TUNNELLING NEAR THE SAN PELLEGRINO THERMAL SPRINGS (ITALY)
Creusement de tunnels près de la source thermale de San Pellegrino Terme (Italie)
Die Grabung eines Straßentunnels in der Nähe der Thermalquellen San Pellegrino (Italien)

G. Barla, Department of Structural Engineering, Politecnico di Torino, Italy
M. Naldi, Geodes, Torino, Italy

ABSTRACT: This paper considers the studies carried out to assess the geological, hydrogeological and rock mass conditions along the alignment of two tunnels to be excavated near the commercially exploited San Pellegrino thermal springs. The predictions made through an extensive investigation programme carried out in advance of tunnelling are described and compared with those obtained during the TBM excavation of a pilot tunnel. Considerations are also reported on the second, widening to full size, phase of tunnelling.

RESUME: Ce texte donne une description des études effectués afin d'évaluer les conditions géologiques et hydrogéologiques du massif rocheux le long deux tunnels qui seront excavés dans une zone près de l'exploitée source thermale de San Pellegrino Terme (Italie). Les prévisions envisagées à travers un programme d'investigations effectué avant le creusement de tunnels, sont décrites et comparées avec les données obtenues pendant l'excavation du tunnel pilote avec tunnelier. Les considérations sur la deuxième phase d'agrandissement jusqu'à la section finale des tunnels sont également exposées.

ZUSAMMENFASSUNG: Dieser Artikel beschreibt die Studien, die zur Definition der geologischen und hydrogeologischen Situation sowie des Zustands der Felsmassen durchgeführt wurden, die längs der beiden kommerziell genutzten Tunnel in der Nähe der Thermalquellen San Pellegrino liegen. Die Vorab-Anlayse basiert auf großangelegten Untersuchungen, die vor der Grabung der Tunnel durchgeführt wurden und dann mit der Ergebnissen der Grabung eines Pilotstollens verglichen wurden, der mit einer TBM-Fräse hergestellt worden war. Außerdem werden Betrachtungen zur zweiten Phase der Verbreiterung der Tunnel angestellt.

1. INTRODUCTION

The prediction of the geological and hydrogeological conditions associated to underground civil works is of primary importance when facing the need of groundwater protection. In such a context, the present paper considers the influence of the excavation of two tunnels on the San Pellegrino thermal springs, which are located along the right flank of the valley of the river Brembo, adjacent to the town of San Pellegrino Terme (Italy).

Because of some concern of the San Pellegrino company about the possible effects of tunnelling on the commercially exploited thermal springs in the area (San Pellegrino and Pracastello springs), an extensive investigation programme has been carried out (deep boreholes drilling, geophysical investigations, geological mapping) to define the geological, hydrogeological, and geotechnical conditions. A numerical model based on the Finite Element Method (FEM) was also created to provide insights on the groundwater problem.

As an additional precaution, a TBM pilot tunnel (3.9 m diameter) has been excavated, in advance of full excavation, to investigate rock conditions along the line of the tunnel and minimise the small risk that tunnelling will interfere with the hydrogeological regime of the area. More in detail, the scope of the pilot tunnel has been as follows:

⇒ to determine the geological and rock mass conditions along the tunnel alignment

⇒ to consider the applicability of a tunnel boring machine to the excavation of the final tunnel section.

The results obtained with the excavation of the pilot tunnel compare well with predictions, both in terms of absence of any influence on the thermal springs and for the rock mass conditions along the tunnel axis. Nevertheless, to minimise any risk of damage to the springs, for the final section enlargement a 12 m diameter TBM has been adopted. The excavation is now underway and is anticipated to be completed in 1997.

2. BACKGROUND

The two tunnels to be excavated are to allow for the realignment of the road which currently passes through the town of San Pellegrino Terme (Figure 1). The required cross sectional area of the road tunnel is approximately 90 m^2, and the total length of the tunnels will be 2.4 kilometres. The longer of the two tunnels will be the Frasnadello tunnel, with a length of 1,700 m. The Antea tunnel will be about 650 m long. The north end of Frasnadello and the

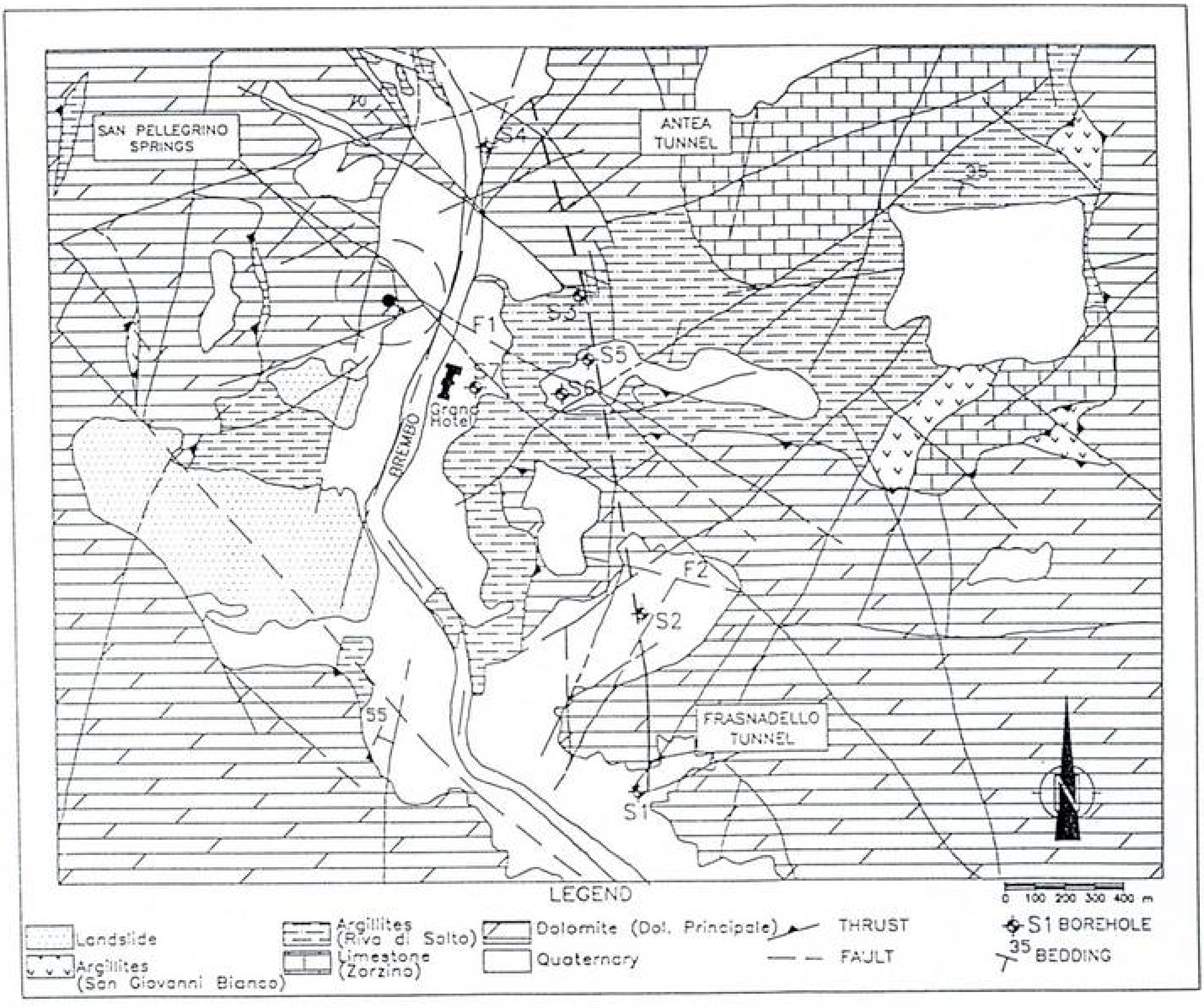

Figure 1 - Geological map.

south end of Antea will be on opposite sides of a narrow valley (Sambusso valley), and a bridge will link them together.

The geology of the San Pellegrino area is quite complex, as a result of the intense alpine deformations (Figure 1). The bedrock consists of a succession dating from Carnian (Lower Triassic) to Norian-Rhaetian (Upper Triassic). The base of the Carnian is represented by fluvial and deltaic sandstone (Valsabbia Formation), eterophic with marly limestone (Gorno Formation). The top of the Carnian is represented by the San Giovanni Bianco Formation, which consists of siltstone and mudstone with overlying lenses of gypsum. The stratigraphic contact between Carnian and Norian is outlined by the Castro Formation (limestone). The massive dolomite forms the high ground of the area, with steep rock slopes.

The main tectonic feature is the Antea fault, which runs from the town of San Pellegrino Terme to the Antea village (north-eastward of San Pellegrino) and divides the Carnian rocks and the Norian-Rethian ones in two tectonic blocks: to the north, outcrop the Carnian units, while the Norian-Raethian units (duplicated by numerous thrust faults) outcrop to the south. In such a context, the investigated area represents a small tectonic window created by a series of thrusts. The Riva di Solto argillites are exposed in the bed of the Brembo River and are thrusted over the Dolomia Principale.

From the structural point of view, three fault systems can be distinguished, orientated N-S (strike slip faults), NW-SE and NE-SW (respectively with the throw normal and reversed). These lineaments follow the tectonic event responsible for the thrusting which further separates the structure of the area into wedges and blocks.

3. GEOLOGICAL AND HYDROGEOLOGICAL CONDITIONS

3.1 Geological Conditions

The geological conditions along the tunnel alignment have been assessed by:

⇒ detailed geological mapping

⇒ geophysical investigations

⇒ borehole drilling.

The geological mapping (the results obtained are shown on the geological sketch of Figure 1) indicates that the Frasnadello tunnel is to be excavated through a sequence of dolomites and limestones thrusted over a sequence of marls and argillites. The Antea tunnel is excavated entirely through dolomites. The mapping shows that the area is affected by significant faulting and thrusting. Some of these faults (faults F1 and F2 in Figure 1) run westward to border the tectonic wedge of the San Pellegrino spring.

In order to investigate the geological conditions along the tunnel alignment, seven boreholes have been drilled. The distribution of these boreholes was defined with emphasis given to the hydrogeological investigation, however keeping in mind the purpose of classifying the rock conditions to be encountered during tunnelling. The main lithological units along the boreholes (with depth ranging from 100 to 430 m) are listed below.

Borehole	Depth (m)	Lithology
S1	0.0-82.4	Black dolomite
	82.4-99.6	Castro limestone
	99.6-105.5	Thrust gauge
S2	0.0-136.0	Zorzino limestone
	136.0-150	R. di Solto argillite
S3	0.0-19.8	R. di Solto argillite
	19.8-301.7	Massive dolomite
S4	0.0-204.0	Massive dolomite
	204.0-281.0	Fault gauge
	281.0-409.0	Gypsum
S5	0.0-173.0	R. di Solto argillite
S6	0.0-230.0	R. di Solto argillite
S7	0.0-360.0	R. di Solto argillite
	360.0-370.0	Massive dolomite

As the groundwater flow is fault controlled, and the tunnel is expected to be driven through the F1 and F2 faults (in some way connected to the San Pellegrino tectonic wedge), a detailed geophysical investigation has been performed to determine the presence, the position and the attitude of the faults and to ascertain whether the faults contained or acted as transmission paths for water (particularly mineralised water).

Both VLF and geo-electric surveys have been carried out along the Frasnadello tunnel (the ground conditions above the Antea tunnel did not allow to perform these investigations). The main purpose was to detect the relative conductivity of the natural conductors (faults). The results of the geophysical investigations have confirmed the position of most of the faults recognised with geological mapping. The detected faults (with attitude determined mainly on the basis of the VLF anomalies) resulted to be dry, with no or minor water content.

Based on the site studies described above the geological section of Figure 2 (*Prediction*) was derived. Also reported in the same Figure 2 is the geological section as revised following the excavation of the TBM pilot tunnel (*Pilot Tunnel Results*).

As shown, from south to north the Frasnadello tunnel has been excavated through the dolomite/limestone sequence (up to chainage 350 m), thrusted over the argillite/marl sequence. The Antea tunnel has been excavated entirely in a tectonic block of dolomite.

The contact between the argillite/marl sequence and the Antea dolomite block is tectonic, with a fault along the Sambusso valley which has down thrown the argillitic sequence. In the northern edge of the Antea tunnel, down to a depth of about 300 m, the borehole S4 has encountered gypsum of the San Giovanni Bianco Formation.

The comparison of prediction and actual conditions based on the pilot tunnel results shows that the main differences are mostly linked to the dip of the major faults, less inclined than predicted.

3.2 Hydrogeological Conditions

To find out under which conditions the Frasnadello and Antea tunnels could affect the discharge of the Pracastello and San Pellegrino thermal springs, a hydrogeologic study has been performed, including:

⇒ precipitation analysis

⇒ spring mapping and analysis of spring discharge at San Pellegrino

⇒ analysis of groundwater chemistry of springs

⇒ modelling of groundwater flow.

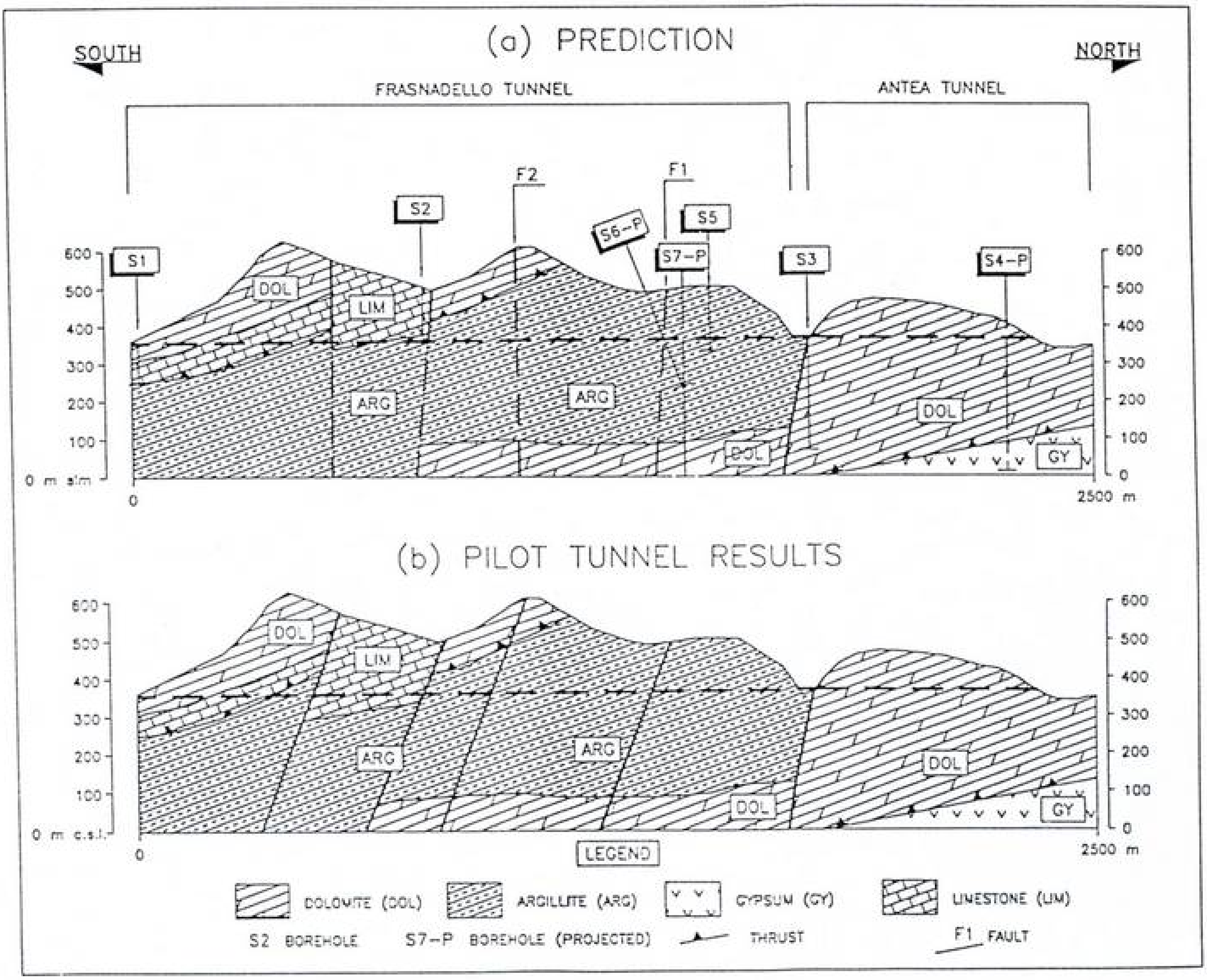

Figure 2 - Geological sections along tunnel axis.

- **Precipitation**

The precipitation station in the vicinity of San Pellegrino Terme is located at the San Pellegrino spring at 360 m above sea level. Due to the great variations in topography, with the highest hills over 1000 m above sea level, it is likely that the measured precipitation at San Pellegrino Terme is lower than the precipitation representative for the infiltration areas.

Data available from 1921 to 1995 show a mean year precipitation of 1558 mm, with a minimum of 863 mm and a maximum of 2416 mm. The maximum monthly precipitation occurs in April or May, when it often exceeds 300 mm. The lowest precipitation occurs in winter, from November to February, when it is often less than 10 mm per month.

- **Spring characterisation**

The San Pellegrino area offers many examples of springs, due to the occurrence of permeable rocks (limestones, dolomites) and impermeable rocks (marls, argillites) which create many occasions of water traps.

The groundwater flows mainly into the dolomite/limestone aquifers, and the water flows out from the springs mainly in two ways:

1. if the dolomite is thrusted over the argillites, the aquifer is suspended and the water is generally cold and low mineralised;
2. If the dolomite is deeply rooted, the groundwater which circulates in the fracture system is forced to rise up, when encountering an impermeable barrier (a fault or a vertical contact with the argillite or marl rock units). In such a case the water is often warm and mineralised, due respectively to the geothermal gradient and to the dissolution of gypsum (belonging to the San Giovanni Bianco Formation).

The San Pellegrino and Pracastello springs belong to the second spring type. Both the springs are located in a tectonic wedge of dolomite surrounded by argillite, which acts as a trap for the deep water. The flow of the water is fault controlled.

The discharge of the San Pellegrino spring has been measured from 1983 to 1991 (the Pracastello spring has been replaced by a well). The measured spring discharge shows high and immediate increase after heavy rains; however, the reaction due to precipitation is quite complex and sometimes with no apparent correlation. This could be due both to the complexity of the groundwater system as well as to the lack of representativeness of the precipitation measured close to the spring (and not in the infiltration area). In any case, the discharge of the San Pellegrino spring ranges from 2.8 and 14.0 l/s, with a mean value of 8.9 l/s.

- **Groundwater chemistry**

Waters from twenty springs and wells have been sampled and analysed. The samples have been divided into four groups with respect to their chemical composition and temperature, as listed below.

Type	T°C	Na (mg/l)	Cl (mg/l)	Ca (mg/l)	SO_4 (mg/l)
I	10÷12	4÷9	8÷33	529÷593	1230÷1766
II	18.5÷26.3	19÷41	39÷71	137÷208	295÷539
III	9÷10	1÷6	1-3	80÷120	46÷156
IV	9÷13	0.5÷3	1÷5	39÷76	7÷21

The Type I water (water in gypsum formations) has a low temperature, medium content of Na and Cl, very high content of Ca and SO_4. The Type II water (thermal water) has a medium temperature (up to 26°C), high Na and Cl content, high content of Ca and SO_4. The Type III water (superficial groundwater in limestone/mudstone) has a low temperature, low content of Na and Cl, low content of Ca and SO_4. The Type IV water (superficial water in dolomite) has a low temperature, low content of Na and Cl, low content of Ca and SO_4.

The springs of the Type II water (thermal springs) show an appreciable difference in chemistry which could be due to different mixing proportions between a deep mineralised water and a non-mineralised shallow groundwater. The mixing proportions between the deep thermal water and the shallow groundwater have been back-calculated from the known temperatures of water in the thermal springs. It is shown that the San Pellegrino spring is characterized by the following mixing proportions ([1]):

- 81% of deep water with a temperature of 30°C;
- 53% of deep water with a temperature of 40°C;
- 39% of deep water with a temperature of 50°C°.

(1) G. Barla et Al., 1995 : "La previsione e la prevenzione del rischio di interferenza con acque sotterranee durante lo scavo di una galleria", Atti del II° Convegno sulla protezione delle acque sotterranee, Ed. Pitagora, Bologna.

- **Groundwater modelling**

The objective of the hydrogeological modelling study performed has been to evaluate the potential impact of the Antea and Frasnadello tunnels on the spring discharge at San Pellegrino for various possible hydrogeological scenarios. The general assumptions for modelling purposes were as follows:

1. the aquifer of the thermal water is the dolomite/limestone complex;
2. the mineralisation occurs for dissolution of gypsum;
3. the water temperature is closely linked to the geothermal gradient;
4. the main groundwater flow occurs through a complex network of vertical and horizontal faults;
5. the groundwater flow within faults and fractures in the rock mass takes place through channels developed by dissolution of the calcareous rock matrix; the hydraulic conductivity is very high along the karstified fractures and faults and low or very low in the intact rock mass. The domain is discontinuous and largely channelled, with a rapid groundwater flow in the main discontinuities and a slow/very slow flow in the intact or poor fractured rock mass.

The results of modelling for different scenarios (see Figure 3 for a typical plot) based on the flow direction (only from west, only from east, both from east and west) gave no influence of the Frasnadello tunnel on the thermal springs. The pilot tunnel has confirmed the prediction:

1. no effects have been recorded at the San Pellegrino spring discharge;
2. only shallow waters (type IV) have been encountered during the excavation (at the south portal of the Antea tunnel and at chainage 135 m in the Frasnadello tunnel).

4. ROCK MASS CONDITIONS

4.1 Summary classification

In addition to hydrogeological and geological studies as described above, the results of core drilling at various points along the route, integrated with laboratory testing of the mechanical properties of the various rock types encountered, have been considered along with all the other available data in order to proceed first to classify and characterize the rock mass through which the tunnels will pass.

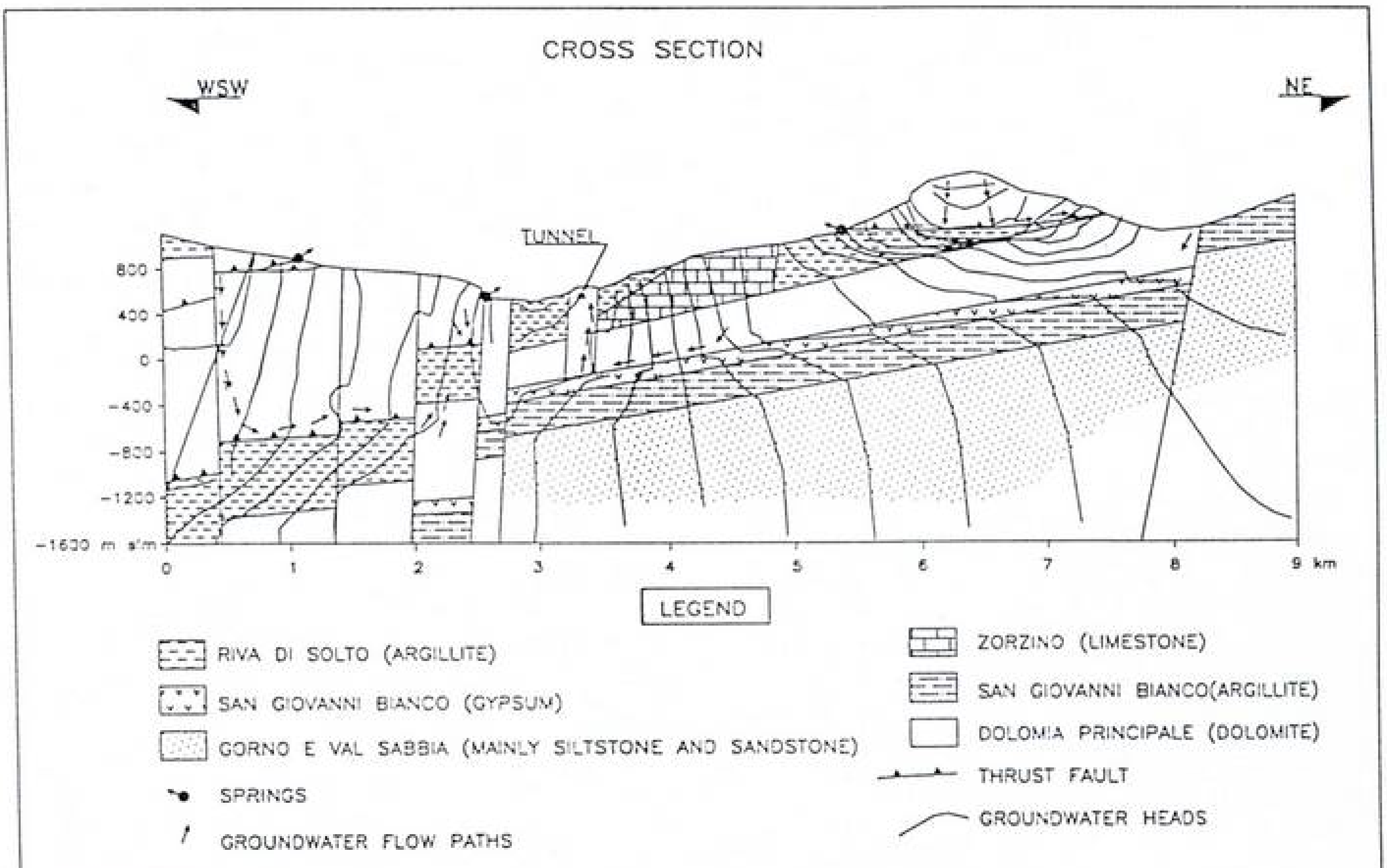

Figure 3 - Groundwater modelling. Example of a typical plot.

On the basis of the foregoing investigations, a summary classification of typical rock mass conditions for each type of rock has been assessed as presented in Table 1, with estimates of the typical intact rock strength (UCS), RQD's, and RMR's appropriate to each.

Rock type	Chainage (m)	UCS (Mpa)	RQD (%)	RMR
Fractured Black Dolomite	0→100	20/40	0/40	20/40
Black Dolomite	100→200	20/80	40/80	40/80
Castro Limestone	200→350	40/100	60/90	50/70
Thrust Zone	350→370	0/60	-	-
Zorzino Limestone	370→500	100/200	60/90	60/80
Marly Argillite	500→700	20/50	30/80	40/60
Argillite	700→1700	60/120	40/80	40/70
Massive Dolomite	0→600	100/250	60/100	70/90

Table 1 - Preliminary rock mass classification

With reference to the geological section along the tunnel alignment as shown in Figure 1a, where the location and extent of each of the rock type is given as anticipated, the rock mass conditions have been described as follows.

1. The Black Dolomite unit (silty and/or breccia dolomite), encountered in the southern portal face of the Frasnadello tunnel, will continue for a distance of approximately 200 m. Initially, this will be heavily fractured but this condition may improve with depth in the hill side, such that the characteristics of the rock mass may change significantly.
2. Beyond the Black Dolomite, two underlying limestones are anticipated. These are the Castro Limestone, which belongs stratigraphically to the Black Dolomite unit, and the Zorzino Limestone, which belongs to a separate unit. It is anticipated that the two limestones will be encountered either side of a major, ancient, low angle thrust. The significance of this for tunnelling deserves its classification as a separate zone, despite its limited extent. The presence of both limestones along the tunnel line is open to interpretation, depending on the local behaviour of the thrust.
3. Beyond the Zorzino Limestone, a thick unit of silty argillite will be encountered. The upper levels of this unit are a marly argillite. This is a significantly weaker than the underlying argillite. Both types of argillite contain siltier layers and occasional conglomerate or limestone bands. Typically, up to three zones of each may be encountered, over a total distance of approximately one kilometre.
4. Massive Dolomite will be encountered in the Antea tunnel over its entire length, and as a faulted contact with the argillite rocks in the valley between the two tunnels. The available data all indicate this rock mass to be of good to very good quality.

4.2 Pilot tunnel excavation

As anticipated in the foregoing section, because of the concern that tunnelling could affect the hydrogeological regime adjacent to the San Pellegrino mineral water springs, and independent of the reassuring results of the geological and hydrogeological investigations, the initial excavation of the tunnel took the form of a pilot tunnel (3.9 m diameter) excavated with a tunnel boring machine (TBM).

In general , the alignment and profile of the tunnel and the anticipated rock conditions have been estimated to be well suited to excavation with a TBM. For all the rock types to be encountered, the intact rock strengths have been assessed to be within the range that can be efficiently cut by a modern TBM, including the strongest rock unit, i.e. massive dolomite.

Given the uncertainty on the conditions of the thrust zone and the importance of the F1 and F2 faults in relation to the San Pellegrino tectonic wedge, probe drilling ahead of the face has been carried out during tunnelling. For the majority of the rock mass conditions summarized in Table 1, adequate temporary support has been obtained by the use of metal plates and/or light steel sets, where needed.

Geotechnical mapping has been carried out during the excavation of the pilot tunnel. The results obtained are summarized in Figure 4 where the distribution of the RMR and Q indices along the tunnel

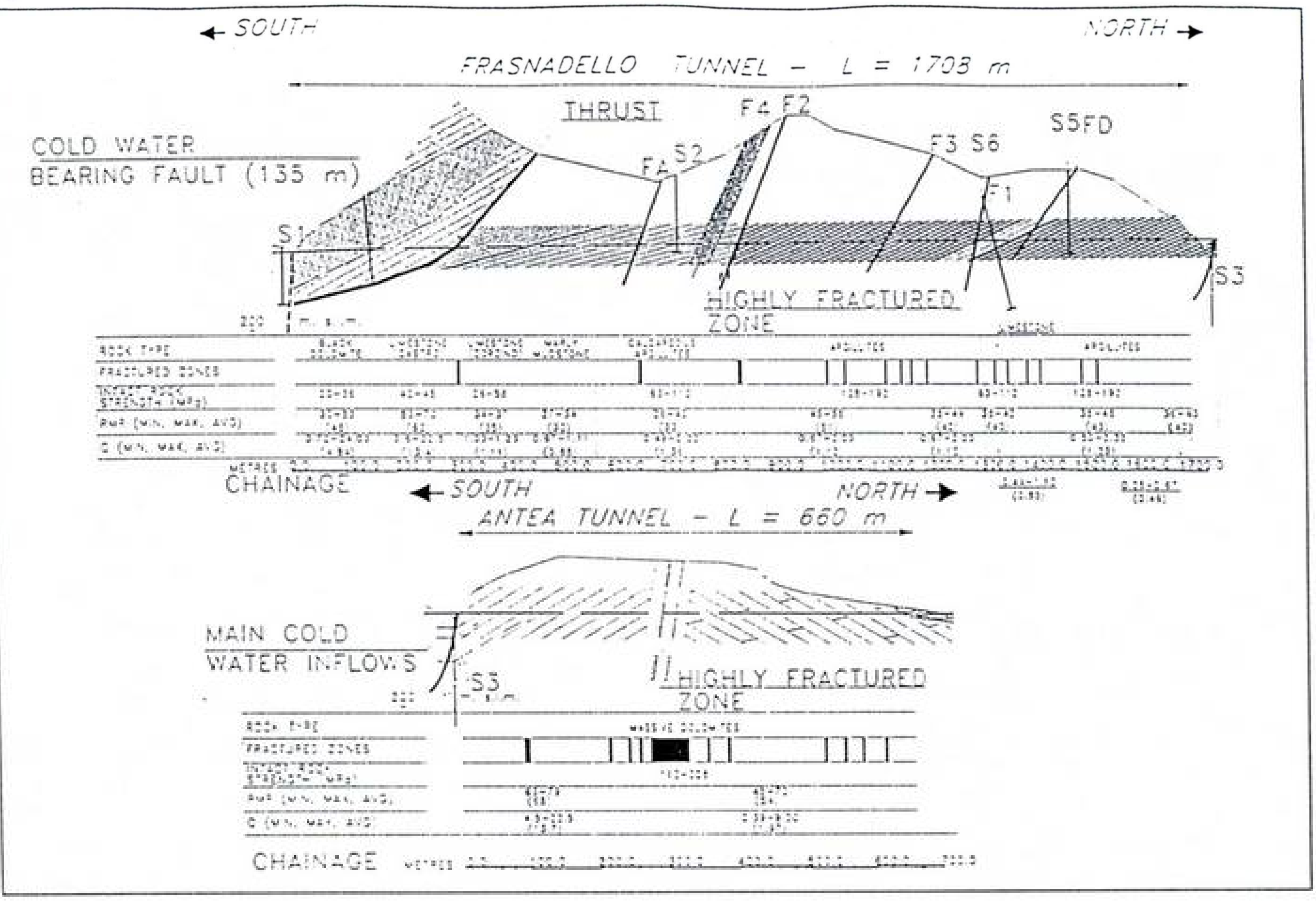

Figure 4 - Rock mass conditions along the pilot tunnels as mapped during TBM excavation

alignment are illustrated for the various rock types encountered.

It is shown that the rock mass conditions mapped along the tunnel length compare satisfactorily with those predicted. Figure 4 presents as well the most significantly fractured rocks in the vicinity of the faults. It can therefore be stated that in addition to objective predictions of the geological and hydrogeological conditions, also the rock mass conditions have been found to be as anticipated.

5. DISCUSSION AND CONCLUSIONS

With the pilot tunnel completed successfully, consideration has been given to the possibility of enlarging the tunnel to full size by means of a mechanical excavation technique for tunnelling as opposed to the conventional use of drilling and blasting.

Whereas the TBM excavation of the fair to very good quality rocks encountered in both tunnels revealed to be very satisfactory, careful consideration was required to predict cutting performance of boom mounted cutters and to assess the suitability of excavation by means of a road header for the second, widening to full size, phase of tunnelling.

Comprehensive studies were carried out on the intact strength of the rock, the energy required to cut it, the numbers of discontinuities present in the rock mass, and the abrasivity of the rock. As a result the excavation by a heavy weight road header was evaluated to be reasonably efficient in the fractured black dolomite and in the marly argillite section of the tunnel.

It was however clear that a road header was in all respect unsuitable for excavation of the massive dolomite and limestone. Therefore, drilling and blasting would be a necessity for the second phase of excavation of these rocks. In addition, in the argillite sections the excavation by road header was considered to be significantly less efficient than is generally desirable for this method of excavation.

Due to the concern of possible effects of blasting on the exploited thermal springs in the area, as an extra precaution, also considering the availability of an existing machine which could be utilized for the job, it was finally decided to excavate the tunnel to full size by a 12 m diameter TBM.