca fault, where the greatest convergences and methane concentrations were found.

– From 1902 to 2610 m all the tectonic elements – orientation of tectonic lenses, schistosity and smaller faults – are steep and NE–SW oriented, the same as the Hrušenski fault.

– The northern contact between the Upper Carboniferous-Lower Permian clastic rocks with carbonates and Triassic carbonates is a steep, cylindrical NE–SW oriented fault plane, called the Hrušenski fault (Kuščer and Budkovič, 1989). It is not a thrust plane as Lein et al. (1995, Fig. 4) believe.

– The dark grey silicified dolomite from 2610 to 2654 m forms a tectonic lense. It is very similar to the basal part of the Schlern dolomite.

– The Werfen Formation from 2654 to 2767m is not completely developed. In this section clastic rocks dominate.

– Compared to the nearby areas the Anisian dolomite is very thin (Ogorelec et al., 1999), and so is Ukve/Uggowitz breccia, deposited on an erosional unconformity on top of the Anisian dolomite.

– The Schlern dolomite from 2851 to 3258 m was the most dangerous aquifer along the whole length of the tunnel. This was proved by a strong water irruption from the subvertical NW–SE oriented fault zone at the 3028. m.

– The Rabelj/Raibl terrigenous beds from 3258 m (Slovene side) up to the Košuta/Koschuta fault on the Austrian side were deposited on the uneven upper surface of the Schlern dolomite, disintegrated along the E–W oriented faults into horsts and grabens. Three water bearing horsts of the Schlern dolomite were intersected on the Austrian part of the tunnel. Lein et al. (1995) believe that this dolomite is Conzen dolomite, which belongs to the Raibl group. In the Mlinca area, where a complete succesion of the Rabelj/Raibl group is deposited on the Schlern dolomite, no such dolomite exists. The enormous quantity of water, springing from these horsts, can originate only from such a voluminous aquifer as Schlern dolomite is.

As a final note we can say that our time consuming extensive geological work and the comparison of the geology of the railway and the road tunnels paved our way to an optimum knowledge of the geological structure of the investigated part of the Karavanke. It also involved several surprises, deriving from insufficient previous data.

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