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THE INSTITUTION OF MINING AND METALLURGY

FRÉJUS MOTORWAY TUNNEL: ITALIAN SIDE

Fréjus motorway tunnel: Italian side

L. Canobbio Dr. Eng.
Società Italiana Traforo Fréjus – SITAF, Turin, Italy

U. Scavia Geometra
Società Italiana Traforo Fréjus – SITAF, Turin, Italy

P. Lunardi Prof. Eng.
Consorzio Traforo Fréjus – CTF, Bardonecchia, Italy

L. Stragiotti Prof. Eng.
Istituto di Arte Mineraria, Politecnico di Torino, Turin, Italy

S. Pelizza Prof. Eng.
Politecnico di Torino, Turin, Italy

Synopsis
Brief comment on the Fréjus motorway tunnel in regard to the European road system precedes a detailed description of the most important technical features of the work, together with essential notes on geological and lithological aspects.

The basic equipment for the excavation (use of explosives with a full-face technique) is described, the organization and development of the works are illustrated and an account is given of the most important technical data with regard to the operations and the materials consumed.

Finally, the tests and controls both at the design and in the excavation stages for the geomechanical studies of the rock mass and the underground water and rock temperature are presented with analyses of data on the physical characteristics of the rock and the results of the *in-situ* tests relating to convergence, rock dilatation and rockbolt strain measurement.

The Fréjus motorway tunnel will link Turin in Italy with Lyon in France along the most direct and obvious route, i.e. by means of roads in the Susa and Maurienne valleys, crossing the Alps at an average height of 1250 m above sea-level. The Mont Cenis road, together with the Monginevro, were the most important connecting roads between Italy and France before the opening of the Mont Blanc tunnel, notwithstanding traffic restrictions during a large part of the year. The Fréjus motorway tunnel will strengthen the natural links between two important economic centres – the Rhône–Alpes departments and the Po valley, enhancing the development of exchanges between these areas, which lie on international route E13. The road will be passable throughout the year from Brest to Venice, touching Lyon, Turin and Milan.

Characteristics of the work

The layout and the technical details of the work are shown in Fig. 1 and Table 1.

LAYOUT AND CROSS-SECTION OF TUNNEL

The Fréjus tunnel links two almost parallel valleys that are about 13 km apart – the Arc valley in France and the Rochemolles valley in Italy. The portal at the French side (north) is in the Rieu-Sec deep valley at 1227 m above sea-level, whereas on the Italian side (south) the mouth of the tunnel opens at 1296 m above sea-level on the west side of the Rochemolles valley.

The ultimate layout of the tunnel was decided after detailed studies had been carried out that related to several significant factors that affected the geological appraisal of different possible locations for the portals (especially on the French side), the most favourable emplacement with regard to the access roads, the position of the air shafts, for which the most economical solution (in the broadest sense) had to be found, and, finally, the existing railroad tunnel between Modane and Bardonecchia. This last factor was of no small significance in view of the geological knowledge, cautiously applied, that it could contribute.

The plan of the layout was chosen by the Italian and French staff after examination, discussion and rejection of seven alternative layouts.

The vertical section shows a constant grade of 0.54%, dipping towards the French side. It was possible to adopt a constant grade layout because of the small water inflow from the rock, based on what was known from the railroad tunnel construction and confirmed by observations during the excavation.

The total length of the tunnel (the layout had to be modified during the excavation because of the decision to bore a vertical shaft, rather than the inclined shaft intended, on the French side) is 12 895 m, including the cut and cover sections (amounting to 26.80 m on the French side and 34.80 m on the Italian). The Fréjus tunnel will be a two-lane tunnel (single-lane each way) with a cumulative useful width of 9 m (including the two sidewalks, each 0.5 m wide), which allows two-way transit when one lane is obstructed. The tunnel height, again selected after careful investigation, that was adopted was 4.5 m – in agreement with existing Alpine tunnels.

The tunnel includes five enlargements of the cross-section of 2 m x 40 m, to allow for vehicles to reverse: two of these are located at the point where the tunnel branches to the ventilation underground stations.

VENTILATION

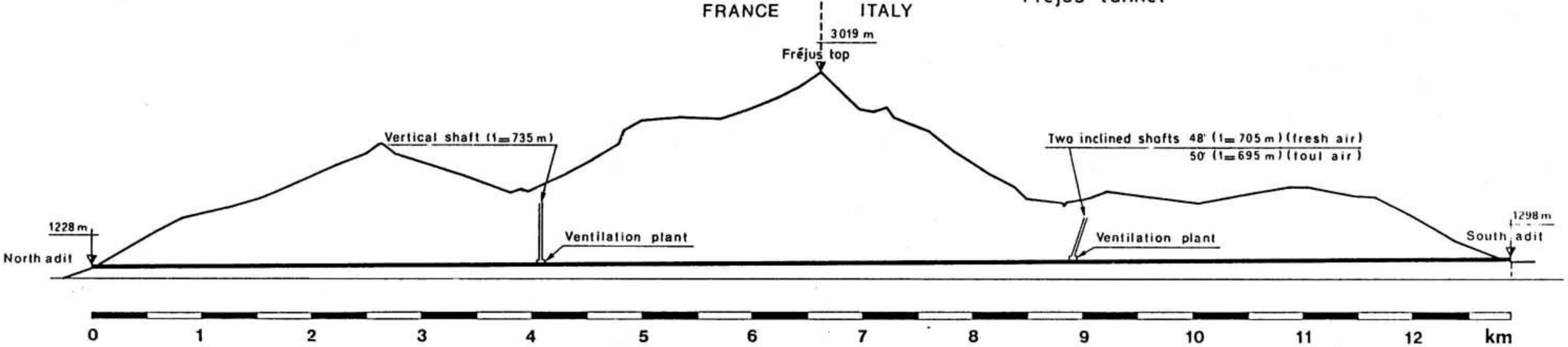
The tunnel (Fig. 1) is divided into six ventilation sections, of average length 2140 m, fed by six ventilation stations; two stations are located above ground and two twin underground stations are linked by ventilation shafts to the surface. The ventilation scheme will be of the pseudo-transverse type, with fresh air inlets that are spaced 9 m apart, via openings in the roof on the east side.

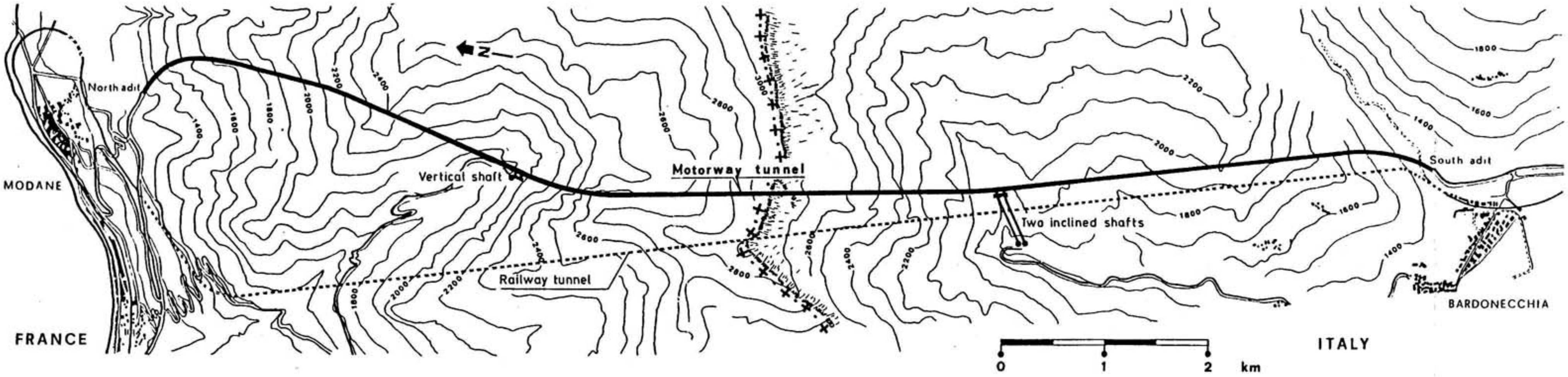
Every ventilation station is fitted with horizontal, variable-pitch axial fans that permit the continuous regulation of air flow.

GEOLOGY

The rocks crossed by the tunnel axis are, from north to south, limestones, dolomites, anhydrites and 'cargneules' of Triassic age that belong to the Brianconnais complex (these rocks, fissile and strongly dipping, lie within the first 500 m of the French portal); more or less calcareous schists, marbles and foliated schists, of mid-Jurassic age, of the Piemontese complex of the 'pietre verdi' (greenstones; the remainder of the tunnel is driven through these rocks); and detrital cover, of limited extent, at the portals.

Fréjus tunnel





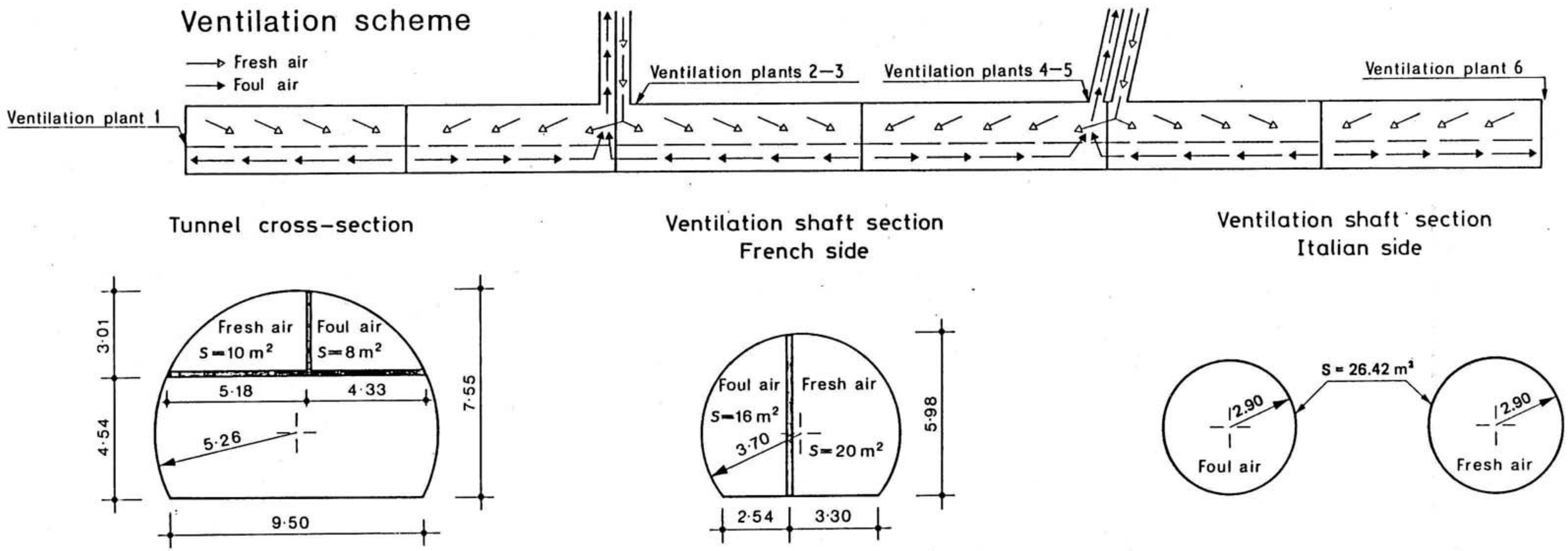


Fig. 1 Profile, layout and ventilation scheme for Fréjus motorway tunnel

The entire Italian section of the tunnel is excavated in the calcareous schist complex, which consists of alternate beds of more or less calcareous and foliated schists, intensely sheared and markedly schistose. The principal plane of the schistosity is gently dipping (5–25°) towards N15°W–N45°W.

Table 1 Dimensions of the works

Tunnel		
Total length, m		12 895
Height of portals above sea-level, m		
Italian side		1 296
French side		1 227
Grade (constant towards French side), ‰		5.4
Cross-section		
Net useful cross-section, m^2		66.25
Traffic compartment section, m^2		45.70
Air inlet section, m^2		10
Air outlet section, m^2		8
Maximum height at crown, m		7.51
Maximum, width, m		10.52
Italian side, m		6 360
Room for ventilation station at progressive distance, m		4 060
Two ventilation shafts at progressive distance, m	3 975	4 060
Ventilation station		
Length, m		101
Height in central area, m		14.40
Height in fan area, m		11.80
Maximum width, m		10
Ventilation shaft	Outlet	Inlet
Useful bore, m	5.80	5.80
Height above sea-level of base, m	1 277	1 279.50
Height above sea-level of top, m	1 765.20	1 760
Grade	$49^{c}.238$	$47^{c}.2165$
Length, m	694.25	705.00

The rock mass is more or less fractured along the tunnel axis. Three principal systems of fractures (two at an angle to the tunnel axis and one almost parallel to it) have been recognized. The schistosity of the rock and the fracture systems can give rise to loose rock prisms that cave easily and undesirable enlargements of the excavation cross-section. No water inflow is, however, associated with the fracture systems.

Construction

The works were started, on the Italian side, on 20 January, 1975, with the installation of the working facilities at Bardonecchia, and, at the time of writing (May, 1979) a total length of tunnel of 6360 m has already been excavated.

MACHINERY

When the excavation method was selected the particular geological-lithological conditions represented by the constancy of the rock type (calcareous schist) on the italian section led to serious consideration of the adoption of a tunnel-boring machine (with a three-stage cutting head). That concept, however, which has been shown to be uneconomic for the excavation of tunnels shorter than 6 or 7 km, was rejected and a conventional method of excavation with the use of explosives was adopted

Knowledge of the rock type and its soundness suggested a full-face excavation method. A large tyre-mounted jumbo drill carriage (Fig. 2) was expressly built by Atlas Copco, equipped with six heavy Atlas Copco COP 1038 MD hydraulic drills, working at a pressure of 15–25 MPa, and with an overall available power of 270 kW. The jumbo carriage has performed very well, and with a high rate of production. It is equipped with automatic devices for the alignment of the drilling arms and the layout/pattern of the contour holes.

Blasting was by means of rounds of 120 boreholes, with a diameter of 51 mm: cut holes are 4.70 m long, whereas other holes are 4.30 m long; drilling rate averages 1.5 m/min. The round was usually loaded with a dynamite-type explosive (average strength, 12.5 N/m^3), but contour holes are loaded with slim charges of Profilix 17 to obtain a smooth wall effect.

Blasted rock was loaded with an electrically powered Brøyt X 4 loader into Astra BM 22 dumper cars (capacity, 12–13 m^3). About 300 m^3/h can be handled without impairment of the working place ventilation.

At the beginning of the excavation of the Italian section detrital cover, which varied in thickness between some tens and some hundreds of metres, had to be crossed obliquely. Since the slope of the mountain lies between 55 and 60°, special care had to be taken to avoid landslides. Moreover, the preliminary tunnel lining had to be set in place simultaneously with the excavation in the loose rock to avoid caving. Steel arches (HEB), set with a spacing of 1 m and sprayed with concrete lining 35–40 cm thick, have been used.

Tunnel driving in the calcareous schists at the rate of 4 m per round has been achieved with no significant difficulty, except at distances of 650–1000 m and 3300–4700 m from the portal, where fault planes that have been rendered slippery by water were traversed. Rockbolting with expanding head bolts 4–4.5 m long, set immediately after the blasts, had to be

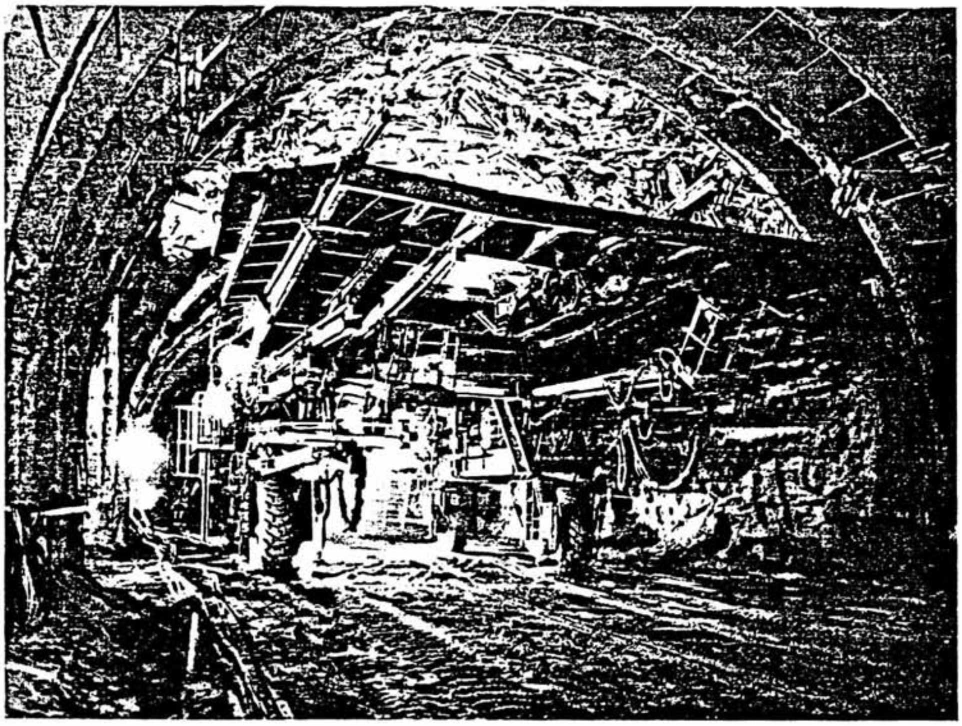


Fig. 2 · Drill carriage

supplemented in these lengths with steel arches and sprayed concrete lining of appropriate thickness. The obvious schistosity (Fig. 3) across the working face along approximately horizontal lines, confused by a closely spaced pattern of local folds, (which have a small radius of curvature and are made visible by thin bands in the schist and by calcite–quartz interbeddings), together with a closely spaced net of very frequent sliding surfaces that run almost parallel to the bedding planes, with polished sliding faces covered by a graphitic coating, caused many problems in the contour trimming. Despite all efforts in the adjustment of the blasting pattern, it was not possible to avoid significant overbreak (especially on the left abutment, where it occurred constantly, the schistosity usually running parallel to the surface of the opening). In that regard it should be emphasized that, in such a geological structural setting, the practice of immediate systematic rockbolting proved to be valuable and effective for quick stabilization of the opening, both for its elasticity (the support can follow the contours of the excavation) and for the ease of fixing of the bolts, which can be erected as the excavation progresses.

The blasting face has neither shown any sign of instability nor given rise to problems in drilling operations, though some late failure has been observed locally in the abutments as a result of the faults with sliding planes coated with graphite and water dipping towards the opening; from the 4500-m point the abutments showed, moreover, plastic flow phenomena that point to an overloading of the bearing strength limits of the rock mass because of stresses induced by the growing lithostatic pressure and the greater deformability of the rock, the frequency of the sliding planes increasing in comparison with the size of the cavity. That situation is clearly indicated by the results of the perimeter convergence measurements, which show a trend towards higher values in association with increase in the absolute roof cover.

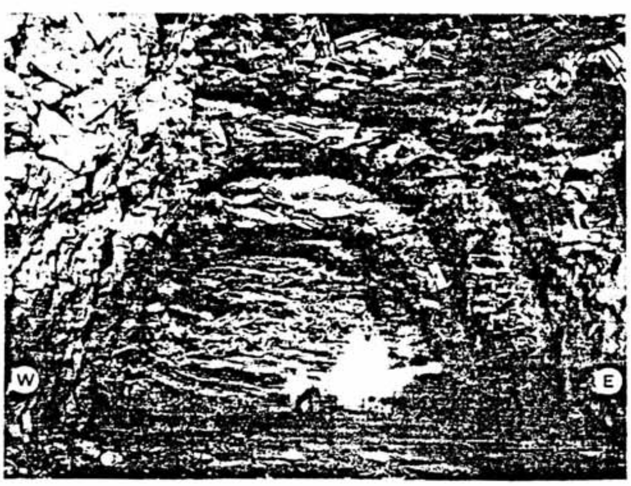


Fig. 3 Advance face (rock schistosity is readily apparent)

DEVELOPMENT OF THE WORKS

A summary of the excavation works is given in Table 2, together with data on the lining construction (Figs. 4 and 5), excavation of the ventilation station room and two inclined ventilation shafts. The ventilation station room has been excavated according to the classic procedure (Fig. 6), which entailed, first, excavation and lining of the crown of the room and, then, excavation of the bottom section and construction of the side walls. The ventilation shaft was first machine-bored (diameter, 3.02 m; Fig. 7) and then reamed out to 5.60 m.

In Table 3 the working times required by the operations performed in an excavation cycle are given. The long face-cleaning (because of the rock structure) and rockbolting times (120–130 rockbolts have to be set for a round of 4-m advance) should be noted.

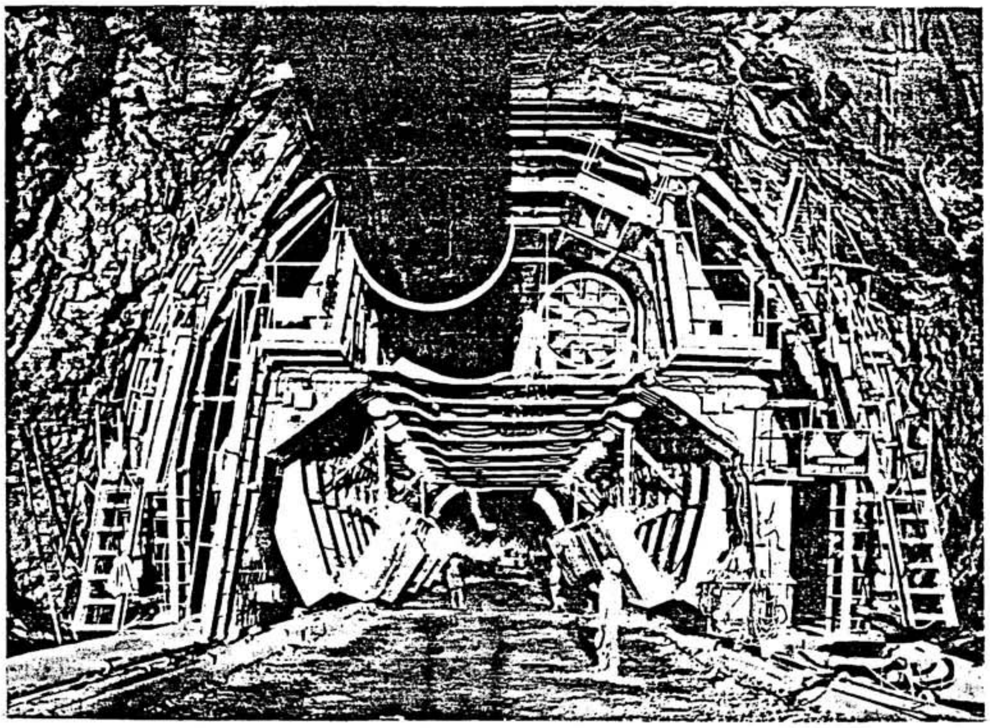


Fig. 4 Carriage for formation of lining

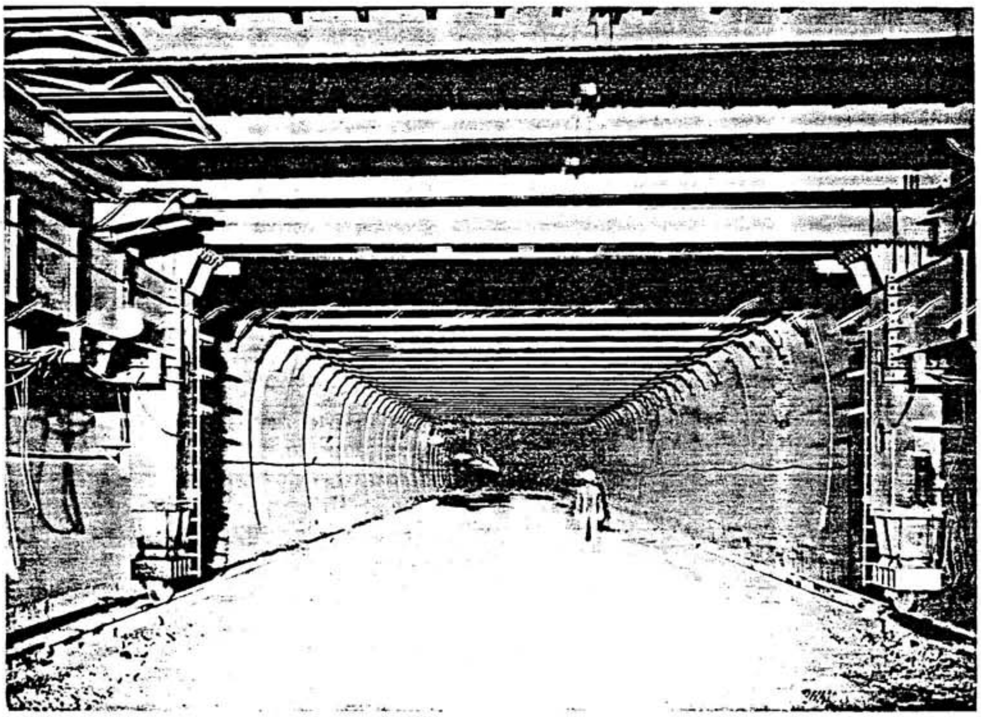


Fig. 5 Carriage for formation of roof

Tests and monitoring
An extensive series of tests and monitoring investigations (see Fig. 8) was carried out both at the design stage and as excavation progressed on geomechanical aspects of the rock mass and control of underground water and rock temperature.

GEOMECHANICAL INVESTIGATIONS
Geomechanical investigations, both in the laboratory and *in situ*, were aimed, first, at the rock characteristics, and, subsequently, at the control of behaviour of the rock and of the lining to achieve a proper design of the rockbolting pattern and of the permanent concrete lining.

From the beginning the rock was carefully tested and classified data presented in Table 4 show a fairly good compression strength, together with a marked anisotropy: the extent to which the tensile strength, the elastic modulus and the propagation velocity of the longitudinal elastic waves are affected by the orientation of the samples is apparent.

The values of these characteristics have been found to remain virtually unchanged throughout the tunnel, except for local unconformities.

Table 2 Technical data on Italian works

General data	
Manpower at 5 April, 1979	300
Daily shifts	3
Workers, underground, per shift	
Tunnel	47
Ventilation room	7
Ventilation shaft	8
Total installed power in works, kW	
In fixed plants	3300
In mobile machinery for excavation and transportation	7500
Tunnel construction work	
Progressive distances at 5 April, 1979	
Excavation (end)	6360
Side walls	6092
Lining	5891
Ceiling	5634
Invert	5612
Days worked to excavate 6360 m	980
Man-hours per m^3 excavated (face workers only)	0.6
Man-hours per m constructed (overall)	210
Average consumption per m^3	
Borehole length, m/m^3	1.35
Explosives, N/m^3	12.5
Electric power, kWh/m^3	29
Shafts excavation	
Start of works with borer, first shaft, 10 April, 1978	
Bored length at 5 April, 1979 $\phi 3.02$	1400.00
Average bored length per working day $\phi 5.80$	466.50
From 28.4 to 102 m (one shift/day)	4.63
From 102 to 225 m (two shifts/day)	2.82
From 225 to 517.50 m (three shifts/day)	8.13
Construction of ventilation station room	
Start of excavation at 22 February, 1978	
Days worked for crown excavation	37
Days worked for crown lining	30
Days worked for lower section excavation	35
Days worked for lower section lining	25

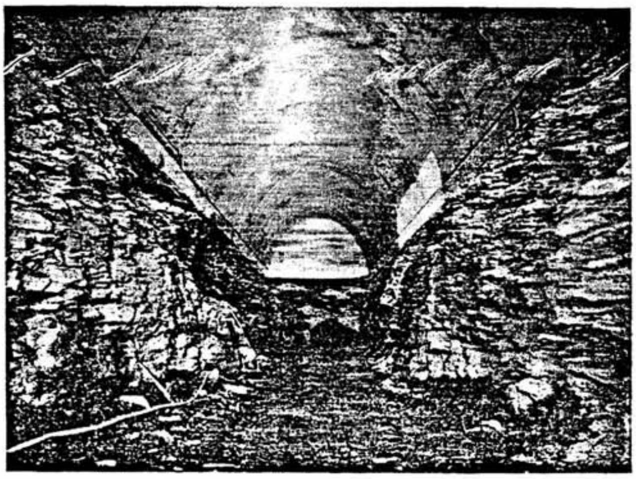


Fig. 6 Ventilation station room with side walls under construction

Seismic wave propagation tests performed continuously along the west side of the tunnel (with measurement bases of 5, 10, 15 and 20 m) showed that the values obtained from *in-situ* tests are far lower (by about one-half) than those obtained in the laboratory tests. A striking fracture effect, both natural and induced by the excavation, at least in the immediate region of the excavation, is implied.

The most interesting results, bearing in mind the practical purposes of monitoring, of the *in-situ* measurements that were carried out during the excavation were obtained from convergence, rock

Fig. 7 First ventilation shaft bored

Table 3 Typical working cycle in tunnel excavation at progressive distance 5000 m for 4-m advance per round

Operation	Time, h
Drilling	2
Borehole loading	1¼
Firing and fume clearing	½
Mucking	3
Face cleaning and mucking	1¾
Rockbolting (and other rock support work)	4
Cycle time	12½
Concrete spraying (related to working cycle; spraying discontinuous)	1½
Total time per 4 m excavated	14

dilatation and rockbolt tension measurements.

Convergence data (Fig. 9) yield, initially, further confirmation of the rock anisotropy, rock deformability being greater at angles with the schistosity. In addition, the influence of the lithostatic pressure on the deformation of the opening can be detected. Fig. 9 shows that as the excavation progresses over the section where the absolute roof cover is constant and lower than 700 m, convergence increases and can attain very large values. As an example, at 5172 m from the portal, with an absolute roof of 1200 m, a deformation of 250 mm at the perimeter and of 350 mm at *D* had been found.

Dilatation measurements give results that agree with the convergence measurements; particularly interesting are the results obtained at 5172 m from the portal (Fig. 10): notable deformation of the rock has been observed in the rock mass (about 60 mm at 10-m depth and at 4.3 tunnel diameters from the working face). A further confirmation of the greater deformation of the rock is given by the behaviour of the rockbolts set in place (Fig. 11), which locally are quickly stressed, reaching the ultimate resistance value (some rockbolt failure has even been observed beyond 4300 m). The situation that emerged in May—September, 1978, required

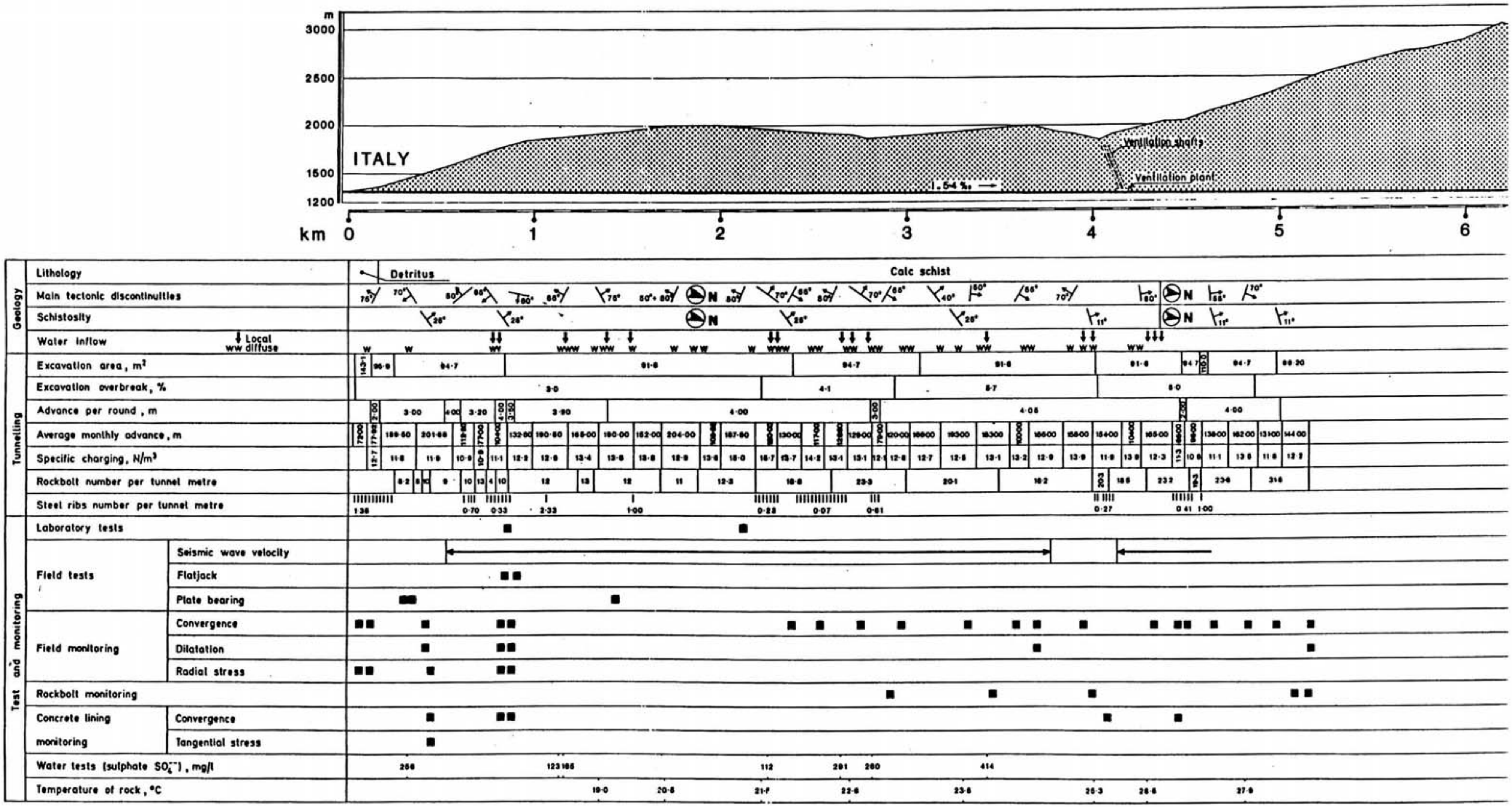


Fig. 8 Summary of main features of excavated Italian section of tunnel

Table 4 Mechanical properties of rock (calc schist)

				∥ Schistosity	⊥ Schistosity
Specific gravity, N/m^3				275	
Compressive strength, MN/m^2				43	93
Indirect tensile stress, MN/m^2				2.47	12.4
Direct shear strength, MN/m^2				τ_{max} ϕ=45° c=0.28	
				τ_{last} ϕ=35° c=0	
Modulus of elasticity	Laboratory	E_{tg}	MN/m^2	56 900	45 800
		E_{sec}	MN/m^2	57 600	35 900
	Flatjack	E_{dt}	MN/m^2	26 600	15 200
	Plate	E_{tg}	MN/m^2	800	7 000
	Bearing	E_{sec}	MN/m^2	10 600	5 730
Poisson ratio		ν_{tg}		0.27	0.18
		ν_{sec}		0.25	0.15
Seismic wave velocity on test, m/sec				5 100	3 040

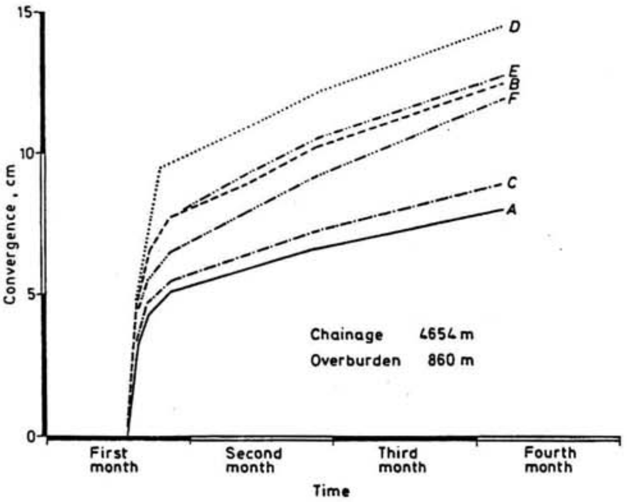
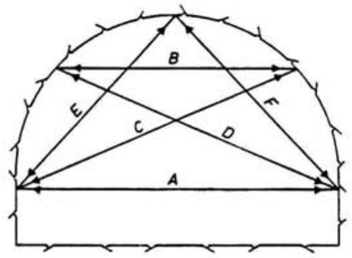
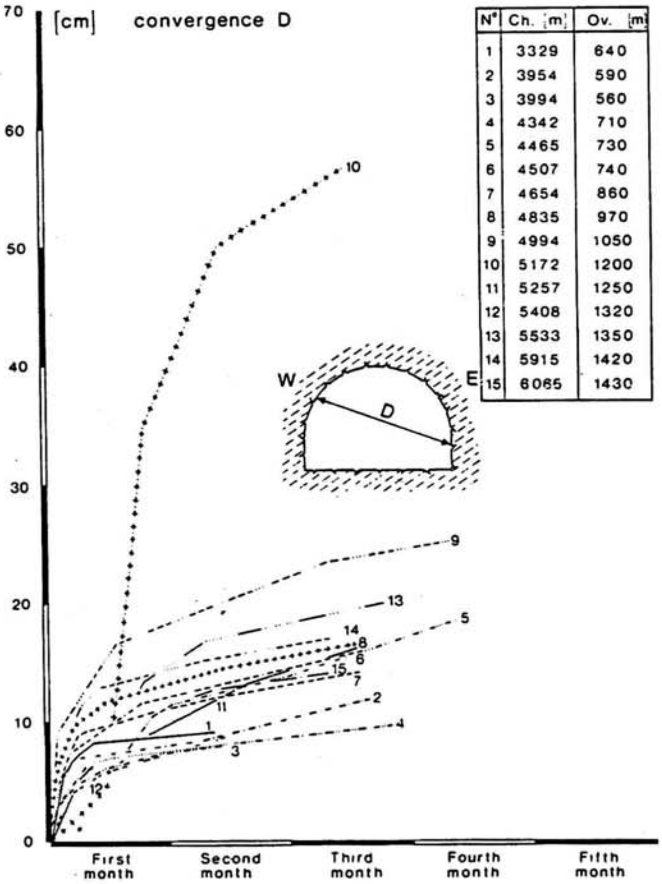


Fig. 9 Convergence charts (*see also adjacent column*)





a change in the bolting pattern, entailing the use of longer bolts, of different bolt lengths at different places to take account of the anisotropy of the rock and, possibly, of new bolt-setting methods to allow a greater deformability of the single bolts and of the overall structure.

OTHER INVESTIGATIONS

Water

Only a moderate inflow of water has been observed (cumulative water inflow, 0.004 m^3/sec with a tunnel length of 6000 m); water inflow is in the form of a moderate drip, except for some localized water accumulations where fractures have been crossed. Waterproofing measures have therefore not been adopted, except for the first length, driven in the detrital cover, and, to a minor extent, in loose rock, where perfect waterproofing has been obtained with PVC sheets.

Water temperature is about half a degree lower than rock temperature. The water is alkaline (pH 9.6–10), and the SO_4 content is rather high in the section where a sizable inflow has been observed (between 2400 and 2860 m); the lining has been built with a concrete obtained from low tricalcium aluminate cement ('pozzolanic' or sulphate-resistant cement).

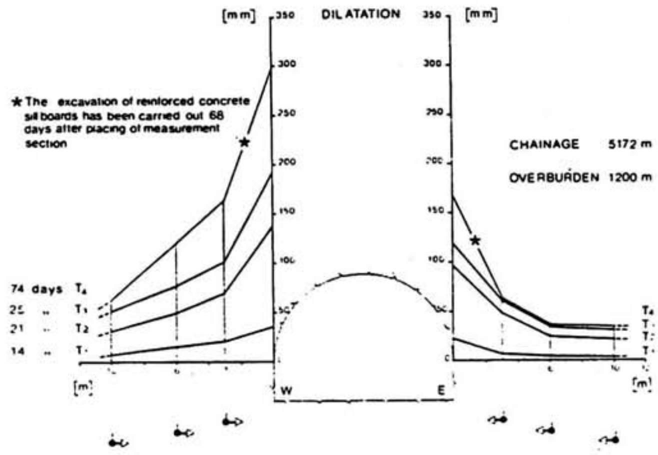


Fig. 10 Initial results of dilatation measurements at progressive distance 5172 m

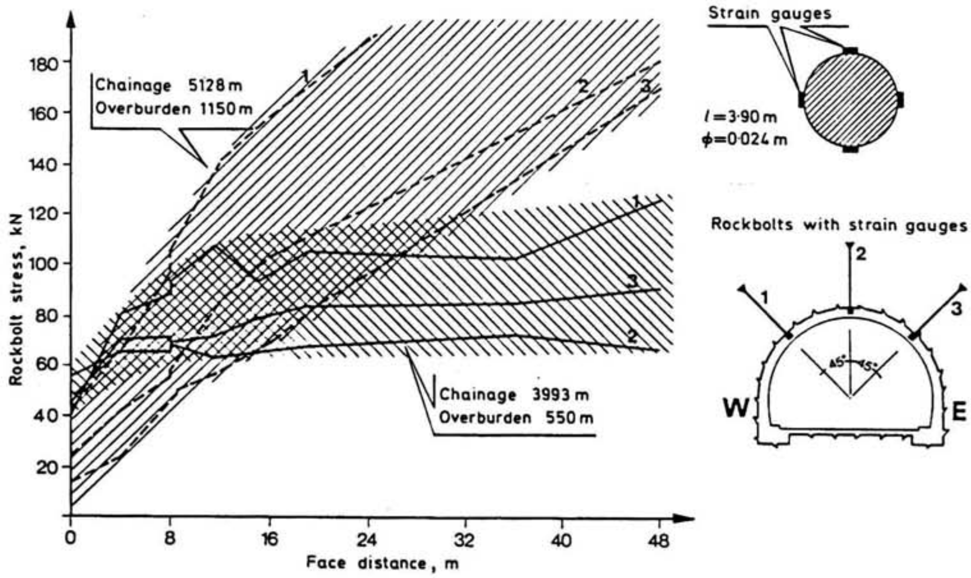


Fig. 11 Strain variation in rockbolts

Rock temperature

Rock temperature increased evenly along with excavation progress. In the first length of 4500 m, with a constant absolute roof cover, values of the vertical geothermal gradient between 3.0 and 4.6°C/100 m have been observed, which can be related to the effect of the lateral rock cover. Beyond that point the geothermal gradient (as measured deep in the rock mass) shows a trend towards lower values (3.0°C/100 m).