GROUND CONDITIONS AT SEDRUN

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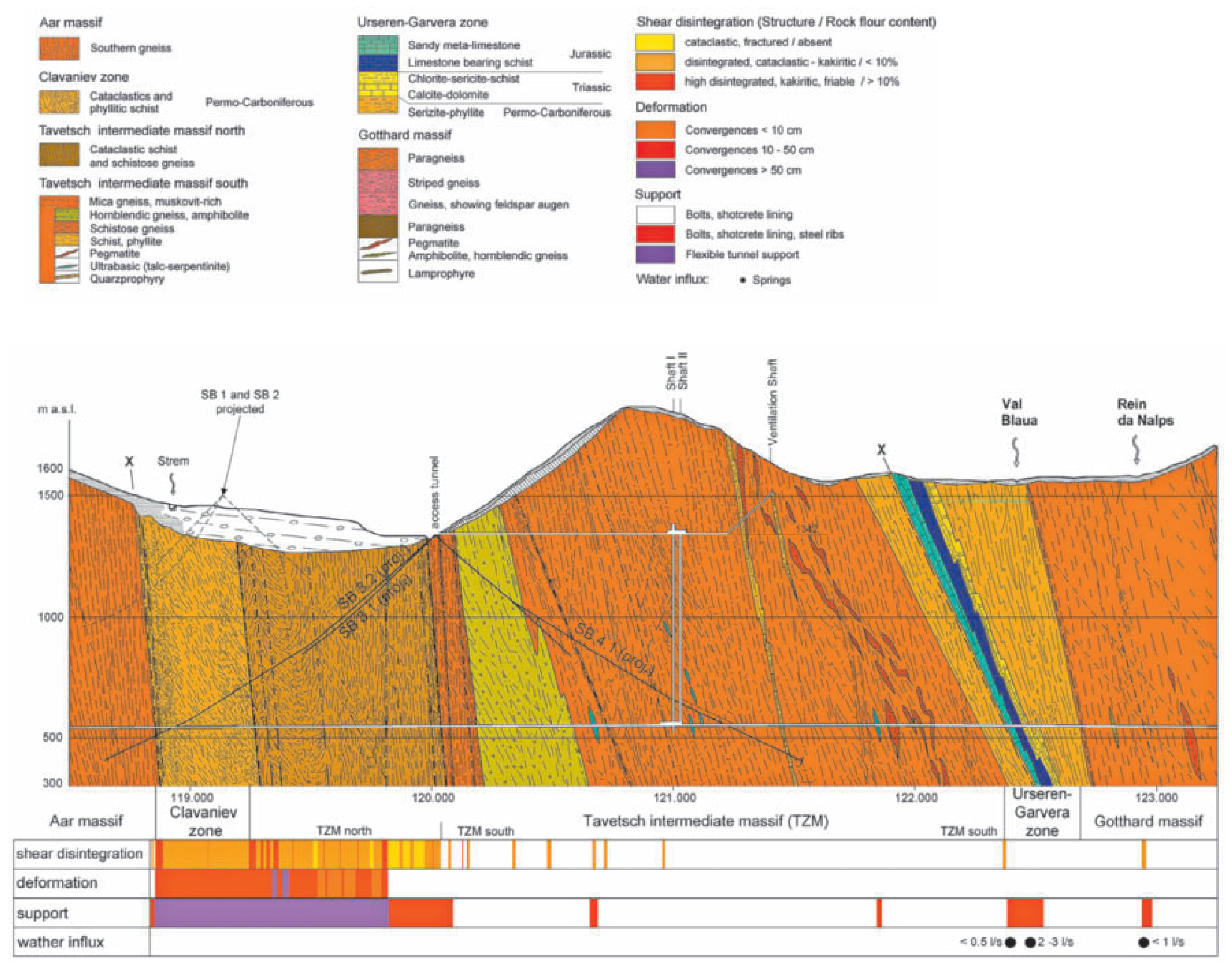
1 INTRODUCTION, GEOLOGICAL OVERVIEW

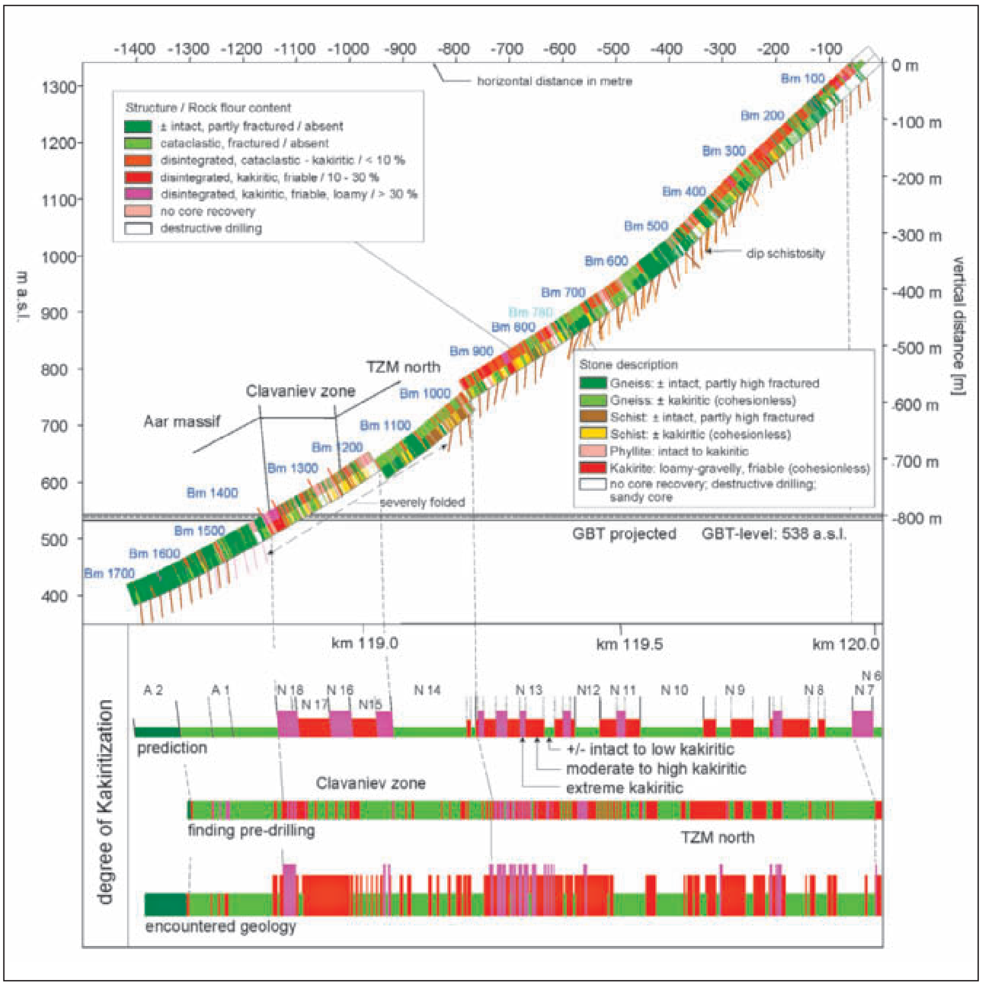
The excavations during the drives in the Sedrun section passed through crystallinebasement rocks of the Aar massif, the Tavetsch intermediate massif and the Gotthard massif between chainage 118.835 and 127.404 km (see ▶ **Fig. 1**). These crystalline units are separated from each other by Mesozoic and Permo-Carboniferous sediment formations of the Urseren-Garvera zone as well as the Clavaniev zone. All these units were pushed on top of each other, metamorphically shaped and steeply tilted when the Alps were folded. The units extend transversely to the Gotthard Base Tunnel (GBT). The Tavetsch intermediate massif north and the Urseren-Garvera zone were two of the GBT's identified risk zones (see II 6 "Exploration of geological risk zones"). The opening up of the two single-track tunnels via the two 800 m deep shafts at Sedrun and the multifunction station (MFS) called for favourable geological conditions so that construction difficulties of a technological nature could be avoided when sinking the shafts and for the large excavated cross sections of the tunnel crossover enlargements in the MFS. The shafts and the MFS were thus positioned accordingly based on findings obtained from the previously excavated access tunnel and the exploration drilling SB 4.1.

In order to identify geological hazards in time during the excavation activities and apply measures (support, ancillary construction measures, injections) to the required degree, an intensive underground advance exploration campaign as well as intensive geological-geotechnical and hydrogeological monitoring was undertaken during the entire construction period



▶ **Fig. 1** *Geological longitudinal cross section at the access tunnel, the shafts and the MFS*

Credit: [19]



Credit: [19]

▸ **Fig. 2** *Rock model of the strongly squeezing Clavaniev zone and the Tavetsch intermediate massif north based on the exploration drilling SB3.2 and the findings from pre-drilling and the excavation*

from 1996 until 2011. These data were collated constantly by the geologists on the spot, evaluated, assessed and distributed amongst the decision makers involved in the project. All data relating to geology, hydrogeology and geotechnics are documented in geological final reports [19]. Results of various kinds were published in part during the construction period. Furthermore, more elaborate assessments of the data were received by the professorship for engineering geology and the professorship for underground construction of the ETH Zurich within the scope of dissertations. A number of the most important results pertaining to the geology, hydrogeology and geotechnics are summarised in the present report.

2 CLAVANIEV ZONE AND TAVETSCH INTERMEDIATE MASSIF NORTH

In the Clavaniev zone (chainage 118.861–119.246 km) and in the Tavetsch intermediate zone north (chainage 119.246–120.039 km) mainly fractured – that is, kaciritic and strongly cataclastic – rocks were anticipated, closely alternating with "intact" rocks. Owing to the predominance of the brittle tectonically defined rocks (>60 %) with extensive distribution of soft, non-cohesive fault brecchias and fault gouges (rocks in which rock fragments "float" in a clayey matrix, called kaciritic and strongly cataclastic) similar to soft ground, the units were jointly classified as a roughly 1 km wide fault zone, with expectations of strongly squeezing conditions. Some of the cores from exploration drilling SB 3.2 revealed plastic behaviour. ▸ **Fig. 2** describes the heterogeneous rock series from this borehole with their varying lithological composition and different brittle shearing. The degree of this brittle shearing was evaluated in keeping with the rock structure and the rock flour proportion.

Extensive technical homogeneous areas were already defined in the prognosis at tunnel level so that the strongly alternating rock series could be presented more simply, for which changing the excavation support appeared justified on account of various geological-geotechnical hazard patterns. As far as these homogenous areas were concerned, a distinction was drawn between three stages of kakiritization (fault gouging) as shown in ▸ **Table 1**, which were ascertained according to the lithological composition and brittle shearing. The individual stages were allocated to possible hazard patterns. Radial, plastic deformations of 20–70 cm were in the forefront. Further determining hazards were predicted to be ravelling of unconsolidated ground, instability of the face (extrusion) and a possible influence exerted by high pore-water pressures that reduces strengths and increases deformations on account of the overburden.

All technical measures were resorted to in accordance with the expected hazard patterns. It was essential for implementation on-site to compare the geological-geotechnical accordance of the rocks with that of exploration drilling SB 3.2. To this end, the degree of kakiritization of the rocks in the 31–193 m long pre-drilling carried out from the tunnel face as well as in the findings on the drive was described in the same way as well as establishing technical homogenous areas (see ▸ **Fig. 2**). As a result, it was possible to hold discussions with the project author, the project engineer and the construction management so that the proper technical measures could be determined.

Homogeneous areas Degree of kakiritization	Dominating lithologies and description of brittle shearing (shear desintegration) based on structure and rock flour ratio	Hazard patterns, phenomena
± Intact to weakly kakiritic	Gneisses and schists, weakly fractured to cataclastic characterisation, with slight (< 10 %) to no rock flour ratio, solid to moderate strength, locally friable, mostly dry, partially with drip points and moisture (fissure water)	Slight and local squeezing properties (radial convergences up to 20 cm), ravelling, face instability through buckling
Moderately to strongly kakiritic	cataclastic – kakiritic schists and gneisses, fractured, with slight (< 10 %) to moderate (30 %) rock flour ratio, low strength, friable to soft, mostly "dry" or moist (water content mostly less than 4 % by weight), with proportion of clay (illite, smectite)	Strong squeezing properties (up to 50 cm radially), ravelling especially from the face
Extremely kakiritic	cataclastic breccias and fault gouges, strongly fractured and sheared, clayey, with rock fragments floating in the rock flour (> 30 %), soft, deformable by hand, plastic, moist (water content mostly less than 4 % by weight), with proportion of clay (illite, smectite, kaolinite) up to 30 % by weight	Extreme squeezing properties (up to 70 cm radially) ravelling especially from the face; additionally expected: pore-water pressure influence on strength

▶ **Table 1** *Construction homogeneous areas and geological-geotechnical relevance, kakiritic and cataclastic: rocks in which rock fragments "float" in a clayey matrix*

Sheardesintegration (structure/rock flour ratio)	Clavaniev zone Tavetsch intermediate massif north 1'177 m	Urseren-Garvera zone 310 m	Fault zone 50b 148 m
± Intact/0 %	15 %	98 %	8 %
Cataclastic, fractured/0 %	11 %	–	41 %
Desintegrated, cataclastic – kakiritic/< 10 %	62 %	1 %	50 %
Desintegrated, kakiritic, friable/10–30 %	11 %	1 %	–
High desintegrated, kakiritic, friable, crumbly/> 30 % (fragments in the rock flour)	1 %	–	1 %

▶ **Table 2** *Findings for the brittle tectonic overprinting of the east tunnel in the Clavaniev zone (chainage 118.861–119.246 km), the Tavetsch intermediate massif north (chainage 119.246–120.039 km), the Urseren-Garvera zone (chainage 122.372–122.682 km) and fault zone 50b (chainage 125.422–125.570 km, Gotthard massif)*

A concept involving a full-face excavation and yielding steel support allowing for sufficient space for deformations as well as intensive face bolting was foreseen to master this risk zone.

The high ratio of brittle tectonically defined rocks was confirmed by the findings, as ▶ **Table 2** and the longitudinal profile indicate (see ▶ **Fig. 1**). The squeezing behaviour occurred during the drive towards the north as from chainage 119.816 km with the appearance of an initial larger zone with extremely kakiritic (fault-gouged) rocks and was only dying out when the Aar massif was reached at chainage 118.861 km. On account of asymmetrical deformations, which were favoured in parts by the unfavourable parallel positioning of the schistosity to the tunnel, the maximum anticipated convergences (70 cm) were exceeded locally involving deformation peaks of 85–90 cm. Re-profiling activities (reworking) was, however, not necessary. To sum up, it can be ascertained that the prognosis described the conditions encountered most accurately. By dint of the excavation and safety concept that was embarked upon, which represented the correct procedure for this rock, the impression was created that the conditions that were encountered were, if anything, more favourable than expected. However, this was not actually the case at all.

3 TAVETSCH INTERMEDIATE MASSIF SOUTH

Alpine, mainly ductile sheared, and solid gneisses and schistous gneisses were expected in the Tavetsch intermediate massif south, which are separated by a large number of shear zones from a few decimetres up to several metres thick as well as phyllitic intermittent layers and cataclastic and kakiritic fault rocks. The Tavetsch intermediate massif south appeared suitable for producing the access structures and the MFS given the presence of these more solid, technically more favourable rocks. Tricky rock sections with major deformations of up to 50 cm were forecast only in the faults and on the south fringe.

The reliability of the prognosis really proved its work around exploration drilling SB 4.1; otherwise, there was a dispersion in terms of thickness and characterisation owing to the undulating course of the faults, the distance between the surface outcrops and the tunnel, and the complex internal structure. The Tavetsch intermediate massif south is 466 m thicker than expected and its boundary pushed 462 m further to the south (chainage 122.372 km). In spite of this spread and a number of deviations, the findings display a satisfactory correlation with the prognosis. The rock model with the assumption of solid gneisses, which are repeatedly separated by fault zones of up to several decametres thick, was confirmed within the forecast range. To sum up, it can be asserted that the choice of the shaft location and the position of the MFS were correct from the geological viewpoint. The greater thickness of the Tavetsch intermediate massif south, the relocation of the Urseren-Garvera zone towards the south and the more favourable rock conditions in the fault zones as crucial deviations from the prognosis ultimately contributed to the fact that no MFS structure had to be excavated in tricky rock conditions. The excavation and safety concept could be applied as planned in the prognosis, and the rock conditions encountered (detachments caused by separation planes, slightly unconsolidated) mastered by means of the support measures laid down in the works contract. Even in the large excavated cross sections of the tunnel junction enlargements in the proximity of the MFS and in the case of the various hollow cavity excavations (cross-passages, shafts), deformations were kept to a minimum thanks to the manner the rock was secured and subsequent supporting of the deformations. The predicted deformations in the shallow faults and on the south fringe of the Tavetsch intermediate massif did not occur. The incidence of underground water from faults and fractured rock remained very low. Inflows were restricted to drops, moisture and individual springs <0.1 l/s and a total water flow rate of <3 l/s. The prognosis relating to underground water in the Tavetsch intermediate massif south was too pessimistic.

4 URSEREN-GARVERA ZONE

The Urseren-Garvera zone sediments were deposited on the Gotthard massif, steeply tilted, folded and tipped over by the formation of the Alps (see ▶**Fig. 1**). The Urseren-Garvera zone (chainage 122.372–122.682 km) had previously been passed through by a number of underground structures (Gotthard road tunnel, Gotthard rail tunnel, Vorderrhein power plant pressure tunnel). Should karstified Triassic rauhwacke (Mesozoic) be encountered, short-term water ingress of up to 1,000 l/s within two days was feared. In the Gotthard road tunnel and in the rail tunnel as well, the low-strength schists and phyllites of the Permo-Carboniferous period (late Palaeozoic) and the Liassic slate with 300 m overburden turned out to be tricky rock sections (squeezing with deformations up to 70 cm). The squeezing rock behaviour was therefore also predicted for the comparable sections of the GBT.

Contrary to project expectations, the Urseren-Garvera zone dips at only 65–70° towards the south rather than steeply at 85–90° and was scarcely disturbed (see ▶**Table 2**). The sequence of Mesozoic extending to the Permo-Carboniferous in the Urseren-Garvera zone corresponds with the anticipated litho-stratigraphic reverse series. The presence of gypsum or anhydrite could not be proved. Cavernous or brecciated dolomitic marbles prevail at tunnel level, albeit there is a lack of rauhwacke deposits as such. The rock behaviour during the drive was substantially better than had been expected in the Urseren-Garvera zone, which was classified as technically unfavourable. No plastic deformations occurred in this rock section and a normal, rigid steel support and merely rock bolts and shotcrete over extensive sections were selected for supporting purposes. There was no need for a heavy support involving deformable, yielding steel ribs in major excavated cross sections. First and foremost, the favourable, cross-cut orientation of the dominant rough cleavage plane and the good strength properties played a central role for the unexpectedly good stability of the excavated profile and the low demands on the support measures (deformations < 20 mm). The feared water ingress in the Mesozoic sediments failed to occur. The drive towards the south gained a considerable time advantage amounting to more than a year vis-à-vis the contractual time schedule.

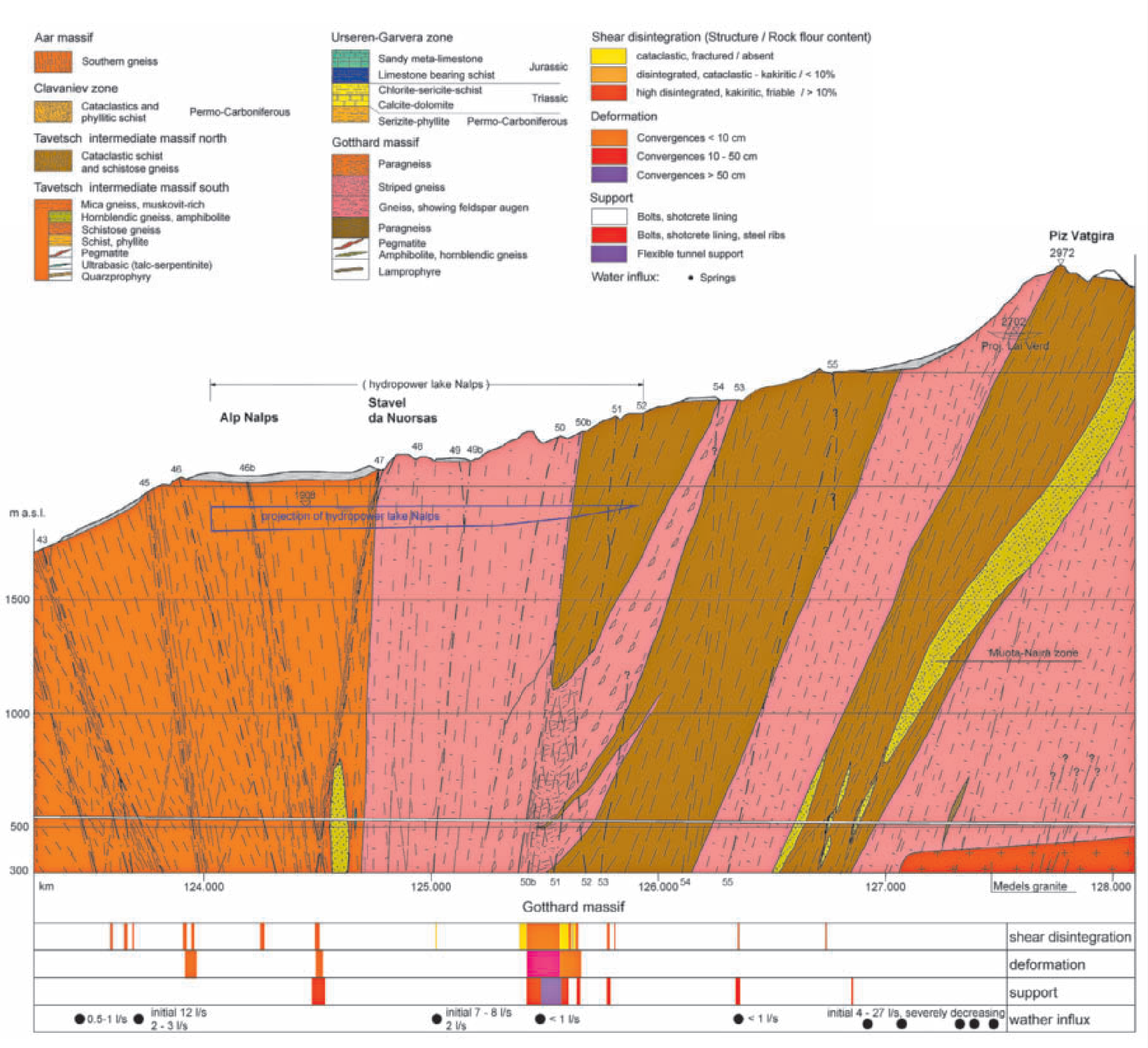
5 GOTTHARD MASSIF

The Gotthard massif (see ▶**Fig. 3**) in the Sedrun section is divided up into gneiss units in accordance with the prognosis. These are separated by schistose-phyllitic fault zones. The major proportion involves pre-Cambrian poly-metamorphic and Palaeozoic bi-metamorphic paragneisses and typical orthogneisses. Along the fault zones, the gneisses are sheared and fractured. Squeezing rock conditions and high initial flow rates of 2 l/s to 130 l/s were forecast for the Gotthard massif's fault zones. The gneisses themselves were defined as favourable for the excavation. It was felt that a higher degree of support would be required in order to master the tricky faults. It appeared likely in the northern Gotthard massif that the drives for the single-track tunnels and the associated rock drainage could lead to surface deformations, extending to the Curnera and Nalps arch dams (see VIII 10 "Groundwater inflows into the Gotthard Base Tunnel and hydromechanically coupled deformations in the Gotthard massif").

As expected para- and orthogneisses predominated in the Gotthard massif (see ▶**Fig. 3**). The most important secondary rock is amphibolites. A total of 96 % of the route penetrating the Gotthard massif is made up of these three types of rocks. schistous gneisses or schits are of subordinate significance. All other rocks mainly occur in fault zones (schists to phyllites, fractured cataclastic gneisses and schits, fault gouges). The maximum measured initial flow rate amounted to 27 l/s with short-term peaks of up to 37 l/s. The total discharge from the two single-track tunnels exceeded a maximum of 60 l/s in a short period. When stationary after driving was concluded, the incidence was less than 30 l/s. The amounts of underground water were clearly overrated in the prognosis.

The Gotthard massif's gneiss sections, which were assessed as being favourable in terms of construction, corresponded well with the expectations. The single-track tunnels could be secured by means of the intended support measures (rock bolts, steel fibre shotcrete). Approximately 20 fault zones of slight to major technical relevance permeate the technically favourable gneisses. Most of them dip steeply and intersect the tunnel axis more or less perpendicularly. The expected deformations, however, only rarely occurred (▶**Fig. 3**). Instead, frequently unconsolidated behaviour was observed. In some cases, a bolting system and steel fibre shotcrete sufficed to master the fault zones; in others, the installation of a steel sets and a spile umbrella were required. Usually the face needed additional supporting by means of a bolting system and steel fibre shotcrete after each round of advance. Several cave-ins confirmed the technical relevance of the fault zones. The squeezing fault zone 50b (chainage 125.422–125.570 km) turned out to be trickier than expected, where deformable steel sets with large excavated cross-sections had to be installed over a section exceeding 130 m on account of extreme deformations (maximum 95 cm radially, with 130 cm floor heaves). Widely, the strongly increasing deformation in the fault zone revealed a correlation with the high proportion of cataclastic and kakiritic rocks (see ▶ **Table 2**) and the unfavourable schistosity orientation (<30° to tunnel axis, see ▶ **Fig. 3**). The overburden (roughly 1,700 m ASL) and the underground water pressure (anticipated around 170 bar, measured at 100 bar during exploration) were already very high. The small-scale changing deformation behaviour was presumably influenced by local differences in strength and varying pore-water pressure reduction in the poor and heterogeneous permeable rocks. The fault zone 50b (see ▶ **Fig. 3**) was ultimately excavated through successfully using the contractual support and ancillary construction measures. At the same time, a considerable delay in the driving schedule had to be accepted.

In this connection, it must be mentioned that the fault zone 50b in the west tunnel should have been tackled by the Faido tunnel boring machine without deploying the extension to the contract section or delays to the construction programme in Sedrun. The ingress of water in the fault zones represents a significant discrepancy from the prognosis: the tunnel was generally a great deal drier than forecast. However, this turned out to be a boon for driving and for influencing the Nalps reservoir.



▶ **Fig. 3** *Geological longitudinal cross section at Sedrun south (Gotthard massif)*

Credit: [19]

The predicted surface deformations occurred in spite of the low ingress of water. Ultimately, an extensive injection campaign to waterproof the water-bearing fault zone 44 (chainage 223.713 km) was necessary.

6 SUMMARY

The Sedrun section was considered technically as the trickiest section of the entire GBT in the construction project phase, after the conclusion of the exploratory work on the Piora zone in the Faido section. Extensive exploratory campaigns enabled a well-founded ground model to be produced for the entire north drive and the MFS area. During the drive, a very good correlation was determined between the prognosis and the findings. The north drive was accomplished more rapidly than agreed in the contract thanks to the project being well geared to these conditions and a well-attuned team on-site.

In the south drive, the prognosis certainty was less secure as the ground model had to be compiled based on the surface outcrops. This led to greater uncertainties in the prognosis owing to the major overburden exceeding 2,000 m. The effects of these uncertainties were then also felt.

Firstly, the Urseren-Garvera zone, classified as technically tricky, was encountered substantially further to the south, covering a smaller area and revealing more favourable behaviour in terms of construction. This led to a whole year being gained in the construction process within a short time. This advantage prompted the client to relocate the boundary limit to the neighbouring Faido section towards the south. Scarcely had this been commissioned, when conditions prevailed in the fault zone 50b which turned out to be considerably less favourable than forecast. As a result, a substantial portion of the time that had been gained had to be used for mastering this 148 m long section. Nonetheless, the drive over the contractual boundaries originally agreed upon was still able to take place within the course of a year.

All told, the Sedrun section turned out to be extremely complex owing to the variability of the ground conditions. However, these conditions were tackled well so that additional drives that assured deadlines would be adhered to could be initiated from Sedrun, which ultimately assured commissioning in 2016. ✚

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