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The Bolmen tunnel project
Evaluation of geophysical site investigation methods

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THE BOLMEN TUNNEL PROJECT

EVALUATION OF GEOPHYSICAL SITE INVESTIGATION METHODS

Roy Stanfors

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Information on KBS technical reports from 1977-1978 (TR 121), 1979 (TR 79-28), 1980 (TR 80-26), 1981 (TR 81-17), 1982 (TR 82-28), 1983 (TR 83-77), 1984 (TR 85-01), 1985 (TR 85-20) and 1986 (TR 86-31) is available through SKB.

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ABSTRACT

In conjunction with planning of the 80-km long Bolmen tunnel, extensive geophysical and geological investigations were performed during the years 1967 to 1972. During the course of tunnel construction supplementary geophysical measurements were also made along numerous stretches.

Continuous geo-mapping of the whole tunnel was carried out in close conjunction with the blasting work. In this work, special attention was paid during penetration of zones of weak rock. The combination of geophysical and geological pre-investigations and careful documentation of the tunnel provides a unique opportunity to compare the predictions based on different geophysical methods of measurement with the actual conditions encountered in the bedrock.

This report presents a summary of all the geophysical measurements along and adjacent to the tunnel and an evaluation of the ability of the various methods to permit prediction of rock mass parameters of significance to stability and water bearing ability. The evaluation was performed for the Swedish Nuclear Fuel and Waste Management Co. and shows that, using airborne electro-magnetic surveys, it was possible to indicate about 80% of alla the zones of weakness more than 50 m wide in the tunnel. Airborne magnetic surveys located about 90% of all dolerite dykes more than 10 m wide.

Ground-level VLF and Slingram methods of electro-magnetic measurement indicated 75% and 85% respectively of all zones of weakness more than 50 m wide. Resistivity methods were successfully used to locate clay filled and water-bearing fracture zones. About 75% of the length of tunnel over which resistivity values below 500 ohm m were measured required shotcrete support and pre-grouting.

Of 141 wide zones of weakness (more than 50 m wide) in the Bolmen tunnel about 60% were indicated by refraction seismic velocities of 4400 m/s or less. The corresponding result for narrower fracture zones (10 to 50 m wide) was about 65%.

1. INTRODUCTION

The Bolmen tunnel forms part of a water supply system for the southern counties of Sweden, to which raw water is transported in an unlined 80-km long tunnel in crystalline rock from Lake Bolmen to the vicinity of Perstorp, where it enters a 25-km long pipeline running to the existing water treatment plant at Lake Ringsjön (Fig. 1). The cross-sectional area of the tunnel is about 8 m^2 and the depth below ground-level varies between 30 and 90 m.

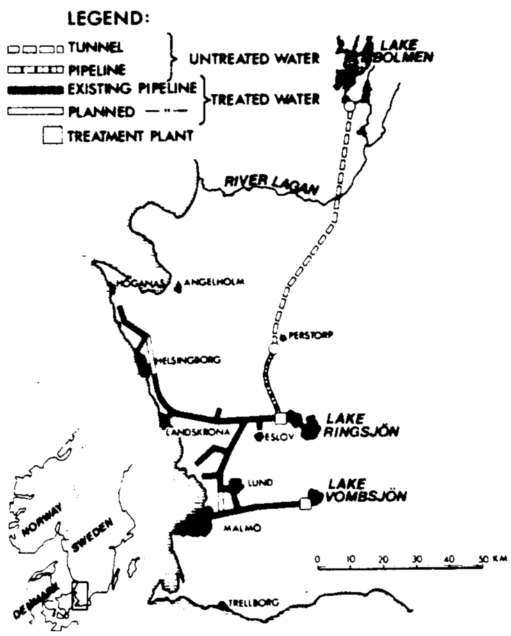


Fig. 1. General map

1.1 Site investigations

The geological investigations for the Bolmen tunnel were carried out at varying rates between 1967 and 1972. Despite the relatively small cross section of the tunnel it was considered necessary, both from rock-construction economy and environmental points of view, to base the route of the tunnel on the best possible knowledge of the geological background of the area considered. From a practical point of view, only the locations of the beginning and of the end - intake and outlet - of the tunnel were fixed. The remaining 80 km was basically open to choice, and this was a natural reason for investing in extensive site investigations, to avoid difficulties during the driving of the tunnel. Between Bolmen and Perstorp, the country-side is mainly flat. Glacial drift and extensive mossy and swampy ground cover the rock almost completely. At only a few points is the rock exposed, permitting geologists an opportunity of assessing it directly.

The existing geological maps were all incomplete and insufficient for making an engineering geological assessment.

The scope of the investigations and their division into stages are described below.

STAGE 1 (1967)

As a first stage in the geological site investigation programme it was decided in 1967 to collect the greatest possible amount of information of general geological interest. The aim was to select the most suitable basic route for the tunnel within an area covering some 1600 km^2 (Fig. 2).

Collection of geo-data from regional road administrations, local authority engineers, rock construction works and welldrilling records gave valuable information as a basis for planning the initial site investigations. General geological mapping was preceded by interpretation of aerial photographs and airborne magnetic measurements. Ground-level geophysics (magnetic and seismic), to a limited extent, and a basic tectonic assessment concluded the first year's investigations.

Result: The tunnel should run roughly Bolmen - Markaryd - Perstorp.

STAGE 2 (1968 - 69)

Investigations were then concentrated to a more limited area along the basic line described above.

At this stage, the additional work included making more detailed geological mapping and, above all, more seismic investigations. A number of dolerite dykes were located in the southern part of the area using magnetic measurements.

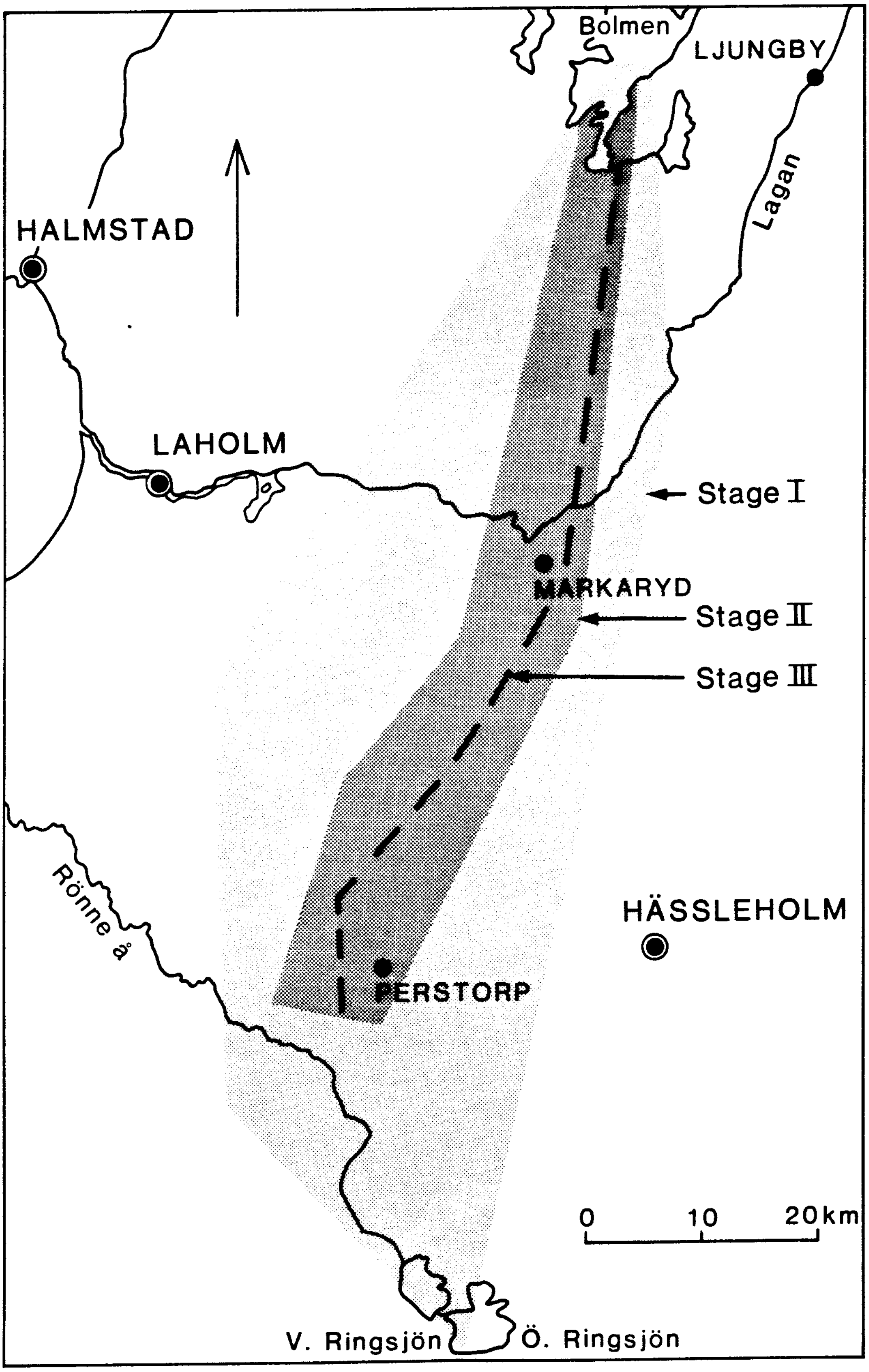


Fig. 2 THE BOLMEN TUNNEL. SITE INVESTIGATION AREA.

Geohydrological studies were performed to assess the possible effects of the tunnel on the Perstorp underground source of water.

A limited amount of diamond coring was performed.

Result: The main route of the tunnel was reduced to one corridor - the tunnel should run east of Markaryd and west of Perstorp.

STAGE 3 (1970 - 72)

During Stage 3, investigations were directed completely towards detailed investigations within the corridor, to obtain as favourable routes as possible through zones of crushed and fractured rock.

The seismic measurements were extended to cover the entire length of the tunnel and several of the presumed zones of weakness were investigated by core drilling.

The summary of all investigations resulted in production of a geological-tectonic model of the area.

1.2 Geological-tectonic model

The geological-tectonic model that could be constructed on the basis of the site investigations described above showed that the bedrock in the area consisted mostly of gneiss of varying colour and composition.

In the northern part, a relatively large amount of amphibolite could be expected and in the southern part, passage through some forty dykes of dolerite was predicted. The strike of the various types of rock was assessed to be mainly WNW, usually with a relatively low dip to the NE or SSW.

The tectonic model indicated a number of crushed and fractured zones running in the principal directions NNE and WNW. From Lake Bolmen, the most serious zones of weakness were regarded as being adjacent to the valley of the river Torpaån (I), the Exen-Staverhult area (II), the valley of the river Lagan (III), the area from Markaryd to the lake Kraxasjön (IV), the extension of the boundary zones of the Hallandsås uplift (the Slättsjö area) (V), the valleys of the rivers Perstorpsbäcken (VI) and Ybbarbsån (VII) (Fig. 3).

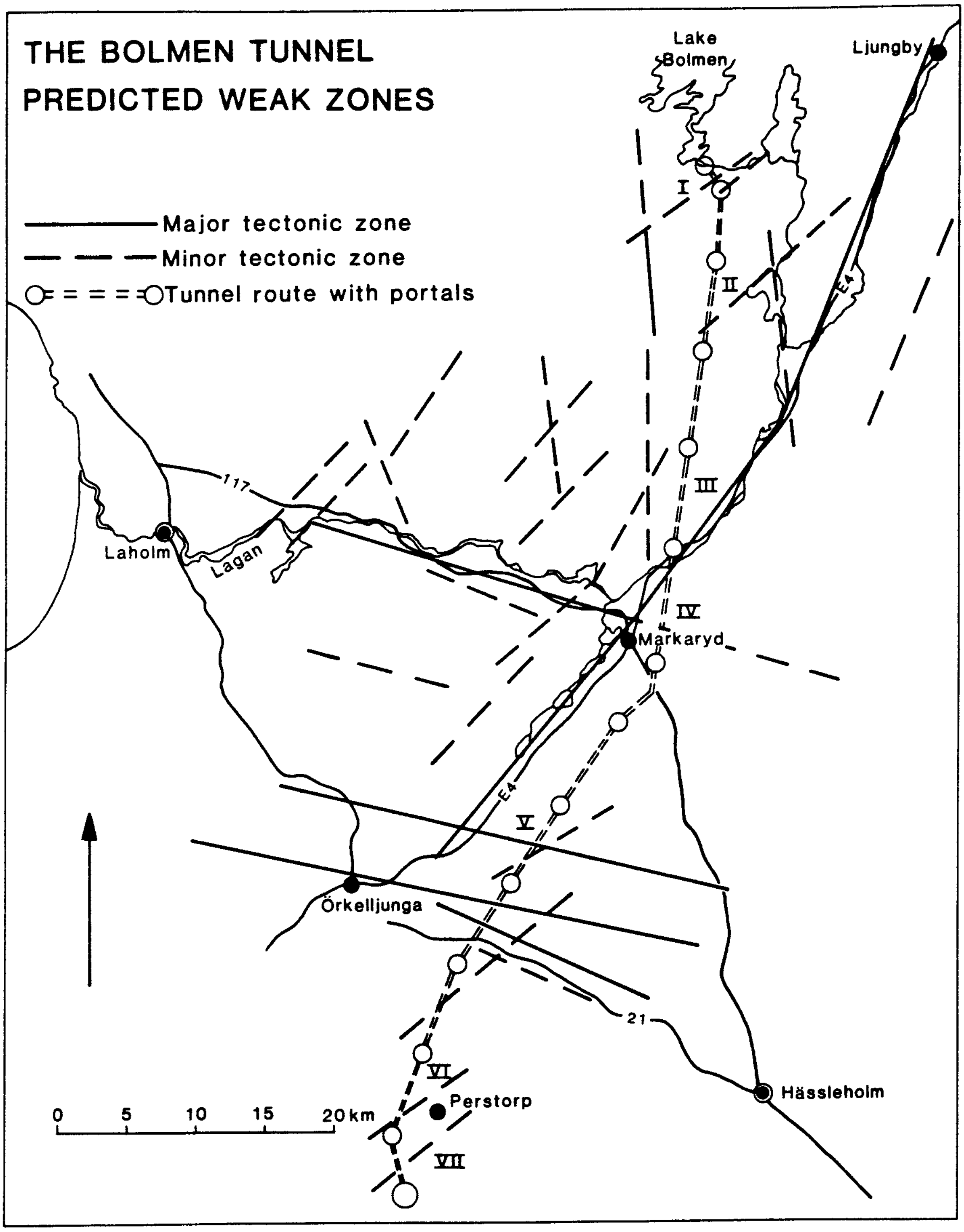

THE BOLMEN TUNNEL
PREDICTED WEAK ZONES
Major tectonic zone
Minor tectonic zone
Tunnel route with portals
Lake Bolmen
Ljungby
I
II
III
IV
V
VI
VII
E4
117
Laholm
Lagan
Markaryd
Örkelljunga
21
Hässleholm
Perstorp
0 5 10 15 20km

Fig. 3

1.3 Supplementary investigations

During the entire tunnelling stage, efforts were made to improve the engineering geology model. By using all the experience that had been gained and, where necessary, performing supplementary seismic and electrical measurements, at total of about ten local changes in the original tunnel route resulted in considerably shorter passages through zones of weakness that required support work. In all cases, the cost of this work paid for itself several times over by reducing the cost of the rock support work required. In this context, the resistivity measurements provided especially valuable basic information for a description of the zones of weakness. An excellent example of a local change in the line of the tunnel was the approximately 75-m lateral move introduced prior to the passage through the Staverhult zone. This change in the tunnel line permitted tunnelling to be carried out in the most intensive part of the zone from the most advantageous angle, thus reducing the need for rock support measures.

1.4 Geological mapping and documentation

Geological mapping was carried out continuously from the start of blasting for the Bolmen tunnel in 1975 up to the time of its completion in 1985.

The aim of the geological mapping was primarily to describe the engineering geological conditions in detail in and immediately adjacent to the sections that required some form of permanent support.

All information from the geological mapping was presented on drawings to a scale of 1:1000, together with information on rock support works carried out.

Figure 4 shows a general picture of the geological-tectonic conditions identified by tunnel mapping. As may be seen from the map, gneiss in various forms is the completely dominating type of rock. Numerous bodies of a more unstratified granitoid type of rock (gneiss-granite) occur principally in the northern half of the tunnel.

The different variants of metamorphic, basic rocks have been gathered under the designation amphibolite. These occur in the form of dykes, massive or thin layers and banks along the entire length of the tunnel, but to very

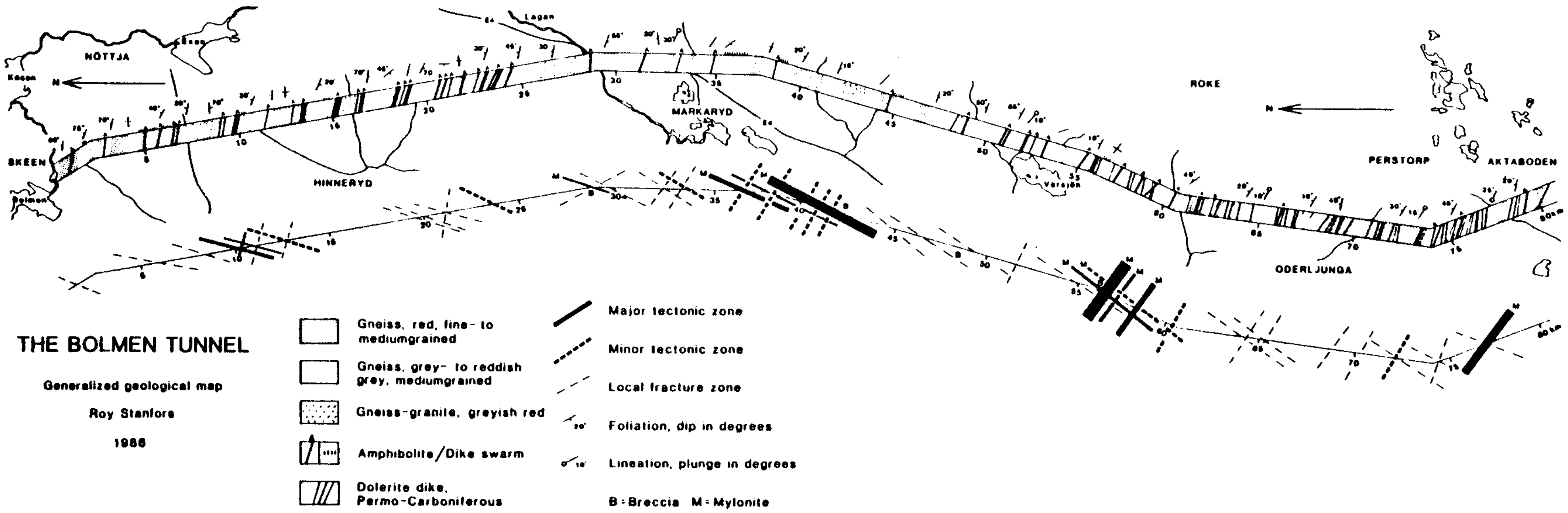


Fig. 4 GENERALIZED GEOLOGICAL MAP

varying extents. Especially in the section between 15 and 25 km the amount of amphibolite is very great - about 20%. Of special engineering geology significance here are the swarms of decimetre-wide amphibolite dykes, which often occur in conjunction with the most serious zones of disturbance. The strike of gneiss and amphibolite is in a WNW direction throughout and its dip is usually low.

In the southern part of the tunnel, from about station 48 km, there is a very noticeable occurrence of young (Permo-Carboniferous) dolerite dykes. These dykes vary in width from about 1 m to 70-80 m, with a strike running NW or WNW and a dip to the SW that is moderately steep (90^o - 60^o). A total of about 120 dolerite dykes were passed in the southern part of the tunnel. Of these, about 40 were at least 15 m wide (Fig. 5).

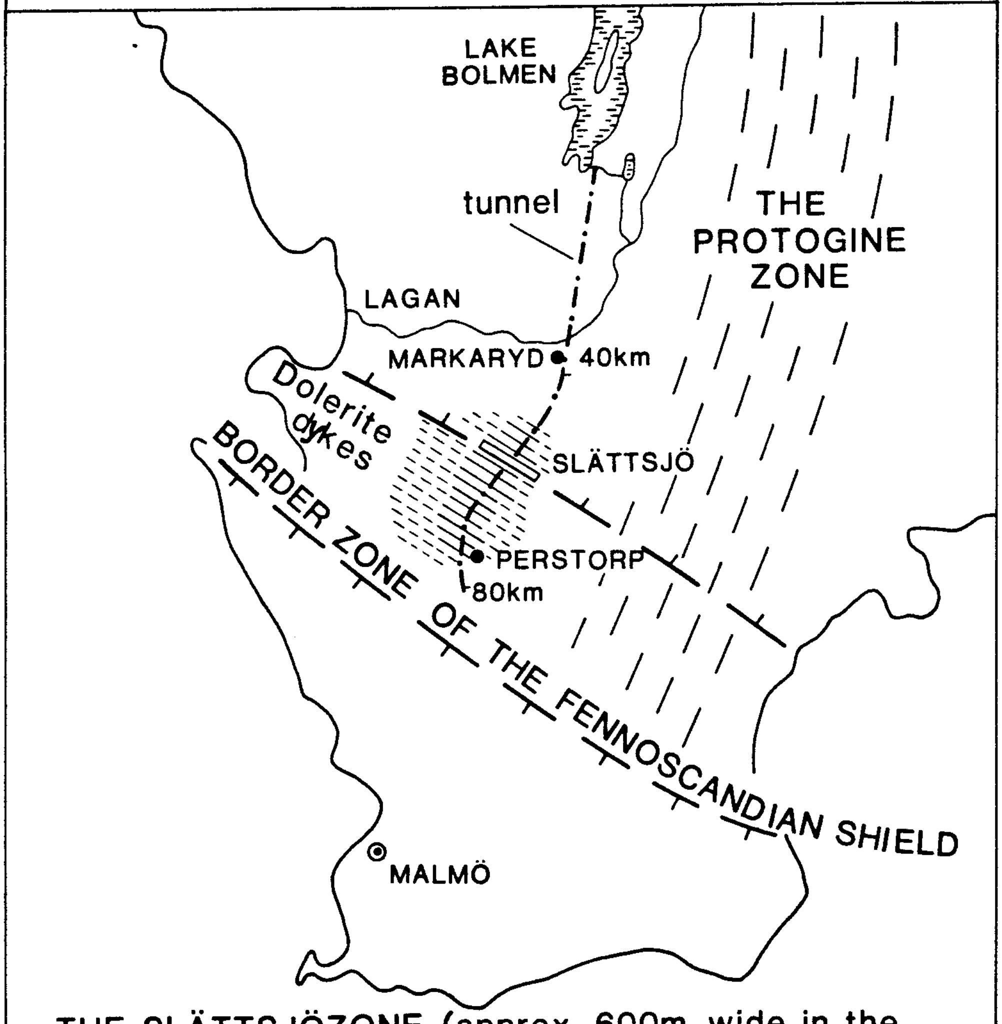
The tectonic picture of the tunnel is dominated by two fracture directions - NNE and WNW. The tunnel passes through two large zones of weakness of a regional nature - one in the stretch 35 to 45 km, parallel to the Protogine Zone, running mainly NNE, and one at about 55 to 58 km, the Slättsjö zone, trending WNW, which seems to be the main zone of weakness bordering the Fennoscandian Border Zone to the north. The zones mentioned above were kilometres wide in the tunnel and very complex in their construction. Both simple faults and overthrust faults have caused intensive fracturing or crushing of the rock. Clay alteration, with smectite as the dominating clay mineral, occurs in large sections.

Brecciation and mylonitization are a common feature in these zones of weakness and passage through these required extensive support work in certain sections. Great problems were encountered especially in the approximately 500-m long stretch after station 56 km (the Slättsjö zone), because of a combination of densely interlayered gneiss - flat amphibolite dykes, crushed and clay altered rock and leakage in of large volumes of water.

As may be seen on the map, several other zones of weakness were penetrated, whose direction almost entirely agreed with the two regional zones, but whose intensity and width was completely different. Consistently observed were the overthrust faults along amphibolite dykes with a flat or medium-steep dip, often open fractures running WNW that cut across and often appear to be younger than the overthrusts. In the extreme south, it was observed that the youngest dolerite dykes had also been subjected to fault movements in a NNE direction.

THE BOLMEN TUNNEL AREA
MAIN TECTONIC ZONES

SCALE 1:1000 000



THE SLÄTTSJÖZONE (approx. 600m wide in the tunnel) is highly fractured and water bearing. The southernmost 30km of the tunnel cuts 40 (15-20m wide) dolerite dykes.

Fig. 5

Water leakage into the tunnel may mostly be related to crushed and fractured regional zones in which there have been inflows and difficulty in grouting.

2. SCOPE OF THE EVALUATION

All geophysical results that were obtained in measurements along or adjacent to the line of the tunnel have been summarized and evaluated (Fig. 6).

The results of geophysical measurements, together with information from mapping in the tunnel that is important for the evaluation, have been summarized on 16 drawings to a scale of 1:10,000 (Drwg. BT-01- 16). All important results are shown on a general drawing (BT- 17) to a scale of 1:50,000.

Results were obtained from refraction seismic and ground-level magnetic measurements along almost the whole length of the tunnel, but there were some gaps due to inaccessible terrain.

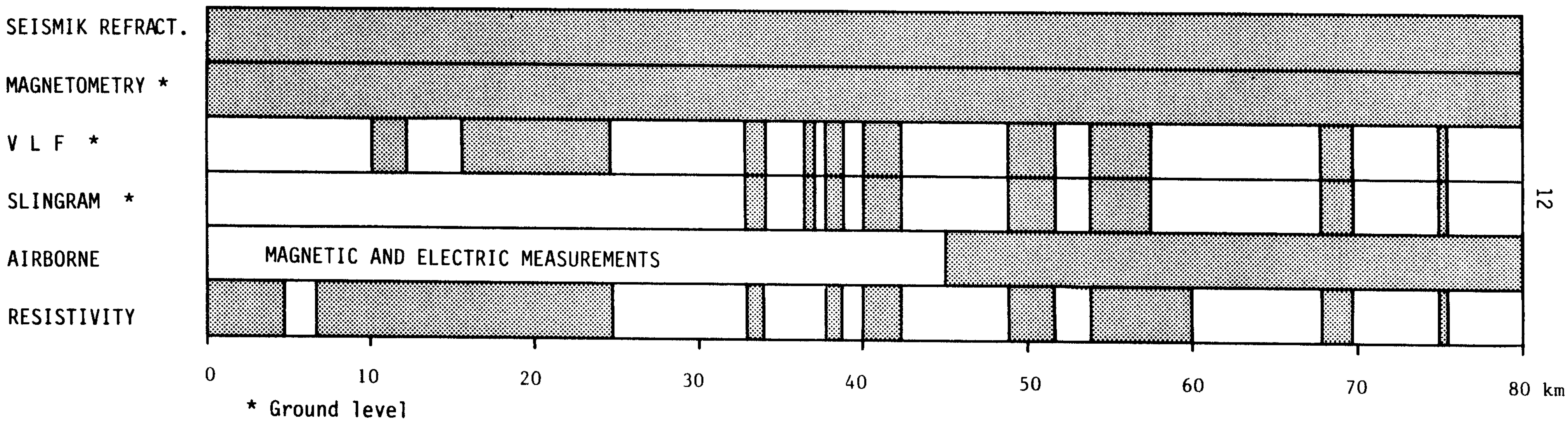
The electric methods of measurement were first used in the complementary pre-investigation stage, when blasting of the tunnel had been started. Most of these measurements were therefore concentrated to the stretches of tunnel where zones of weakness were expected and where studies of alternative local alignments were considered.

Results are available for Slingram measurements for about 13 km of the tunnel, VLF measurements for about 23 km and resistivity measurements for about 37 km.

In step with SGU's production of airborne geophysical measurement results, these were also used for the southern part of the tunnel (about 45-80 km). Primarily the results of airborne electric and magnetic measurements were used.

It is important to point out that the evaluation is mostly based on the geophysical measurements that were presented in reports by respective contractor. These reports generally contained no engineering geology interpretation.

Fig. 6 GENERAL VIEW OF THE SECTIONS OF THE BOLMEN TUNNEL INCLUDED IN THE EVALUATION (shown cross-hatched).



3. MAGNETIC MEASUREMENTS

3.1 Method and conditions

In magnetic measurements, variations in the natural magnetic field of the earth are measured. Anomalies in the magnetic field are caused by the fact that the magnetic intensity of different rock types varies with their content of magnetic minerals. The principal minerals of practical significance are magnetite and to a certain extent ilmenite and magnetic pyrrhotite. The contents of these minerals impart to the host rock a certain magnetic susceptibility. In very general terms, acid rocks like granite and gneiss usually contain only small amounts of magnetite, while basic rocks, such as dolerite, gabbro and certain amphibolites, normally contain larger quantities of magnetic minerals.

If there is a sufficiently large difference in susceptibility between two rock types the boundary between them can be located by magnetic measurements, even if the bedrock is covered by soil. A common practical example is that it is often possible to locate a basic rock type such as dolerite surrounded by acid rocks such as gneiss. Oxidation of magnetite to hematite in fracture zones sometimes cause magnetic minima (Henkel-Guzmàn, 1977).

Magnetic investigations may be performed both from the air and at ground level. Airborne measurements are usually made at an altitude of about 30 m, with about 200 m between flight lines. These measurements involve the recording of the total magnetic intensity.

Detailed magnetic investigations over a more limited area are normally performed at ground-level. These measurements are usually made along lines, with 10 to 20 m between measurement points, and generally involve recording the total or the vertical magnetic intensity. Ground-level magnetic measurements form an important complement to airborne magnetic investigations.

When the site investigations for the Bolmen tunnel were started in 1967, there were no geophysical maps of the area of the type now being prepared by the Geological Survey of Sweden (SGU).

Airborne magnetic reconnaissance measurements were made in 1967 by Craelius-Terratest at the request of AB Sydvatten. These measurements were made along a number of profiles, but as they only coincide with the location of the tunnel to a very limited extent, they are not included in this evaluation.

The problems within the area investigated for the Bolmen tunnel that were primarily considered suitable for solution using magnetic methods of measurement were principally location of the dolerite dykes and basalts that were expected in the southern part of the area. The amphibolites in the northern parts of the area could also be expected to give magnetic anomalies.

As mentioned above, the conditions that permit location of a rock magnetically are dependent on the difference in susceptibility that it exhibits in relation to the surrounding rock. Before ground-level measurements were started, therefore, susceptibility determinations were performed on samples of different rock types that occur in the area, to provide a good basis for assessing the results of magnetic measurements. The results are shown in Table 1 below.

Table 1

ROCK TYPE	SUSCEPTIBILITY (in emu/cm^3)
Dolerite	$3000 - 5000 \cdot 10^{-6}$
Basalt	appr. $5000 \cdot 10^{-6}$
Intermediate gneiss	$< 500 \cdot 10^{-6}$
Amphibolite	$< 500 \cdot 10^{-6}$
Charnockitic gneiss	$500 - 1000 \cdot 10^{-6}$

The table illustrates that with the large difference in susceptibility between dolerite and basalt in relation to the surrounding gneiss clear anomalies could be expected. The dolerites also exhibit a consistently higher remanent magnetization (q-value about 2).

The table also indicates that it would hardly be possible to locate amphibolites as they occur exclusively as inclusions in gneiss that has approximately the same magnetic properties. The purpose of the ground magnetic profile measured along the final tunnel centre line was primarily to locate a number of expected dolerite dykes along the southernmost part of the tunnel. The measurements were made using an Askania Gfz type magnetometer, with measuring points at 10-m centres.

3.2 Results and discussion

Examination of the ground magnetic profile, Drwg. BT-17, reveals on the stretch from 0 to about 56 km a "sawtooth" anomaly picture that corresponds well to the inhomogeneous gneiss bedrock through which the Bolmen tunnel passes. On the stretch between approximately 15 and 25 km - where the amount of amphibolite is very great - the anomaly curve is smoother and the magnetic intensity here is consistently lower than in the gneiss. Another low magnetic section is located on the stretch between approximately 39 and 42 km. Here the bedrock has been largely crushed and altered and the magnetite has probably been altered to hematite (oxidation zone).

The low magnetic section between about stations 48 and 51 km is probably not connected with either amphibolites or crushed and clay-altered gneissic bedrock.

These three examples show how difficult it may be to locate zones of weakness in bedrock using magnetic measurements on their own.

South of station 48 km, the tunnel passes through about 50 dolerite dykes 10-m wide or more. These dolerites are, as indicated by the susceptibility measurements, considerably more magnetic than the surrounding country rock. The anomalies are often distinct and amount to 500-2000 nT. It has generally been possible to locate the dykes to within 10-20 metres and to state their width to within 20-30 %. Indications about the dip were made more difficult by consistently high remanent magnetism. It has been possible, using ground level magnetic measurements, to locate about 90 % of the dolerite dykes located in the tunnel that were 10 m wide or more.

The areomagnetic maps cover the entire length of the tunnel from station 45 km and south. The magnetic "dolerite indications" from these maps has been plotted on Drwg. BT-17. It may be noted that about 90 % of the dolerite dykes (> 10 m) coincide with distinct positive anomalies. The dykes were located, however, for obvious reasons, with less accuracy (100-150 m) than by the ground-level magnetic measurement.

One low magnetic stretch (oxidation zone) at about station 58 km on the map Kristianstad NV is the location of a clay-altered and water-bearing zone in the tunnel. An other stretch - at about station 61 km - corresponds to no zone of weakness in the tunnel. It is noteworthy that the very intensive, about 600 m wide regional zone of weakness at Slättsjö (about station 56 km), is not indicated more distinctly by a low-magnetic anomaly on the areo-magnetic map. A narrow low magnetic stretch at about station 79 km may be related to a clayey crushed zone in the tunnel and a wide stretch of low magnetism at about station 79 km may be related to a minor crushed zone.

3.3 Conclusions

1. The areomagnetic maps form an excellent basis for the primary planning of an engineering geology project to a regional scale.

2. In the Bolmen tunnel, the airborne magnetic measurements exhibited largely the same indication frequency for dolerite dykes as the ground-level measurements. But the accuracy of locating the positions of the dykes is considerably greater using ground-level measurements.

3. Stretches of low magnetism may be indications of oxidation zones (zones of weakness), but must be checked using other geophysical measurements.

4. Ground-level magnetic measurements are inexpensive to perform and are suitable as a complement to airborne magnetic measurements, specially for more exact position determinations of dolerite dykes, for example.

4. ELECTRICAL MEASUREMENTS

4.1 Methods and conditions

Determinations of resistivity deviations in the soil cover and upper parts of the bedrock have traditionally been performed to solve different types of geological problem since the twenties. But only in recent years has this method become common in conjunction with site investigations for rock installations.

The most common method, especially for solving hydrogeological problems, employ conventional galvanic resistivity measurements - measurement of the resistance. Profiling or sounding can be used, depending on the nature of the problem. The method is best suited to the examination of problems in horizontal layering, but is used for all types of problem. It is relatively expensive and time-consuming as it involves relatively large amounts of work for each measuring point.

There are thus several different methods for locating resistivity deviations (or resistivity anomalies) and for determining the "apparent resistivity", which in simple terms may be said to be the average resistivity of the soil and rock down to the depth to which the measurements penetrate.

In conjunction with the site investigations for the Bolmen tunnel we used the conventional galvanic resistivity method (Terrameter SAS 300 type instrument), and two types of electro-magnetic methods: VLF (Geonics EM 16 instrument) and SLINGRAM using an SGU type Slingram instrument (horizontal loop EM, operating at 18 kHz) (Stanfors et al., 1982).

Kurt Klitten and Leif Eriksson were responsible for most of the electrical measurements performed during the stage of complementary investigations.

In resistance measurements (resistivity measurements) the apparent resistance is determined directly, and the depth of penetration is determined by the measurement geometry, i.e. the relative distances between the power source and measuring electrodes. The measurements are performed as both profile measurement, in which the horizontal variation of the apparent resistivity is surveyed, and as deep sounding, in which the vertical variation of the resistivity is calculated.

The EM (electro-magnetic) methods involve measurement of how the soil cover and the upper parts of the bedrock affect a radio signal, i.e. a time-varying electro-magnetic field. The measurements are normally only performed as profiles, in which sudden deviations in the resistivity appear as anomalous electro-magnetic effects caused by secondary currents in nearby electric conductors.

The depth of penetration is dependent on the frequency of the radio signal selected and on the geometrical relationship between the transmitter and receiver. The apparent resistivity can be calculated in certain cases, but it is normal to state only the variation in the amplitude of the secondary field and the phase displacement and from these calculate the positions of electrical conductors present.

In the VLF method the distance to the radio transmitter (which is stationary) is very large. A British station - the Rugby transmitter - is the one normally used in the survey of the Bolmen tunnel. In the slingram method, the transmitter and receiver follow one another at a constant distance, 60 m, for example.

The electrical conducting ability of a rock is normally stated as its resistivity, i.e. its specific electrical resistance. The resistivity of a material is defined by Ohm's law, which states that the electrical field strength, E, at a point in the material is proportional to the intensity of the current, I, in this point, in accordance with:

$$E = \rho \cdot I$$

where E is expressed in volt/m, I in ampere/m^2.

The resistivity is therefore expressed in ohm m. Low conductivity corresponds to high resistivity and high conductivity corresponds, naturally, to low resistivity.

Dense, dry crystalline rocks normally exhibit very high resistance, often above 50,000 ohm m, if they do not contain ore minerals or graphite. Substantial contents of these minerals can result in a drastic reduction of the resistivity to well below 100 ohm m.

The quantity of water in a normally fractured crystalline bedrock below the water table is relatively little compared with the quantity of water in the loose deposits. This limited quantity of water, however, is sufficient to exert a certain influence on the conductivity of the bedrock. Rock types such as gneiss and granite in the Swedish bedrock that do not contain a noteworthy amount of ore mineral generally give rise to a resistivity of between 1,000 and 10,000 ohm m, depending on the intensity and pattern of fracturing, but naturally also on the amount of dissolved salts in the water. A resistivity down to about 200 ohm m may be detected in zones of crushed and fractured rock containing considerable amounts of clay mineral.

The conditions for using electrical methods for predicting zones of weakness and possible water leakage into a rock installation are that it must be possible to identify sections of rock containing large numbers of fractures, and thus large water/clay content, as zones with lower resistivity than is common for a rock mass with a normal incidence of fractures.

4.2 Resistivity measurements (Kurt Klitten, 1982)

The geo-electrical resistivity method is based on a direct determination of the apparent resistance by measuring the resistance from ground level.

The resistance measurement is performed by measuring the voltage, V, (potential) between two internal electrodes, M and N, and by measuring the strength of the current, I, for an electric current sent through the ground between two external electrodes A and B. The electrodes are located along a line on the ground and penetrate about 20-30 cm into the ground, symmetrically around the measuring point (see Fig. 7).

The apparent resistivity (a) in the soil down to the depth covered by the measurement may be expressed by the formula:

$$a = K \frac{V}{I}$$

$$\text{where } K = \frac{2\pi}{\frac{1}{AM} - \frac{1}{BM} - \frac{1}{AN} + \frac{1}{BN}}$$

is a constant that is only dependent on the geometry that has been selected for the electrode arrangement.

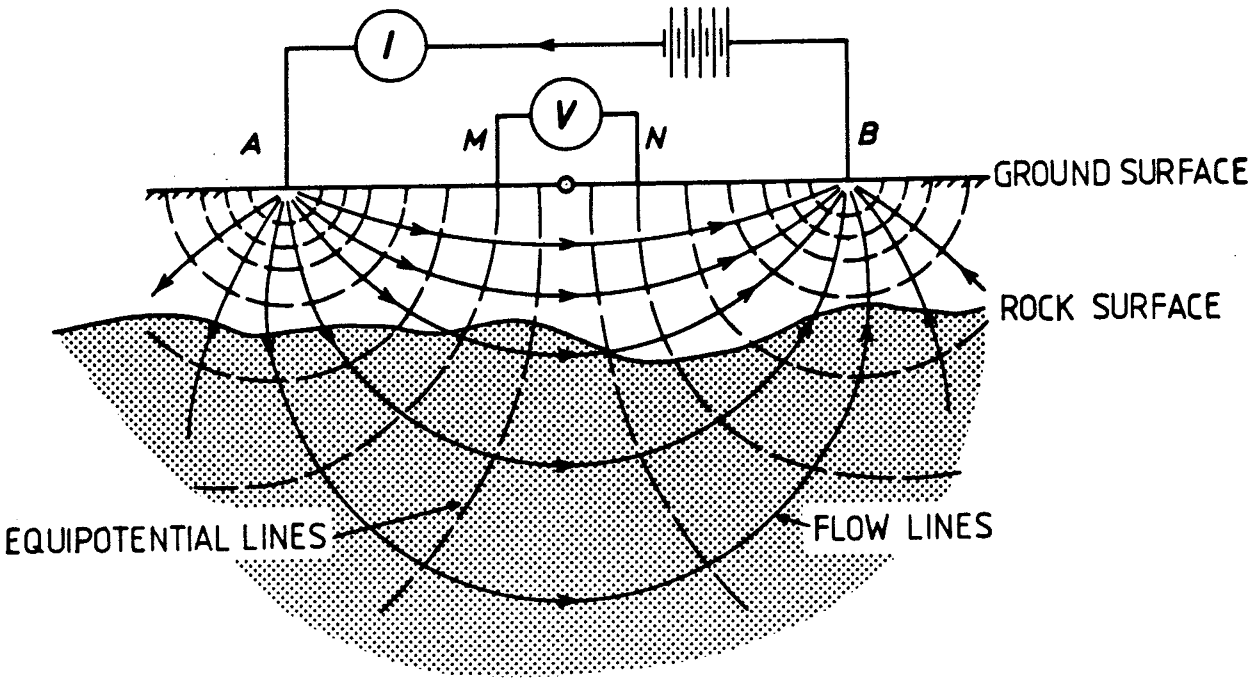


Fig. 7. Resistivity measurement configuration (Kurt Klitten, 1982)

The penetration depth for the current field through the soil increases with increasing distance between the current electrodes. As a rule of thumb, the measurements are generally regarded as penetrating to a depth corresponding to the distance AM between the current electrode and the potential electrode.

In practice, the measurement principle is used in both longitudinal profile measurement and in deep sounding.

In profile measurement, all measurements are performed with the same distance between electrodes and the whole measurement set-up is moved along the profile line. The volume of soil or rock involved is therefore constant from one point to another and any variation in the apparent resistivity along the profile line must therefore indicate a variation in the geological conditions within the volume of rock being subject to measurement.

If a relatively small distance between electrodes is used, (e.g. AM=MN=NB=10 m - shallow profiling), it is mainly the soil cover that contributes to the measured apparent resistivity. High resistivity values along the profile line therefore indicates either shallow soil cover resting on a dense, dry bedrock or dry sand or gravel deposits above the water table.

The resistivity of clay, glacial till and sand or gravel below the water table is generally much lower than that of rock.

When investigating the resistivity of bedrock, the penetration depth must be increased considerably to ensure that most of the volume of material investigated is rock.

Because of the depth of the Bolmen tunnel below ground level (50 - 100 m), the measurements were made with a distance of 190 m between A and B, which gives a penetration depth (A-M) of about 90 m.

Despite the large distance between electrodes, the apparent resistivity is also influenced by the soil cover as the resistivity, as mentioned earlier, is an average of the real resistivity values for the different layers within the volume being subject to measurement. The apparent resistivity is a weighted average, in which not only the thickness but the depth also determines the influence of a certain layer. A 5-m thick low-resistivity zone near the surface also exerts a much greater influence than it would at a depth of 10 m, for example. The effects of this include the fact that a relative resistivity minimum in a longitudinal section, measured with large electrode spacing may not necessarily be an indication of low rock resistivity. It could just as well be the result of extra low resistivity in the soil cover. To permit evaluation of the variations in the apparent resistivity with greater reliability, specially as regards location of zones of low rock resistivity, the deep profiling may be supplemented by the addition of superficial profiling with a relatively small distance between electrodes. This was performed on certain parts of the stretch investigated to permit comparison of the apparent resistivity values from the two measurements.

4.3 Electro-magnetic measurements (Leif Eriksson, 1982)

Most electro-magnetic methods (EM methods) are based on the principle of measurement of the secondary electro-magnetic effects (induced fields) that occur whenever a radio signal passes through rock and soil of varying electrical properties. Traditionally, the EM methods have been used since the twenties to locate ores in bedrock below the soil cover. It is then possible to consider the ores as more or less good, usually slab-shaped, conductors in largely non-conducting surroundings (Fig. 8).

The factors that are important in utilizing the method in these types of problem are the frequency of the radio wave and the geometrical relationship between the transmitter and the receiver. Higher frequencies provide greater sensitivity but less penetration of the signal in the poorly conducting surroundings (soil cover and bedrock). As the distance between the transmitter and receiver is reduced it becomes possible to record even smaller objects, i.e. we achieve ever greater resolution (mine-detecting equipment has only about 10 centimetres between the transmitter and receiver, the slingram normally has 40 or 60 metres).

The electro-magnetic measurements carried out in the frequency range from 10 to 30 kHz have shown themselves to be very sensitive to water-bearing zones, even when they exhibit relatively little resistivity contrast with the surrounding rock.

These measurements may be performed with methods in which the measurement are made using the local field or induction field, from a nearby fixed or moving transmitter (slingram). Another possibility is to use distant VLF (very low frequency) radio transmitters, so that the measurements are made in the distant field from the transmitter that is located at a very large distance from the receiver.

In the case of very weak electrical conductors like the ones of interest here, it is possible in the case of EM measurements in the local field to consider any indications as principally local inductive phenomenon.

4.3.1 Slingram measurements

The principle of the SLINGRAM is shown in Fig. 9. The variable primary magnetic field, which is generated in the transmitter pole, induces currents in nearby electrical conductors. These currents in their turn give rise to secondary magnetic fields that are measured at the receiving pole and which are also stated as a percentage of the undisturbed primary field (what is received whenever there is no electrical conductor). To make clear the phase position of the secondary field in relation to that of the primary field, the real component (in phase with the primary field) is read off as well as the imaginary component (90^{0} out of phase with the primary field). The distance between the transmitter and the receiver, the measuring distance, is normally 40 m, and the point between the transmitter and receiver is regarded as

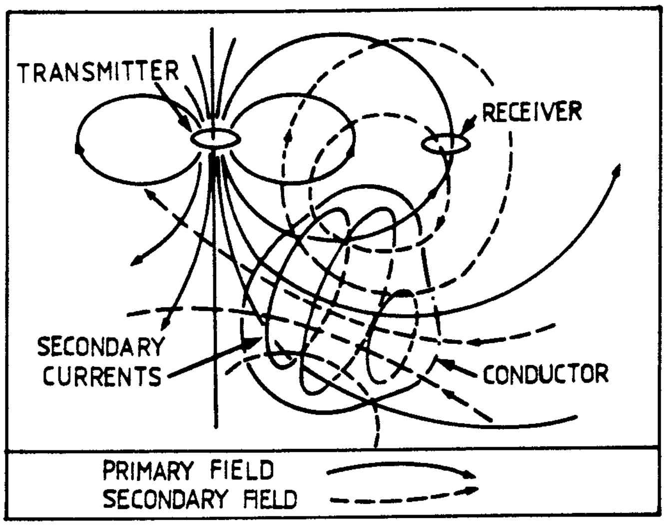


Fig. 8. Principle for electrical measurements using radio waves (Leif Eriksson, 1982)

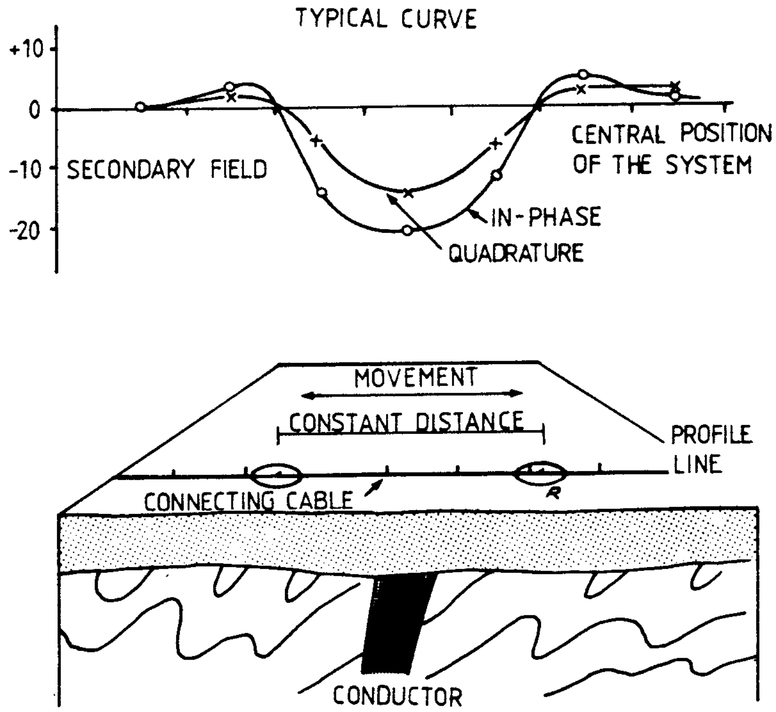


Fig. 9. The slingram method, with the transmitter and the receiver 60 m from one another (Leif Eriksson, 1982)

the measuring point. Measurement is carried out with points at 20-m intervals along profiles at 80 m from one another. The profiles should be oriented at right angles to the direction of strike, to give the best possibility of interpreting the strike, dip, conductivity etc. (Fig. 9).

4.3.2 VLF measurements

When using the VLF method (Fig. 10) the distance to the radio transmitter is very large. This implies that the work is performed in a relatively homogeneous planar polarized remote field, in which the strength of the primary field is attenuated very slowly with depth. The depth of penetration is normally several hundred metres. Secondary currents are induced in the same manner, but to a considerably greater depth than in slingram measurements. The amplitude and phase of the secondary field is recorded in a small mobile receiver. Note that the shape of the typical curve is basically different.

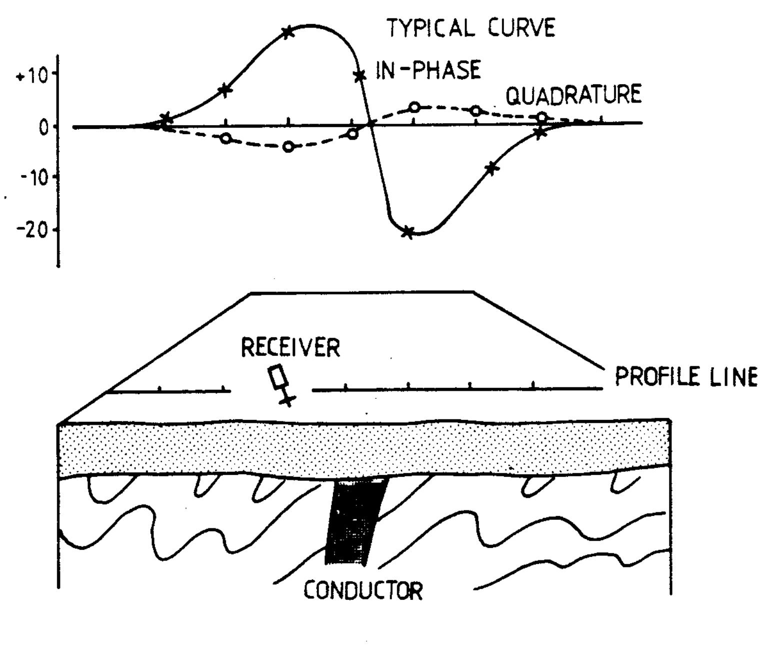


Fig. 10. The VLF method with a stationary transmitter located at great distance

When using a distant VLF transmitter, EM measurements in the remote field become possible indications caused by a more complex, perhaps predominating conductive phenomenon. The general currents in the bedrock caused by the radio wave field are concentrated to the weak conductors at the expense of current flows thus weakened in the surroundings.

Different sensitivity to zones with different geometrical positions (dip, strike, etc.), depth and extent is obtained depending on the method of measurement and configuration or frequency. The sensitivity of the different methods to disturbing influences from the soil above the bedrock varies greatly. The influence of overlying soil containing saline clays or saline deposits may be so great that anomalies due to the bedrock are damped or disappear completely.

Telephone and power lines can also have varying disturbing effects on measurements.

4.4 Results and discussion

A study of the general summary of all resistivity measurements made shows clearly that the measured values seldom exceed 5000 ohm m and are frequently 1000 ohm m or lower. This is remarkable because crystalline bedrock often exhibits resistivity values exceeding 10,000 ohm m.

Table 2 shows the number of zones of weakness that were indicated using the resistivity method. The zones have been divided into three groups according to their width as noted in the tunnel.

As the table shows, no less than 96% of all the wide zones within the 0-3000 ohm m range were indicated. It is especially interesting to note also that up to 80% the very narrowest zones (< 10 m) in this resistivity range were indicated.

Almost all the indicated zones were water-bearing and more or less clay altered. Within the section range 0-500 ohm m, zones were indicated with very large clay contents, with or without water leaking in.

Table 2

THE BOLMEN TUNNEL GEOPHYSICAL EVALUATION RESISTIVITY MEASUREMENTS									
*ZONES OF WEAKNESS NOTED IN THE TUNNEL		NUMBER OF ZONES OF WEAKNESS INDICATED WITHIN RESPECTIVE "ohm m" RANGE							
WIDTH (M)	No.	< 500		500-1000		1000-3000		> 3000 ohm m	
		No.	%	No.	%	No.	%	No.	%
> 50	47	12	25	18	38	15	32	2	5
10-50	53	3	6	12	23	30	57	8	17
<10	70	0	0	21	33	33	47	16	20
*ZONES OF WEAKNESS ARE CONSIDERED TO BE THOSE REQUIRING SHOTCRETE AND/OR PRE-GROUTING									

Especially at tunnel stations 10-11 km (the Staverhult zone), 40-42 km, and 56-60 km (the Slättsjö zone) there are good examples of how, using the measured resistivity values, it has been possible to obtain a very detailed picture of the zones as a basis for assessing the various support measures.

Table 3 shows the support measures in relation to the various resistivity ranges. In this table the combined length of tunnel (expressed as a percentage) that required support work and/or pre-grouting is shown for four resistivity ranges.

Deep sounding using the resistivity method was carried out on several occasions to determine the approximate dip of principally clay-altered zones. This type of sounding has also been found to be useful in gaining an impression of the depth of a clay-weathered zone.

Table 3

THE BOLMEN TUNNEL GEOPHYSICAL EVALUATION RESISTIVITY MEASUREMENTS		
Ohm m RANGE	LENGTH OF TUNNEL (expressed as a percentage) THAT NEEDED	
	SHOTCRETE SUPPORT	PRE-GROUTING
< 500	75 %	*50 - 100 %
500 - 1000	50 %	70 %
1000 - 3000	20 %	25 %
>3000	3 %	7 %
*VARIATION MOSTLY BECAUSE OF THE CLAY CONTENT OF THE ZONES. A COMPLETE CLAY ALTERED ZONE MAY BE WATERTIGHT (RESISTIVITY VALUE DOWN TO ABOUT 200 ohm m)		

As mentioned earlier, the resistivity values measured in the bedrock between zones of weakness are very low (3000 - about 5000 ohm m). An explanation of this is probably the consistently high frequency of open water and/or clay-filled fractures of the rock in the Bolmen tunnel area. Rock stresses at the normal level of the tunnel (60-70 m) are also below the average of those previously measured in Precambrian terrains (Bjarnason-Leijon 1986).

Airborne measurements using the VLF method, carried out in conjunction with SGU's regular activities, were only available for the southern part of the tunnel. On the stretch between about stations 47 and 80 km, 32 VLF indications were noted (Drwg. BT-17). Three of these correspond to no zone of weakness in the tunnel. About 78% of the wide zones (> 50 m) and 25% of the narrow zones (10-50 m) in the tunnel were indicated by airborne measurements using the VLF method (Table 4). Over the entire length of the tunnel on which ground-level measurements were made using the VLF method, 74% of the wide zones were indicated and 62% of the narrow ones (10-50 m).

In this context, however, it should be pointed out that the indication frequency is considerably lower in the northern part of the tunnel (0-30 km) than in the southern part. The reason for this is probably the large proportion of low dipping zones in the northern part.

Table 4

THE BOLMEN TUNNEL
GEOPHYSICAL EVALUATION
V L F MEASUREMENTS

TUNNEL STATION	ZONES OF WEAKNESS NOTED IN THE TUNNEL		NUMBER OF ZONES INDICATED *AIRBORNE		GROUND-LEVEL	
KM	> 50 m	10-50 m	> 50 m	10-50 m	> 50 m	10-50 m
10-15	4	3	-	-	3	2
15-20	3	9	-	-	0	3
20-25	4	7	-	-	1	2
30-35	2	2	-	-	2	2
35-40	5	3	-	-	5	3
40-45	4	3	-	-	4	2
45-50	**3(1)	6(1)	2	-	1	1
50-55	3(1)	9(6)	2	4	1	4
55-60	6(5)	6(2)	5	2	5	2
60-65	2	8	1	-	-	-
65-70	2	7(3)	3	2	-	3
70-75	5	8	4	3	-	-
75-80	5	7	1	1	-	-
			18(78%)	12(25%)	22(74%)	24(62%)

*AIRBORNE MEASUREMENTS ARE ONLY AVAILABLE FOR THE STRETCH FROM STATION 47 TO STATION 80 KM.

**THE FIGURE IN BRACKETS INDICATES THE NUMBER OF ZONES ENCOUNTERED IN THE TUNNEL WITHIN THE SECTION IN WHICH GROUND-LEVEL VLF MEASUREMENTS WERE MADE.

Slingram measurements were only performed as ground-level measurements along a stretch of about 12 km. VLF measurements are also available for this entire stretch. No great difference in the indication frequency of zones of weakness is noticeable between the two methods. 85% of the wide zones (> 50 m) and 60% of the narrow ones (10-50 m) were indicated by the Slingram measurements.

As regards the intensity of the zones (degree of crushing, any clay alteration or the amount of water), the VLF and slingram methods exhibit good agreement in the case of the most intensive regional zones (the Hallandås uplift boundary fault). There are insufficient indications in other zones to provide a basis for evaluating the intensity.

Individual VLF and Slingram profile measurements generally provided insufficient bases for evaluating the widths of zones. But in the case of wide and intensive zones, distinct anomalies were often obtained at the outer limits of the zones, against better rock. In this context, the ability of the EM methods to permit determination of the dip of the zones under certain circumstances should be emphasized.

4.5 Conclusions

1. The results reported here indicate that zones of weakness in bedrock can be successfully located using all electrical methods. This applies particularly to wide clay-altered zones and/or those containing large quantities of water of a regional character.

2. Steep zones can be located with considerably greater success than those with a low dip.

3. The possibility of obtaining an indication is affected principally by the quantity of clay and water in the zone. This means that the possibility of assessing the quantity of water leaking into a zone is made considerably more difficult under geological conditions that include a high incidence of clay-altered zones.

4. It is generally not possible to indicate "a single water-bearing fracture" in sound rock.

5. Distinct, well defined fracture zones surrounded by basically fracture-free, good rock are more easily located than fracture zones in more diffuse surroundings.

6. The depth of soil cover, its composition and content of water, are probably of major significance for detection of fracture zones.

7. At the reconnaissance stage, the EM methods (specially VLF) have great advantages because of the mobility they permit and their relatively low cost. Any aerial measurement information (SGU) should naturally also be used and complemented by ground-level measurements.

8. One disadvantage that applies particularly to the EM methods is the disturbing effect that overhead power lines, electric railway installations and urban development can have. These factors should be taken into account at the planning stage.

9. Resistivity measurements are very suitable for more detailed investigation of the extent and intensity of zones of weakness.

10. Very low resistivity values (< 500 ohm m) usually indicate more or less completely clay-altered zones of weakness, with very variable water-bearing properties. These areas frequently require relatively heavy support work.

11. Deep soundings at local points of resistivity minima may clarify whether the minimum is due to extremely low resistivity in the soil cover or low bedrock resistivity (zone of weakness).

12. Anisotropic resistivity conditions caused by a difference in fracture intensity along and across the wide zones may give rise to different results depending on the orientation of the electrode configuration. The lowest rock resistivity is obtained when measuring parallel to the main orientation of the fractures.

13. Good results are obtained from the use of the parallel profile measurements and the resulting resistivity map for determining alternative routes through the wide zones of weakness.

5. REFRACTION SEISMIC TECHNIQUE

5.1 Method and conditions

The seismic refraction method utilizes the fact that compressional waves travel at different speeds in different materials in the ground. The method is often used for determination of the soil depth and velocities of waves in rock, and, under favourable conditions, it can provide information about soil types and the level of the groundwater table.

Compressional waves in the ground are generated by an explosive, usually Dynamex, which is initiated using electric detonators. The size of the explosive charge is adjusted in accordance with certain factors, including the composition of the soil, soil depth, distance between the explosion and the geophones and any disturbing waves from traffic, for example.

Soil depth and wave velocity determinations are carried out in straight lines along which the instrument's geophones, normally 12 or 24, are placed directly on the ground, usually at 5-m centres. The distance between the shot points is usually from 25 to 50 m, depending on the soil depth and size of the charge. For each configuration of geophones, a number of shot points are located between the geophones and two between 25 and 50 m on each side of the geophone configuration.

The compressional wave from the shot travels through the ground, either directly, in the upper soil layer or through underlying layers, whose seismic velocities are higher, to the geophones. The geophones are very sensitive to vibration and convert the vibration energy into electric energy. They are connected to a recording instrument that registers the time taken by the compressional waves to travel from the shot point to the instrument. The travelling time between the shot points and the geophones are plotted on a wave-time graph. The velocities in the soil and rock and the depth of soil may be calculated by interpreting this graph.

Most site investigations only involve the use of the velocity of the compressional wave (P wave).

Seismic velocities in soil normally vary between 400 and 2700 m/s. The velocity in sound crystalline rocks is usually between 4000 and 6000 m/s.

The rock velocity stated in a normal seismic report is usually the average of the "highest velocities" for a certain section of the profile. The velocity in the upper part of fractured and weathered rock is lower than in the sound rock below. This lower velocity may be reported as the "superficial rock velocity".

As the Bolmen tunnel is generally at a depth of about 50 m or more below ground level, the "highest seismic rock velocity" has been used throughout in evaluation as it is regarded as best representing the level of the structure in the rock.

5.2 Results and discussion

According to current Swedish practice, the seismic rock velocity 4000 m/s has often formed the boundary between rock of acceptable quality and rock that is regarded as having less good properties from a building and construction point of view. Seismic velocities in rock between about 3000 and 6000 m/s are common in Swedish crystalline bedrock. Rock with seismic velocities above 4500 m/s is normally expected to contain few fractures and to be generally sound, whereas a velocity below 4000 m/s is regarded as corresponding to a greater incidence of fracturing and a certain amount of clay alteration (weathering). Velocities below 3000 m/s are suspected of being indicative of crushed or more or less completely clay altered rock. The range from 4000 to 4500 m/s is usually considered to correspond to something between "good" and "less good" rock.

In the site investigations, roughly the divisions into seismic velocities in rock described above were used to classify the rock and assess the support measures required in the Bolmen tunnel.

In evaluating the seismic method, the zones of weakness documented in the tunnel were divided into three groups according to their width - above 50 m, 10-50 m and below 10 m. These zones generally required some form of support. In the initial part of the evaluation a correlation was made between the seismic velocities in rock and the zones of weakness. In this the seismic velocities were divided into three ranges, taking into account the percentage deviation from an estimated "highest" average velocity for the bedrock being considered. This velocity was estimated to be 5500 m/s (Cecil, 1971). The following three ranges were selected: 10-20%, 20-30% and above 30% deviations from 5500 m/s. Expressed in metres per second, they are 5000-4400, 4400-3900 and less than 3900.

Table 5 shows the total number of zones of weakness requiring support in the Bolmen tunnel that were indicated seismically within the rock velocity anomalies stated above. The number of zones requiring more qualified support work, in the form of reinforcing and more than 50 mm shotcrete, is indicated in brackets.

Table 5

THE BOLMEN TUNNEL GEOPHYSICAL EVALUATION SEISMIC REFRACTION						
THE TOTAL No. OF ZONES OF WEAKNESS, REQUIRING SUPPORT WORK, THAT WERE INDICATED SEISMICALLY						
SEISMIC VELOCITY IN ROCK (M/S)	ZONE WIDTH					
	> 50 M		10 - 50 M		< 10 M	
	No.	%	No.	%	No.	%
5000 - 4400	42(11)	30(18)	34(6)	16(13)	64(4)	22(20)
4400 - 3900	42(12)	30(20)	52(11)	24(23)	60(6)	20(30)
< 3900	43(32)	30(53)	87(28)	40(58)	36(3)	12(15)
Unregistered zone	14 (5)	10 (9)	44 (3)	20 (6)	138(7)	46(35)
	141(60)		217(48)		298(20)	
THE NO. OF ZONES REQUIRING MORE QUALIFIED SUPPORT WORK (REINFORCED SHOTCRETE > 50 MM) IS SHOWN IN BRACKETS						

Because of the varying depth of the Bolmen tunnel below ground level, the results shown in Table 5 have been divided up by tunnel depth as shown in Table 6 below.

Table 6

THE BOLMEN TUNNEL
GEOPHYSICAL EVALUATION
SEISMIC REFRACTION

SEISMIC VELOCITY IN ROCK (M/S)	ZONE WIDTH					
	> 50 M		10 - 50 M		< 10 M	
	No.	%	No.	%	No.	%
5000 - 4400	11 (7)	26(24)	7 (3)	11(17)	23 (4)	27(33)
4400 - 3900	9 (7)	23(24)	12 (4)	20(22)	9 (4)	10(33)
< 3900	17(13)	43(45)	28(11)	47(61)	9 (1)	11 (9)
Unregistered zone	3 (2)	8 (7)	13 (0)	22	45 (3)	52(25)
	40(29)		60(18)		86(12)	

THE NO. OF ZONES OF WEAKNESS REQUIRING SUPPORT WORK THAT WERE INDICATED SEISMICALLY AT AVERAGE TUNNEL DEPTH ≥ 70 M

SEISMIC VELOCITY IN ROCK (M/S)	ZONE WIDTH					
	> 50 M		10 - 50 M		< 10 M	
	No.	%	No.	%	No.	%
5000 - 4400	10 (1)	22 (8)	11 (0)	13	17 (0)	14
4400 - 3900	16 (2)	35(15)	27 (4)	31(26)	31 (0)	26
< 3900	13 (9)	28(69)	33(10)	38(67)	15 (1)	13(50)
Unregistered zone	7 (1)	15 (8)	15 (1)	18 (7)	56 (1)	47(50)
	46(13)		86(15)		119 (2)	

THE NO. OF ZONES OF WEAKNESS REQUIRING SUPPORT WORK THAT WERE INDICATED SEISMICALLY AT AVERAGE TUNNEL DEPTH 50 - 70 M

SEISMIC VELOCITY IN ROCK (M/S)	ZONE WIDTH					
	> 50 M		10 - 50 M		< 10 M	
	No.	%	No.	%	No.	%
5000 - 4400	21 (3)	38(17)	16 (3)	23(20)	24 (0)	29
4400 - 3900	17 (3)	31(17)	13 (3)	18(20)	20 (2)	12(33)
< 3900	13(10)	24(55)	26 (7)	37(47)	12 (1)	14(17)
Unregistered zone	4 (2)	7(11)	16 (2)	22(13)	37 (3)	45(50)
	55(18)		71(15)		93 (6)	

THE NO. OF ZONES OF WEAKNESS REQUIRING SUPPORT WORK THAT WERE INDICATED SEISMICALLY AT AVERAGE TUNNEL DEPTH < 50 M

Table 7 shows the total number of zones of weakness that were not recorded with anomalies of 10% or more (seismic velocity 5000 m/s) as regards the highest recorded velocity in rock. The corresponding value when taking into account the seismic velocity in superficial rock is shown in brackets.

Table 7

TUNNEL DEPTH	ZONE WIDTH		
	> 50 M	10 - 50 M	< 10 M
≤ 50 m	4 (4)	16(13)	37(26)
55-70 m	7 (3)	17 (9)	56(22)
≥ 75 m	3 (1)	11 (3)	45(17)
	14 (8)	44(25)	138(65)

Table 8 shows the relationship between the seismic velocity in rock and the temporary support and/or pre-grouting operations performed. The tunnel was divided into sixteen 5-km long sections from north to south. The seismic velocities, which are the highest recorded velocities throughout, have been divided into five ranges. The length of the tunnel requiring temporary support (pre-grouting) is expressed in a percentage of the length of the respective seismic velocity ranges in the tunnel.

It may be seen from the above that 21% of the tunnel that had seismic velocities in rock as high as 4500 to 5000 m/s required support (shotcrete, 25-50 mm). It is also worth noting that stretches in which the seismic velocity in rock was less than 3900 m/s have generally been given some form of temporary support.

The relationship between the seismic velocity in rock and the need for pre-grouting because of water leaking must be handled with great care, but despite this there is a clear agreement between low seismic velocities in rock (< 4000 m/s) and water leaking into the Bolmen tunnel.

Both Cecil (1971) and Sjögren (1979) discuss correlation between the need for support in tunnels and seismic velocities in rock. Cecil states a "Seismic Velocity Ratio" of 0.80 as the boundary for "probable zones of weakness that usually require considerable support". The figure 0.80 is in good agreement with the deviation of 20% from the assumed maximum velocity of 5500 m/s used in this evaluation. As mentioned above, rock with seismic velocities in the range 4500 - 4000 m/s exhibited a 43% need of support in the Bolmen tunnel. For approximately the same range (41000-4400 m/s), Sjögren (1979) states the need for "more extensive support". Both Cecil and Sjögren relate their values to "small or medium-sized tunnels".

The relationships between seismic velocities in rock and the need for support shown in the table should be capable of forming the basic information for a relatively good assessment of the need for support in small and medium-sized tunnels in crystalline bedrock. Attention should naturally also be paid to the depth of the structure and local geological conditions. As pointed out above, in conjunction with the discussion on resistivity measurements, special interest should be paid to the rock stress conditions. A large incidence of fracturing has been noted throughout the Bolmen tunnel - even at relatively large tunnel depths - despite seismic velocities of about 5000 m/s (see Drwg. BT-17). Rock stress measurements performed in the Bolmen tunnel show that the horizontal rock stresses are below the average down to relatively large depths (60-70 m). The normal increase in the seismic velocities in rock of 10-15% that normally occur in crystalline bedrock may therefore be assumed to be insignificant in most of the Bolmen tunnel. In other words, "superficial rock conditions" may be expected in the Bolmen tunnel, even at large depths, with a large incidence of open, water-bearing or clay filled fractures.

As regards agreement between the seismic low-velocity stretches and corresponding zone widths in the tunnel it is found in the case of the widest zones (> 50 m) that 16 of 127 were narrower and 24 were wider than expected in the tunnel. Correspondingly for the 172 zones from 10 to 50 m wide, 47 were narrower and 26 wider than expected in the tunnel. Of the 150 narrowest zones (< 10 m), 108 were considerably narrower in the tunnel than indicated by the seismic anomalies.

It has not been possible to relate a total of 33 seismic anomalies (≥ 10%) with any weak zone at the tunnel level.

Narrow zones (< 10 m) may often be related to small changes in velocity (< 10% of the assumed maximum velocity = 5500 m/s).

5.3 Conclusions

1. The refraction seismic technique is generally an excellent method of locating zones of weakness in crystalline bedrock. But the method has considerable limitations as regards the dip of the zones - low dipping zones are generally not indicated.

2. There was no great difference in indication frequency of fracture zones at different depths in the Bolmen tunnel.

3. There is hardly any general correlation between seismic velocities in rock and water leakage into the rock installation. But in the Bolmen tunnel there is a clear relationship between low-velocity zones (< 3900 m/s) and pre-grouting performed because of water leakage into the tunnel.

4. The relationship between support works performed in the tunnel and seismic velocities in rock shown in Table 8 should provide sufficient information for assessing support measures, even in other similar installations in Swedish crystalline bedrock.

5. The indication frequency increases considerably if the reported seismic velocities in superficial rock are taken into account. This implies that "superficial rock conditions" exist to a relatively large depth in large parts of the Bolmen tunnel.

6. A certain amount should be known about the rock stress conditions in the rock being considered to be able to interpret the significance of the seismic results in a more reliable manner from the point of view of stability in a rock installation.

Table 8

THE BOLMEN TUNNEL
GEOPHYSICAL EVALUATION
SEISMIC REFRACTION

RELATIONSHIP BETWEEN THE SEISMIC VELOCITY IN ROCK AND THE TEMPORARY SUPPORT AND PRE-GROUTING OPERATIONS PERFORMED

DRAWING NO.	AVER. TUNNEL DEPTH	SEISMIC VELOCITY IN ROCK (M/S)										TUNNEL PART (KM)
		> 5000		4500-5000		4000-4500		3500-4000		< 3500		
		SU(%)	P-G(%)	SU(%)	P-G(%)	SU(%)	P-G(%)	SU(%)	P-G(%)	SU(%)	P-G(%)	
BT-01	20	6	1	29	16	57	17	49	75	100	100	0- 5
BT-02	50	4	7	22	12	47	27	100	100	-	-	5-10
BT-03	55	4	7	22	15	47	47	100	100	-	-	10-15
BT-04	65	5	5	8	4	32	29	92	100	71	-	15-20
BT-05	55	*28	*13	*80	*47	*60	*17	*100	*100	*67	*52	20-25
BT-06	70	7	16	19	34	30	69	51	33	100	100	25-30
BT-07	50	12	20	27	27	74	91	90	94	100	70	30-35
BT-08	50	2	2	2	19	42	81	32	76	66	100	35-40
BT-09	65	15	42	20	46	29	46	84	84	100	100	40-45
BT-10	75	1	14	10	33	25	86	25	48	100	100	45-50
BT-11	80	10	12	35	40	31	32	57	100	100	100	50-55
BT-12	80	12	11	28	30	62	55	95	89	100	79	55-60
BT-13	80	5	6	24	14	8	12	51	38	100	85	60-65
BT-14	95	1	7	8	34	45	68	100	91	75	100	65-70
BT-15	65	1	2	4	14	66	12	100	33	100	5	70-75
BT-16	55	4	5	52	15	49	4	100	45	87	5	75-80
AVER. VALUE		6	11	21	24	43	45	75	74	92	79	

* NOT INCLUDED IN THE AVER. VALUES BECAUSE OF PREDOMINANTLY LOW DIPPING STRUCTURES

SU = TEMPORARY SUPPORT P-G = PRE-GROUTING

NB. 6% OF THE LENGTH OF THE TUNNEL - WITH SEISMIC VELOCITY IN ROCK > 5000 M/S - REQUIRED SUPPORT WORK (SHOTCRETE AT LEAST 25-50 MM)

6. SUMMARY OF RESULTS

6.1 Airborne geophysical measurements

Evaluation of the airborne geophysical measurements shows that it has been possible, using electro-magnetic measurements, to indicate about 80% of the zones of weakness wider than 50 m on the 47-80 km stretch. The corresponding figure for narrower zones (< 50 m) was 25%. Of the dolerite dykes wider than 10 m, 88% have been indicated magnetically (Fig. 11).

6.2 Ground-level magnetic measurements

The results of ground-level magnetic measurements show largely the same indication frequency as the airborne magnetic measurements. But for obvious reasons, dykes were indicated with considerably greater accuracy (10 to 20 m) than was possible with airborne measurements (100 to 150 m).

6.3 VLF measurements (ground level)

Using the VLF measurements, it has been possible to indicate about 75% of the wide zones (> 50 m) and just over 60% of the narrower ones. But the variation along the length of the tunnel was great, presumably due to the locations of the zones in relation to the transmitter and probably also due to the variation of dip of the zones (Fig. 12).

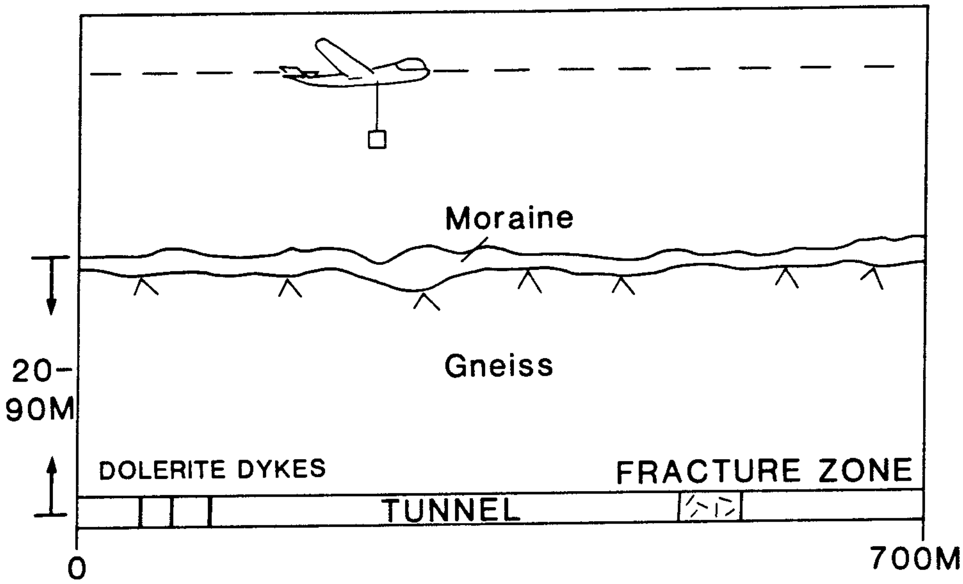
6.4 Slingram measurements (ground level)

Using Slingram measurements, which were only made on a stretch about 12 km long, about 85% of the wide zones (> 50 m) and about 60% of narrower zones (10 to 50 m) were indicated. The electro-magnetic indications generally provide no information on the width and intensity of zones (Fig. 12).

6.5 Seismic refraction measurements

The seismic velocities measured in conjunction with the preinvestigations along the tunnel were correlated to the zones of weakness documented during the tunnelling work. Unless otherwise stated, the velocities are the maximum seismic velocities in rock. The "seismic anomalies" are divided into three groups, with 10 to 20%, 20 to 30% and more than 30% deviation from an estimated maximum average seismic velocity in rock of 5500 m/s, which may be

THE BOLMEN TUNNEL



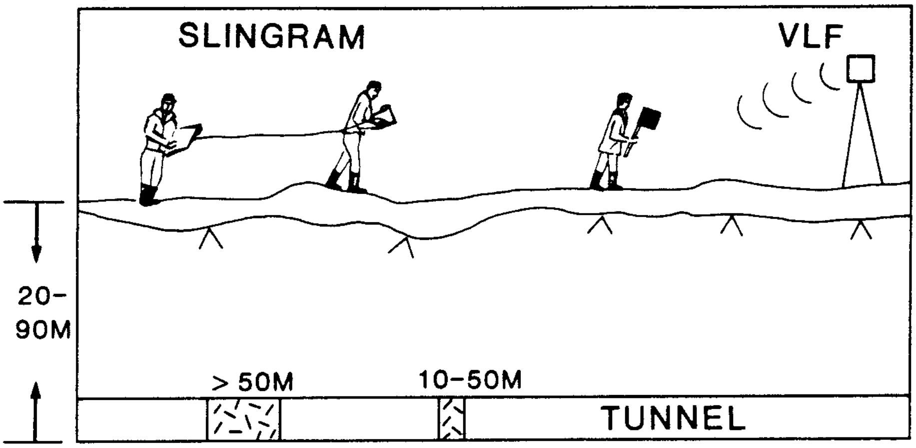
AIRBORNE MAGNETIC AND ELECTRO-MAGNETIC MEASUREMENTS

~90% OF ALL DOLERITE DYKES (>10M WIDE) MAPPED IN THE TUNNEL WERE INDICATED BY MAGNETIC MEASUREMENTS!

~80% OF ALL FRACTURE ZONES (>50M WIDE) IN THE TUNNEL WERE INDICATED BY ELECTROMAGNETIC MEASUREMENTS !

Fig. 11

THE BOLMEN TUNNEL
VLF (GROUND) AND SLINGRAM (GROUND) MEASUREMENTS



85% OF ALL FRACTURE ZONES, > 50M WIDE, AND 60% , OF THE 10-50M WIDE ZONES, MAPPED IN THE TUNNEL, WERE INDICATED BY SLINGRAM MEASUREMENTS.

VLF INDICATED 75% OF THE LARGER ZONES (> 50M) AND 60% OF THE SMALLER (10-50 M) FRACTURE ZONES.

Fig. 12

regarded as representativ of the gneiss-amphibolite bedrock in the region. These percentages give the velocity ranges 5000-4400m/s, 4400-3900 m/s and < 3900 m/s.

The zones of weakness were also divided into three groups on the basis of their width at the tunnel level: more than 50 m, 10 to 50 m and less than 10 m. The evaluation shows that of the 141 wide zones (> 50 m), only 31% were indicated by velocities below 3900 m/s, 30% were indicated in the range 3900 to 4400 m/s and 29% between 4400 and 5000 m/s. For the 216 zones 10 to 50 m wide, the distribution was 40%, 24% and 16%, and for the 288 narrowest zones (< 10 m), the figures were 13%, 17% and 22% (Fig. 13).

It is particularly noteworthy that almost one third of all zones indicated were in the velocity range 4400 to 5000 m/s.

If the velocities indicating highly fractured superficial rock also are taken into account, it is found that of the total of 196 zones that were not indicated by "maximum seismic velocities" in rock of 5000 m/s or less, approx. 50% more were indicated. This indicates that basically "superficial rock conditions" continue almost down to the level of the tunnel, even where the rock cover is relatively deep (70-90 m).

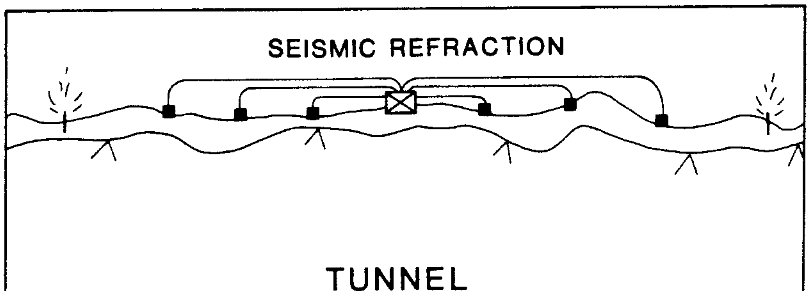
It is also interesting to note that only about 50% of the narrowest zones (< 10 m) were indicated by seismic velocities of 5000 m/s or less, and that most of the zones that were indicated seismically continued to a depth of 50 to 80 m.

The narrowest zones often exhibit a clear relationship with the change in seismic velocity in rock that is in many cases less than 10% of the assumed maximum velocity (5500 m/s).

Of the total of 482 seismic velocity anomalies, it has been possible to relate all but 33 to zones of weakness in the tunnel. Of these, the velocity in 19 was between 4400 and 5000 m/s, in 9 it was between 3900 and 4400 m/s and in 5 it was below 3900 m/s.

The relationships between seismic velocities in rock and support measures/pre-grouting shows that about 6% of the length of the tunnel that had velocities above 5000 m/s required support work (shotcrete) and about 10%

THE BOLMEN TUNNEL
CORRELATION BETWEEN FRACTURE ZONES IN TUNNEL AND SEISMIC VELOCITY IN THE OVERLYING BEDROCK



SEISM. VELOC.	> 50m	10–50m	< 10m
<3900	31%	40%	13%
3900–4400	30%	24%	17%
4400–5000	29%	16%	22%

N.B. 31% OF ALL FRACTURE ZONES (>50M WIDE), MAPPED IN THE TUNNEL WERE INDICATED BY A SEISMIC VELOCITY < 3900 M/S.

Fig. 13

was pre-grouted. Corresponding figures for seismic velocities in rock within the 4400 to 5000 m/s range were 21% for support work and 24% for pre-grouting. In the case of stretches with velocities between 3900 and 4400 m/s, 43% required support work and 45% pre-grouting, and for sections with velocities between 3500 and 3900 m/s, support work and pre-grouting was carried out over about 75% of the distance. Of the rock in which velocities below 3500 m/s was recorded 92% required support work and about 80% pre-grouting (Fig. 14).

6.6 Resistivity measurements

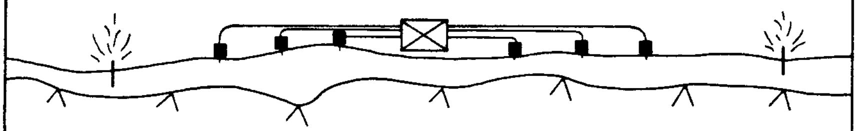
The experience gained from the resistivity method shows that, above all, the zones of weakness containing a combination of water and clay can be located and described with success using this method. In rock in which readings below 3000 ohm m were obtained, 95% of all wide zones (> 50 m) were indicated, and 80% of the narrowest zones (< 10 m) (Fig. 15).

Some 75% of the length of tunnel in which readings were below 500 ohm m required shotcrete support and 50 to 100% required pre-grouting. The large scatter as regards pre-grouting is due principally to the varying clay content. Corresponding figures for sections in which resistivity readings were between 500 and 1000 ohm m was 50% for support and 70% for pre-grouting.

The sections in which resistivity readings were below 500 ohm m required reinforced concrete or steel-fibre concrete support over about 50% of their length. The corresponding figure for rock in which values were below 300 ohm m was 75%.

Deep sounding using the resistivity method permits assessment of the zones' dip and change in intensity with depth.

THE BOLMEN TUNNEL CORRELATION BETWEEN SEISMIC VELOCITY IN BEDROCK AND NEED FOR SHOTCRETE SUPPORT AND GROUTING IN THE TUNNEL



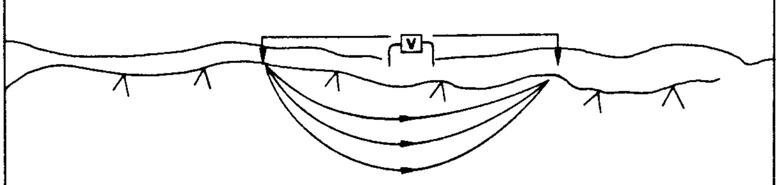
TUNNEL

SEISM. VELOC.	SHOTCRETE	GROUTING
M/S >5000	6%	10,5%
4500–5000	21%	23,5%
4000–4500	43%	45%
3500–4000	75%	74%
<3500	92%	80%

N.B. 6% OF THE TOTAL TUNNEL LENGTH WITH A SEISMIC VELOCITY IN THE OVERLYING BEDROCK > 5000 M/S REQUIRED SHOTCRETE SUPPORT AND 10% REQUIRED GROUTING.

Fig. 14

THE BOLMEN TUNNEL
RESISTIVITY MEASUREMENTS
CORRELATION BETWEEN FRACTURE ZONES IN TUNNEL AND RESISTIVITY IN THE OVERLYING GROUND



RESISTIV. IN Ω M	> 50m	10-50M	< 10m
< 500	25%	6%	0%
500-1000	38%	28%	33%
1000-3000	32%	57%	47%
>3000	5%	17%	20%

N.B. 25% OF ALL FRACTURE ZONES. > 50M WIDE IN TUNNEL, WERE INDICATED BY RESISTIVITY < 500 Ω M.

Fig. 15

7. GENERAL CONCLUSIONS

The results from an extensive programme of geophysical measurement for the 80-km long Bolmen tunnel have been summarized and evaluated on the basis of the information on the quality of the bedrock that was obtained by thorough geo-mapping in the blasted tunnel.

The aim of the evaluation was primarily to determine the ability of the various methods of geophysical measurement to indicate the zones of weakness that required support and/or pre-grouting in the tunnel. The ability of the magnetic measurements to differentiate between different types of rock has also been studied.

The overall experience gained from the evaluation may be formulated in the following points:

1. Geophysical measurements are a necessary aid in the pre-investigation stage for subsurface construction projects constructed completely or partly in soil-covered terrain.

2. The geophysical pre-investigation strategy should be carefully adapted to the nature of the rock structure and the general geological conditions.

3. A combination of two or more geophysical methods is often necessary for making good predictions of subsurface conditions.

4. A well planned geophysical programme will provide a good chance of locating vertical or medium-steep zones of weakness more than about 10 m wide in the bedrock. Narrower zones and, above all, low dipping zones are considerably more difficult to locate.

5. A reliable prediction of water leakage into a rock installation cannot generally be made solely on the basis of geophysical measurements.

6. Using principally refraction seismic and resistivity measurements there is a good chance of making a general assessment of the support measures that indicated zones of weakness will require.

7. A reasonably good idea of the rock stress situation at the level of the proposed installation in the rock considerably improves the chance of making a correct engineering geology interpretation of the geophysical measurements.

8. ACKNOWLEDGEMENTS

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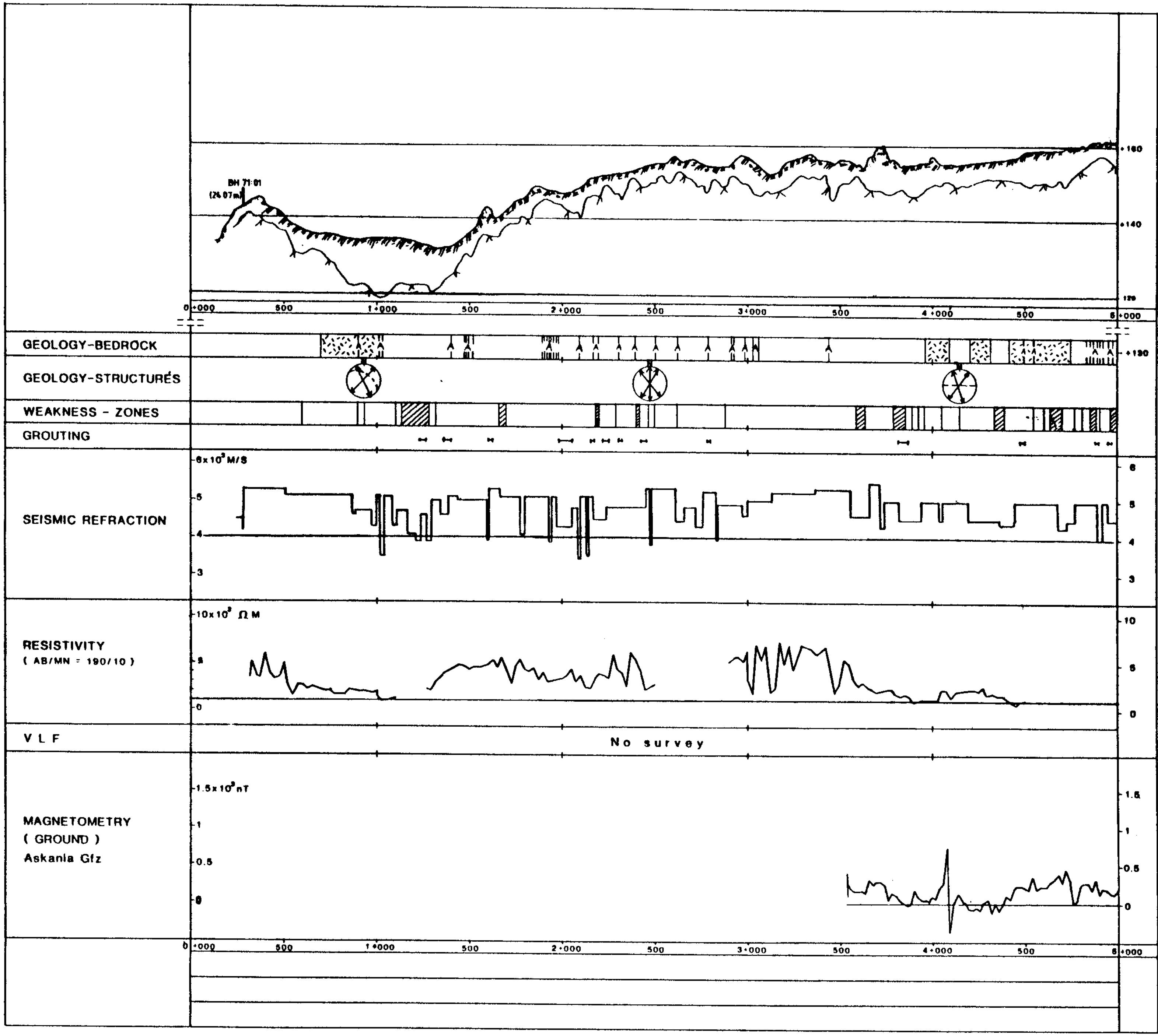

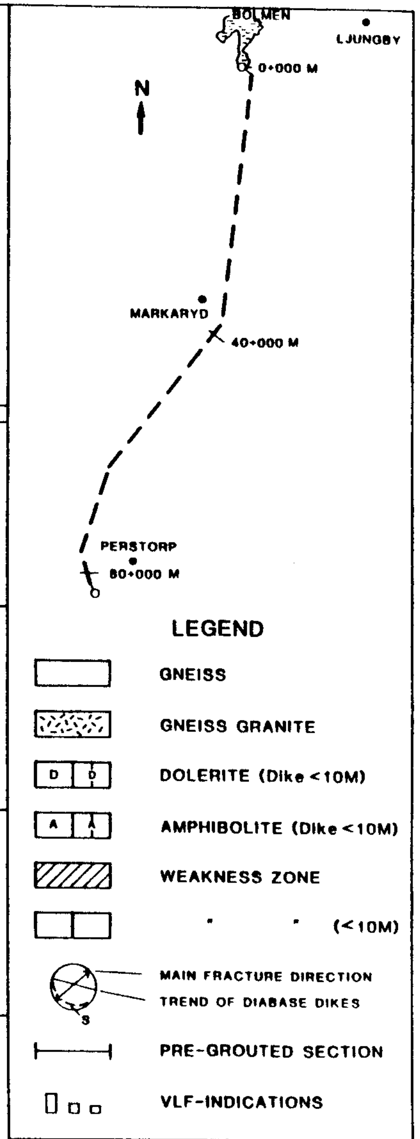

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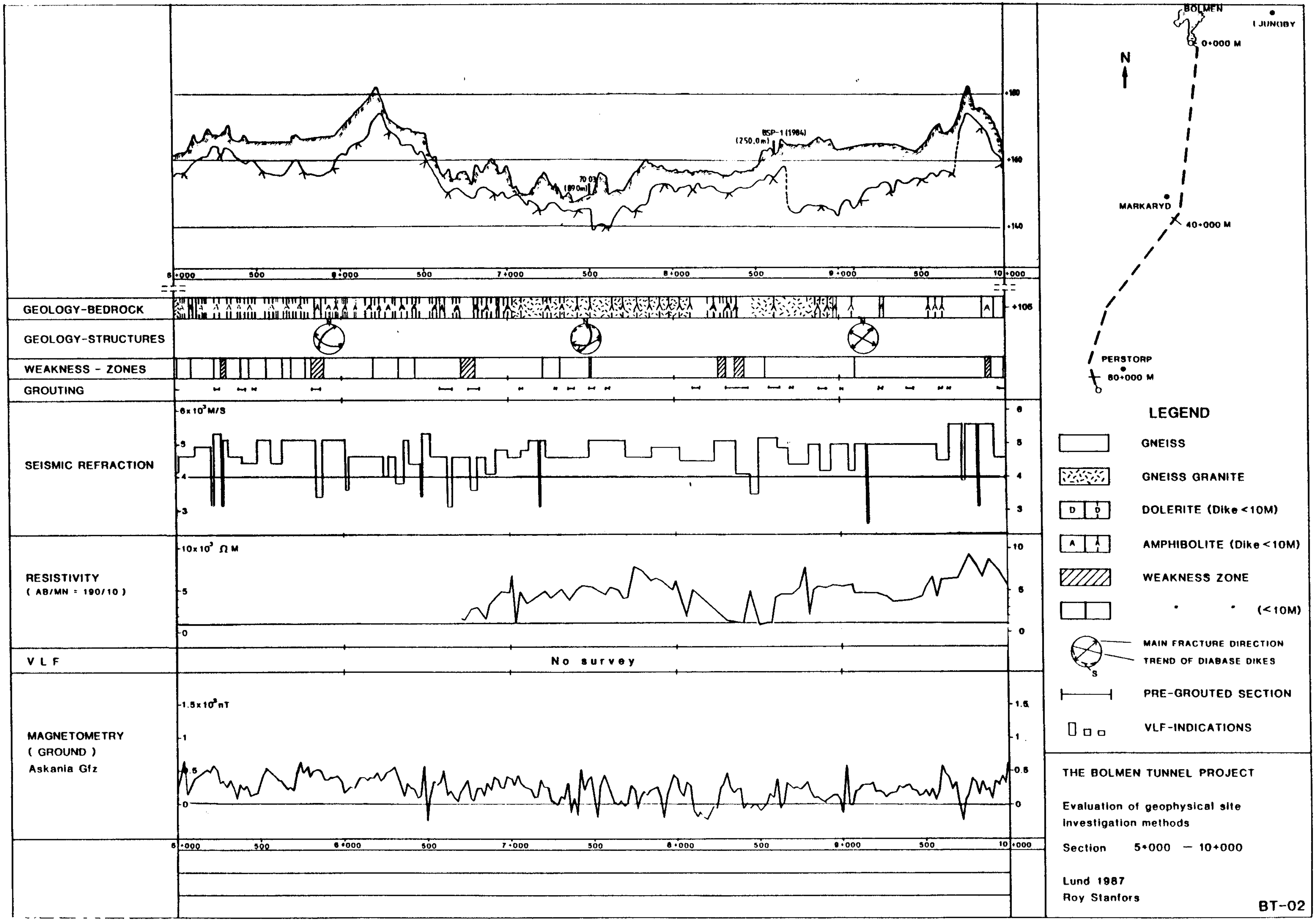

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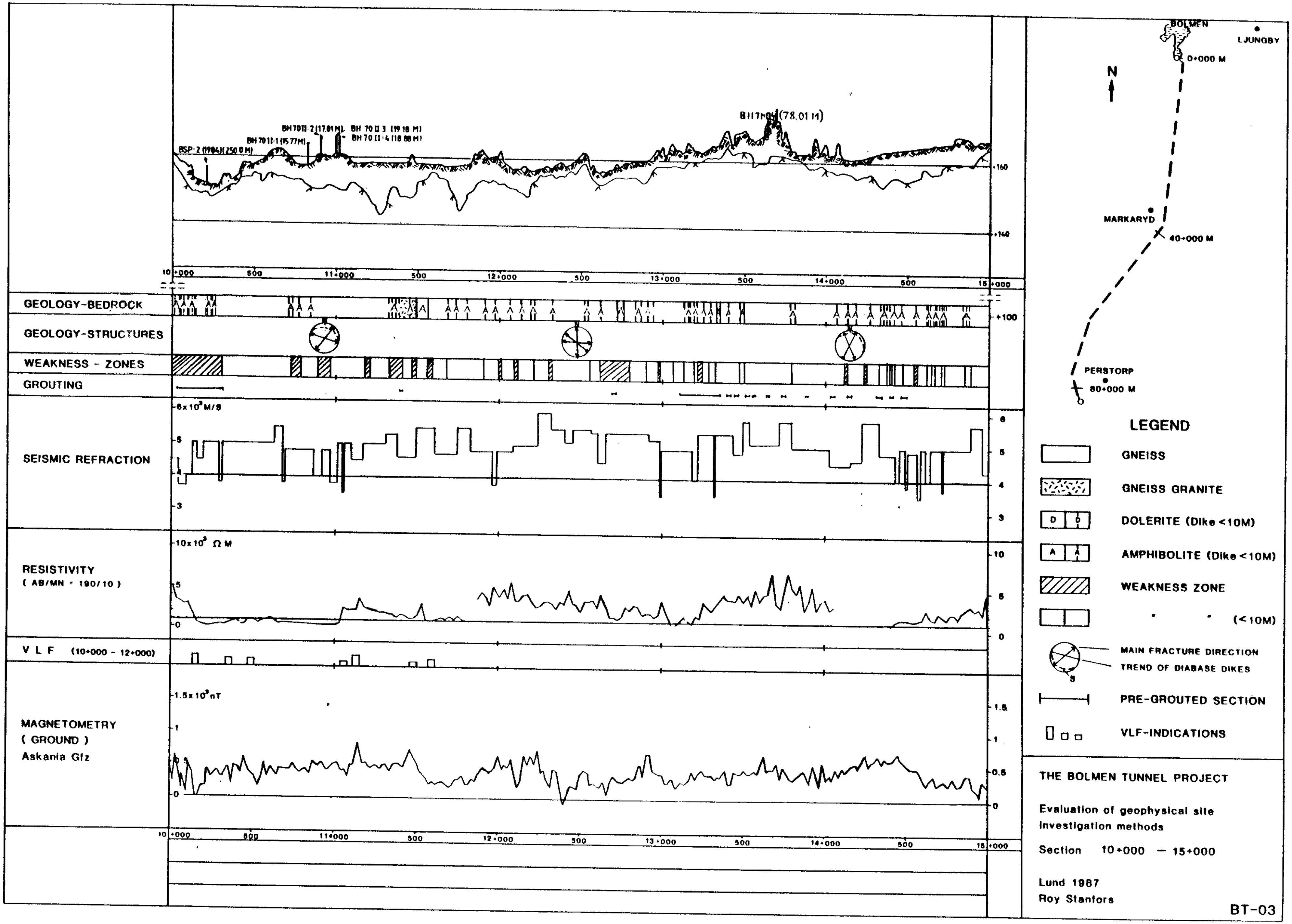
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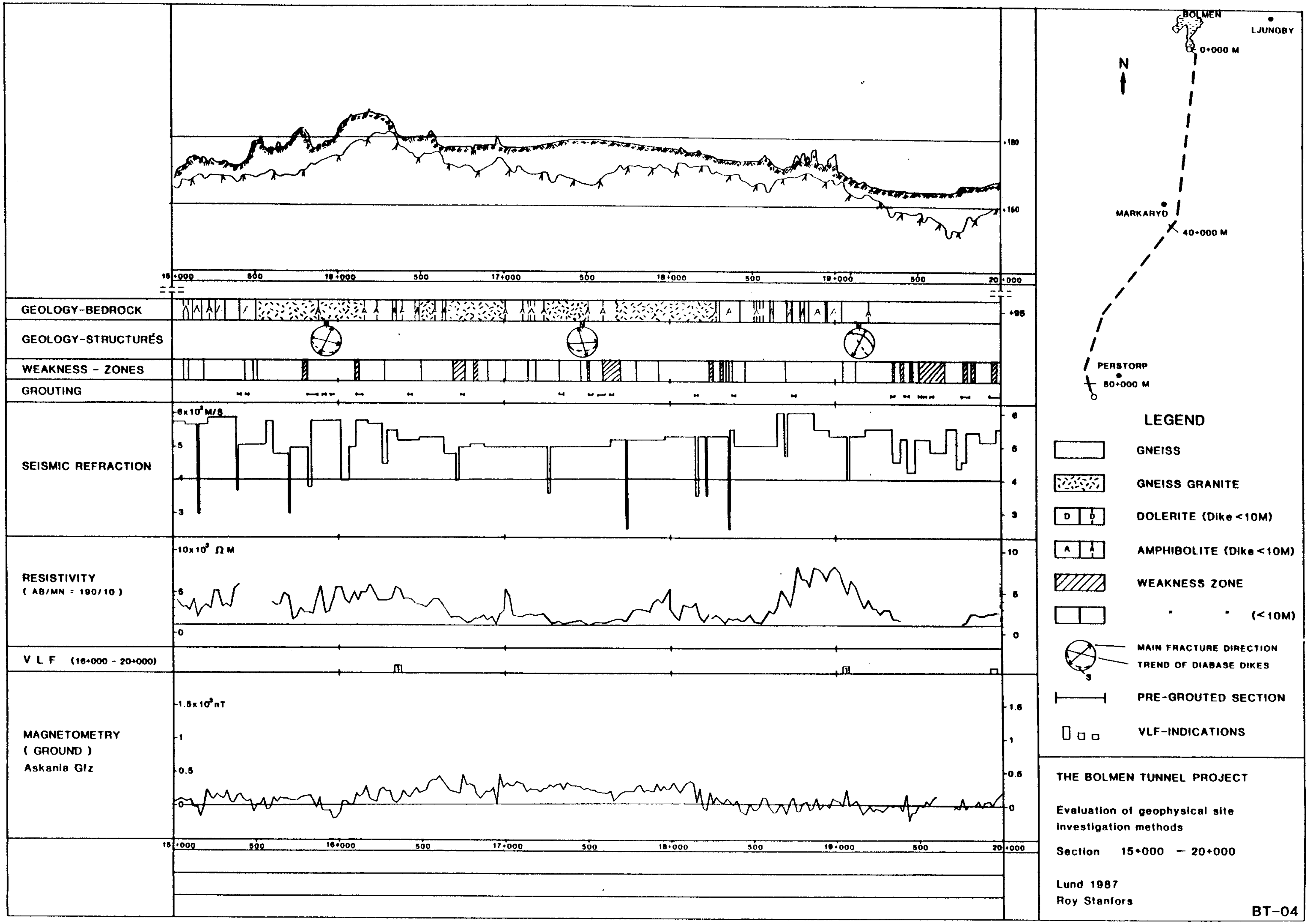

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(GROUND)
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10x10³ Ω M
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40+000 M
PERSTORP
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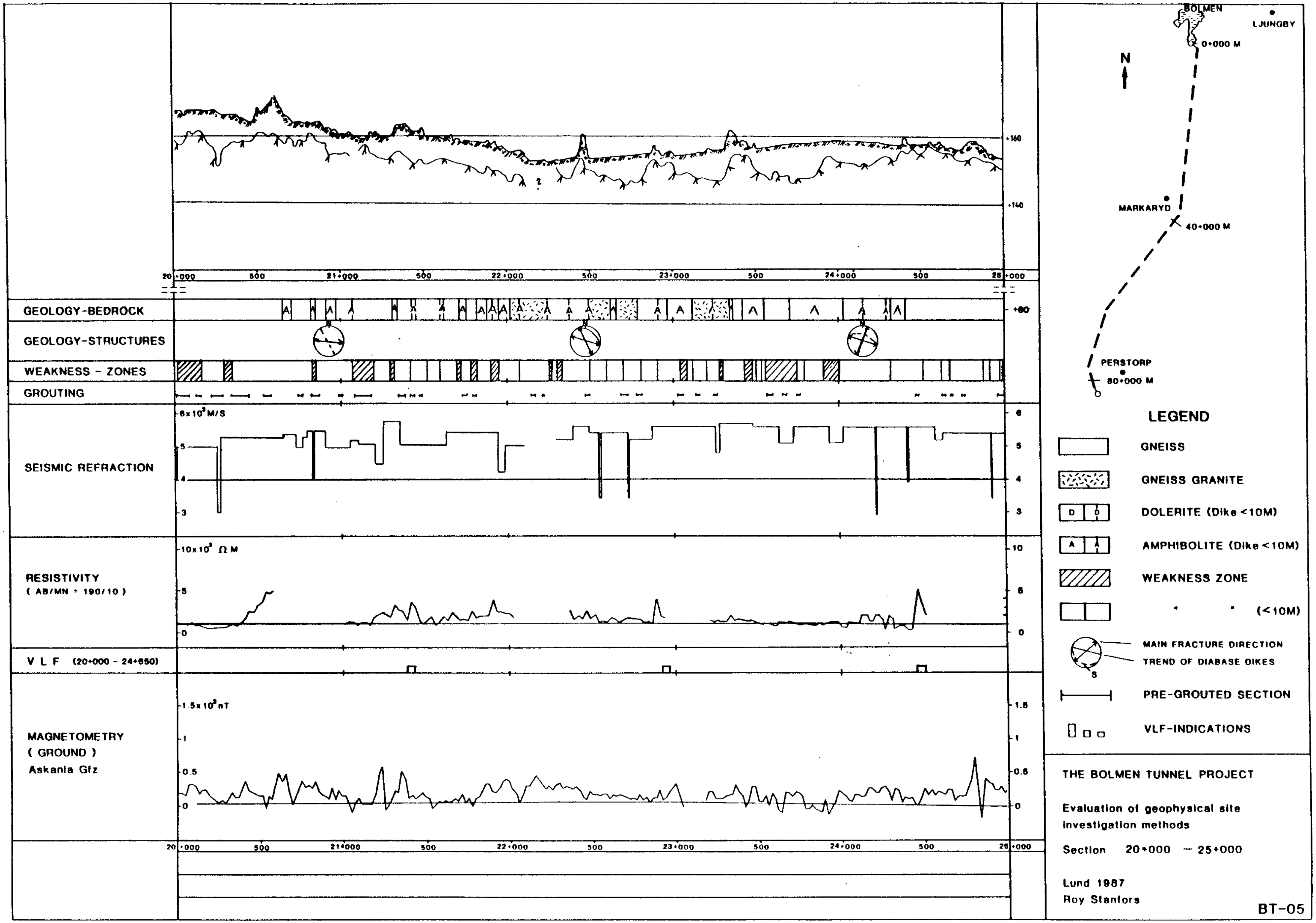
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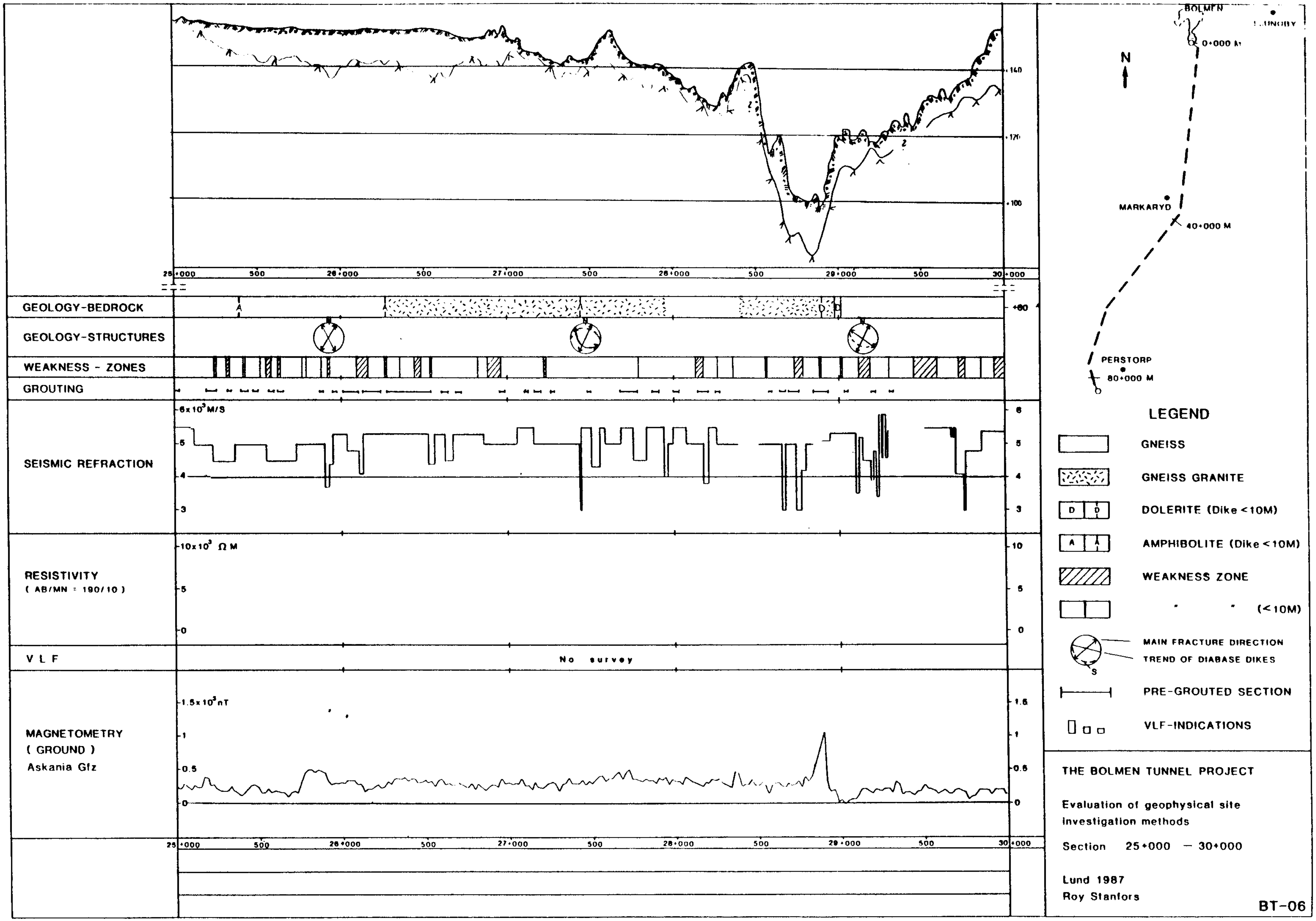

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V L F
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TREND OF DIABASE DIKES
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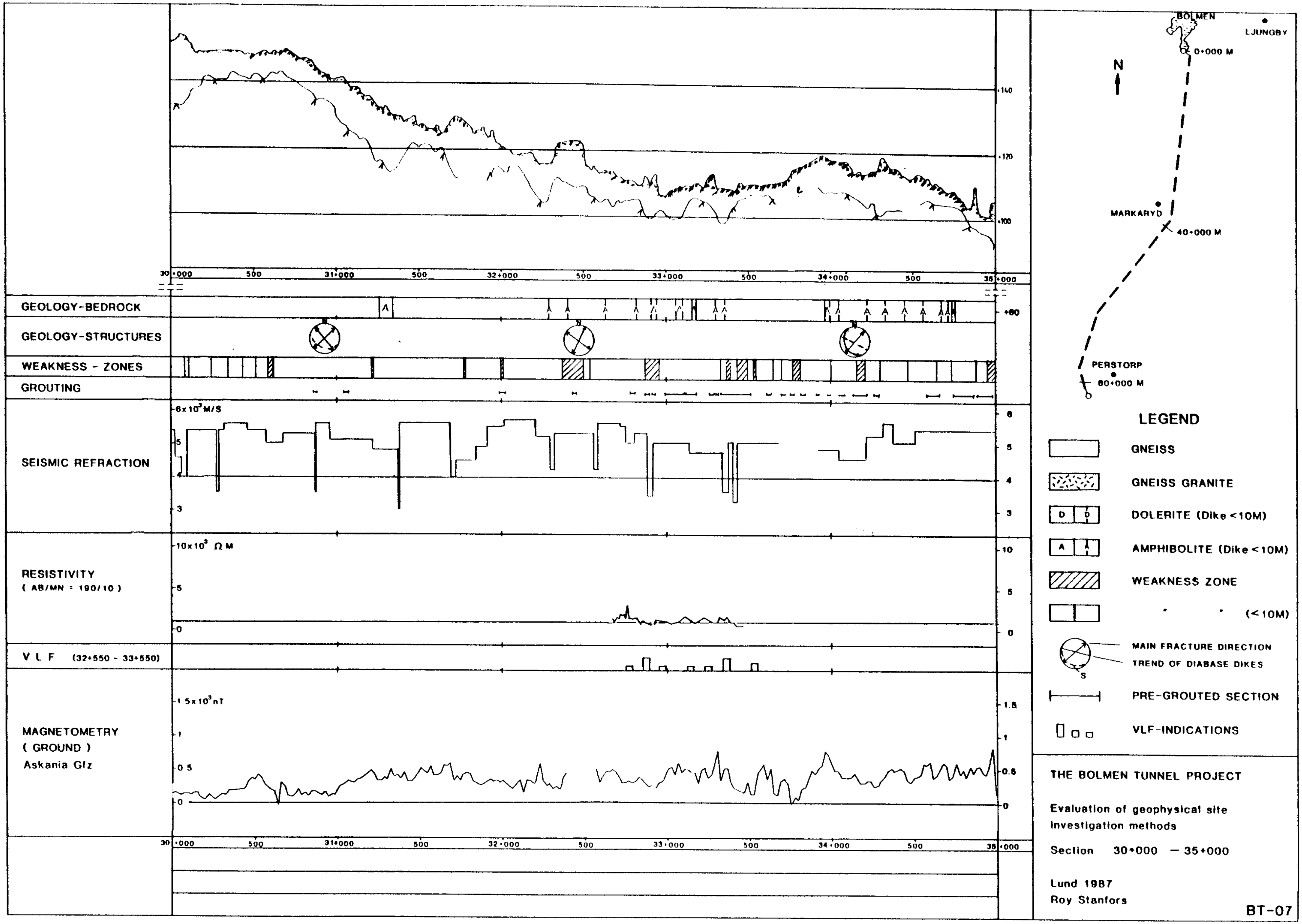
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GROUTING
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RESISTIVITY
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10x10³ Ω M
V L F (32+550 - 33+550)
MAGNETOMETRY
(GROUND)
Askania Gfz
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MARKARYD
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80+000 M
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TREND OF DIABASE DIKES
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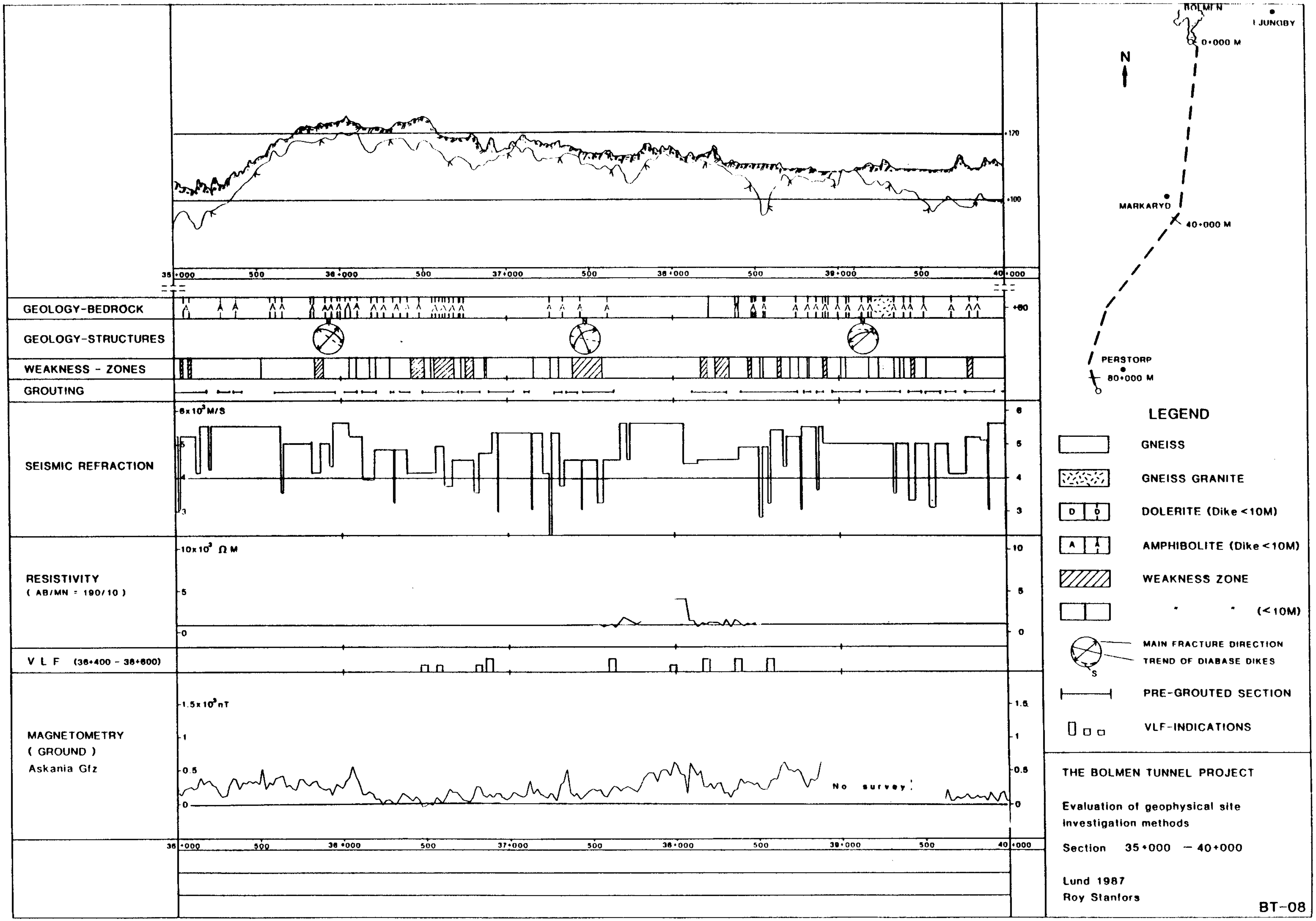

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Evaluation of geophysical site investigation methods

Section 35+000 – 40+000

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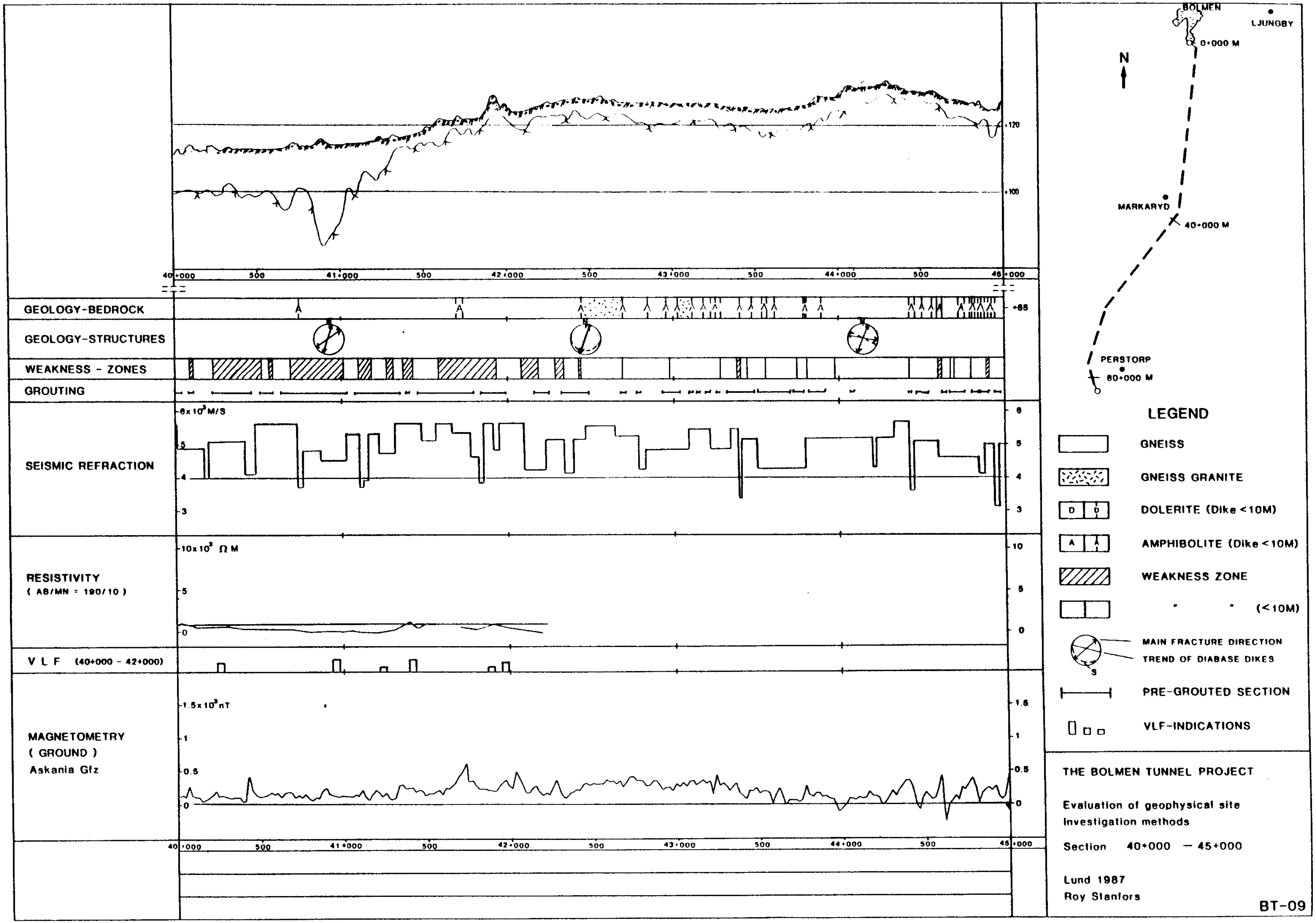

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GROUTING
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V L F (40+000 - 42+000)
MAGNETOMETRY
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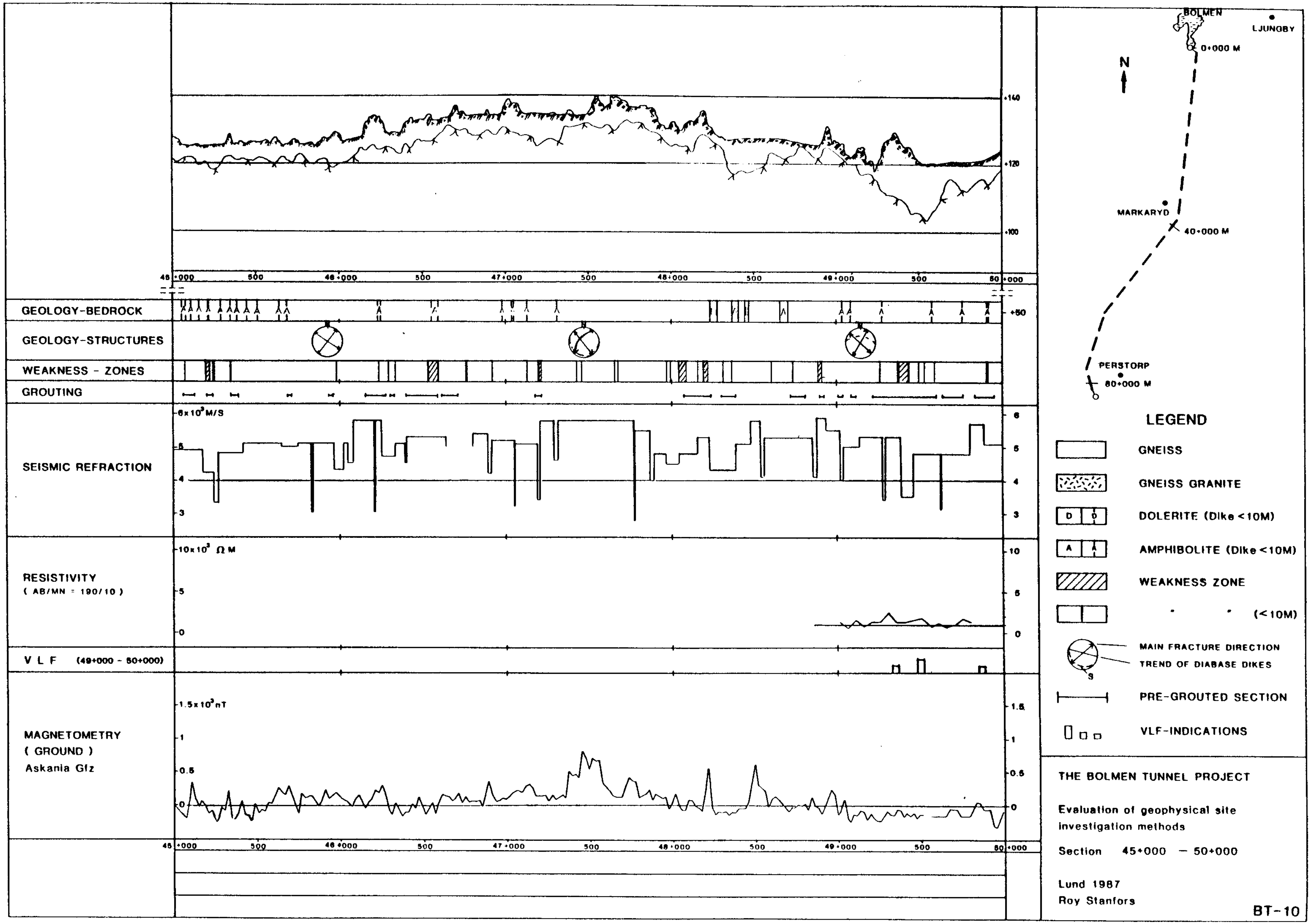
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GROUTING
SEISMIC REFRACTION
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10x10³ Ω M
V L F (49+000 - 50+000)
MAGNETOMETRY
(GROUND)
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48+000
49+000
50+000
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+120
+100
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N
MARKARYD
40+000 M
PERSTORP
80+000 M
LEGEND
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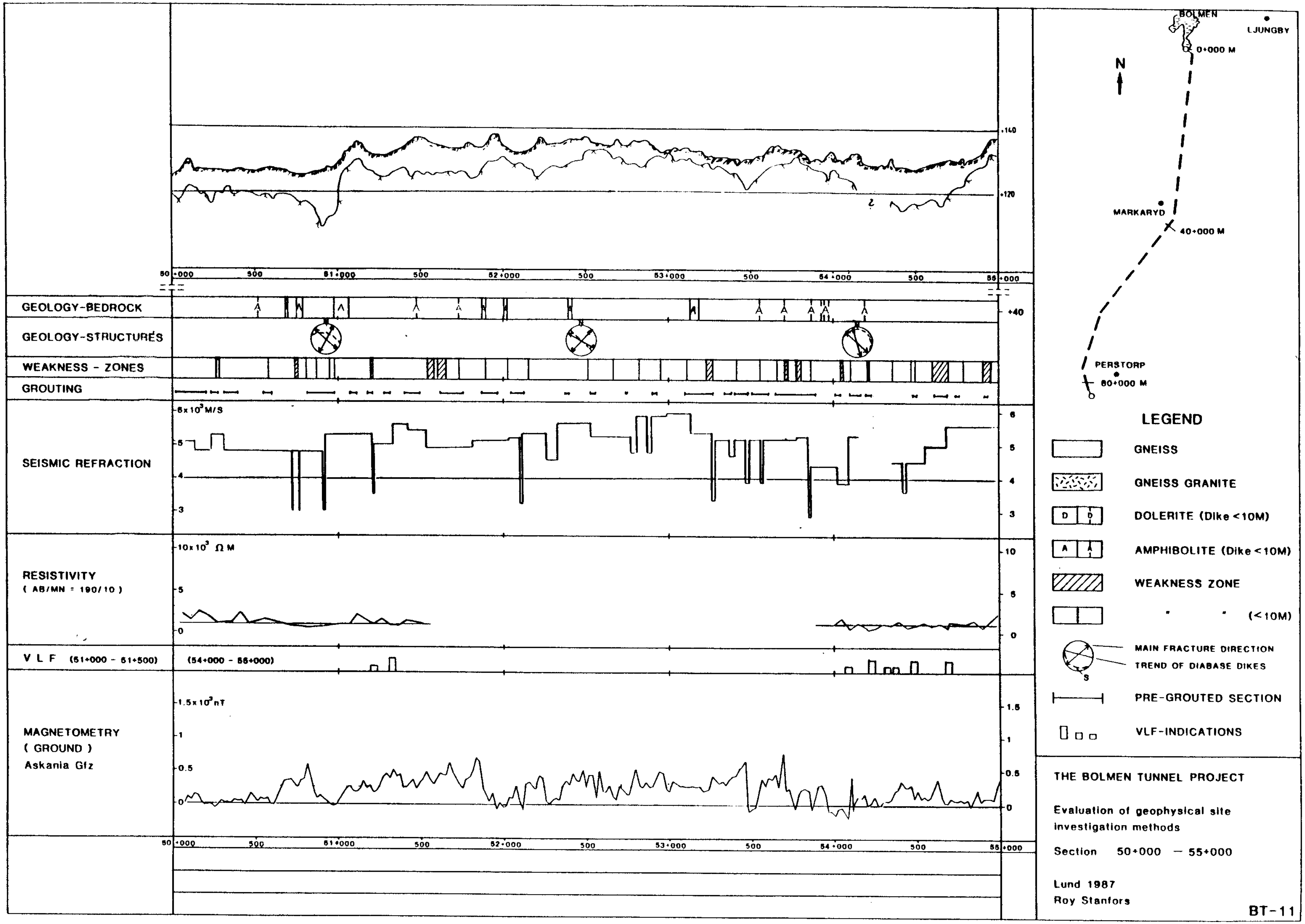
MAIN FRACTURE DIRECTION
TREND OF DIABASE DIKES
PRE-GROUTED SECTION
VLF-INDICATIONS
THE BOLMEN TUNNEL PROJECT
Evaluation of geophysical site investigation methods
Section 45+000 – 50+000
Lund 1987
Roy Stanfors
BT-10


GEOLOGY-BEDROCK
GEOLOGY-STRUCTURES
WEAKNESS - ZONES
GROUTING
SEISMIC REFRACTION
RESISTIVITY
(AB/MN = 190/10)
V L F (51+000 - 51+500)
(54+000 - 55+000)
MAGNETOMETRY
(GROUND)
Askania Gfz
50+000
500
51+000
52+000
53+000
54+000
55+000
+140
+120
+40
6x10³ M/S
10x10³ Ω M
1.5x10³nT
BOLMEN
LJUNGBY
0+000 M
N
MARKARYD
40+000 M
PERSTORP
50+000 M
LEGEND
GNEISS
GNEISS GRANITE
DOLERITE (Dike <10M)
AMPHIBOLITE (Dike <10M)
WEAKNESS ZONE
(<10M)
MAIN FRACTURE DIRECTION
TREND OF DIABASE DIKES
PRE-GROUTED SECTION
VLF-INDICATIONS
THE BOLMEN TUNNEL PROJECT
Evaluation of geophysical site investigation methods
Section 50+000 — 55+000
Lund 1987
Roy Stanfors
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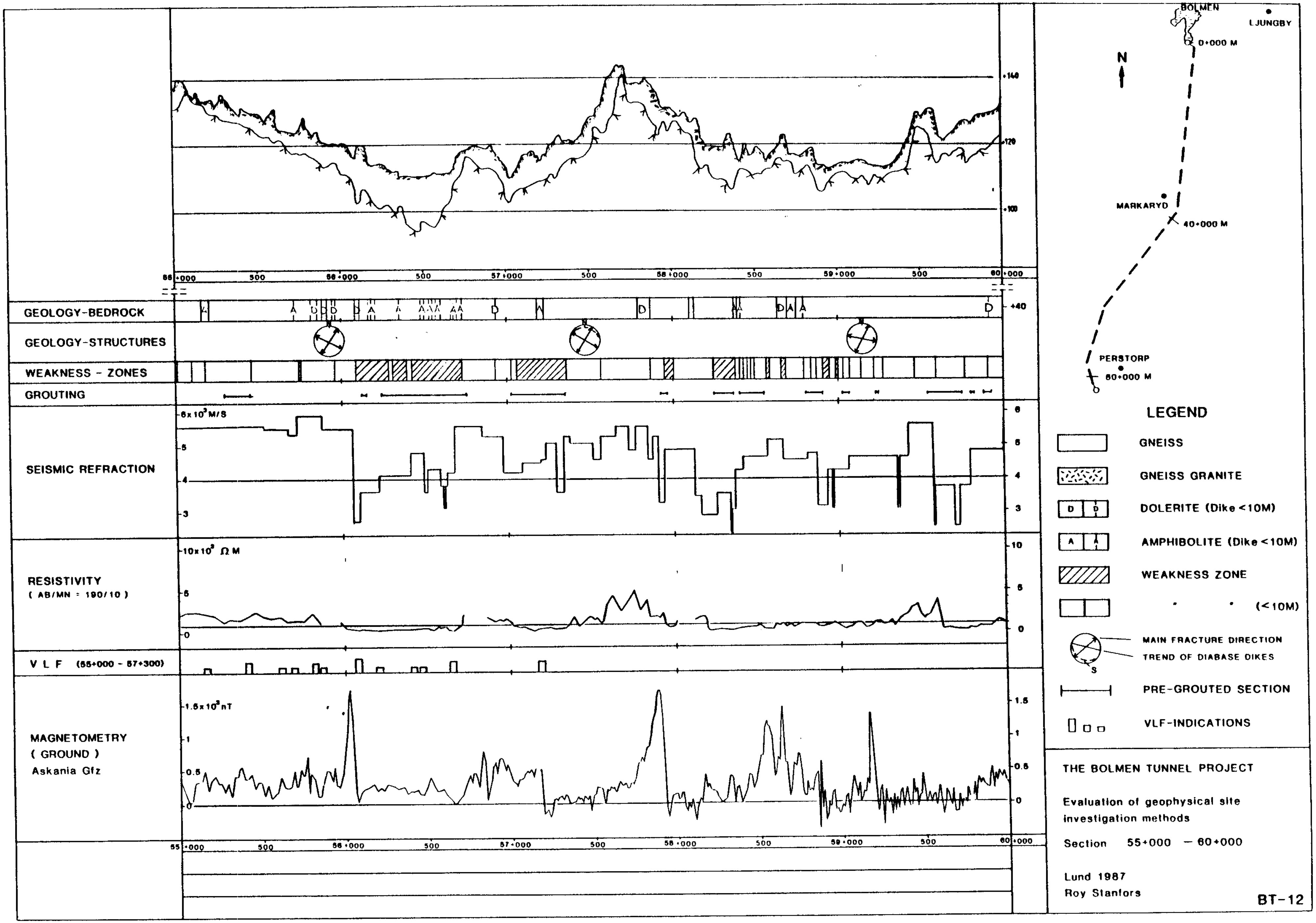
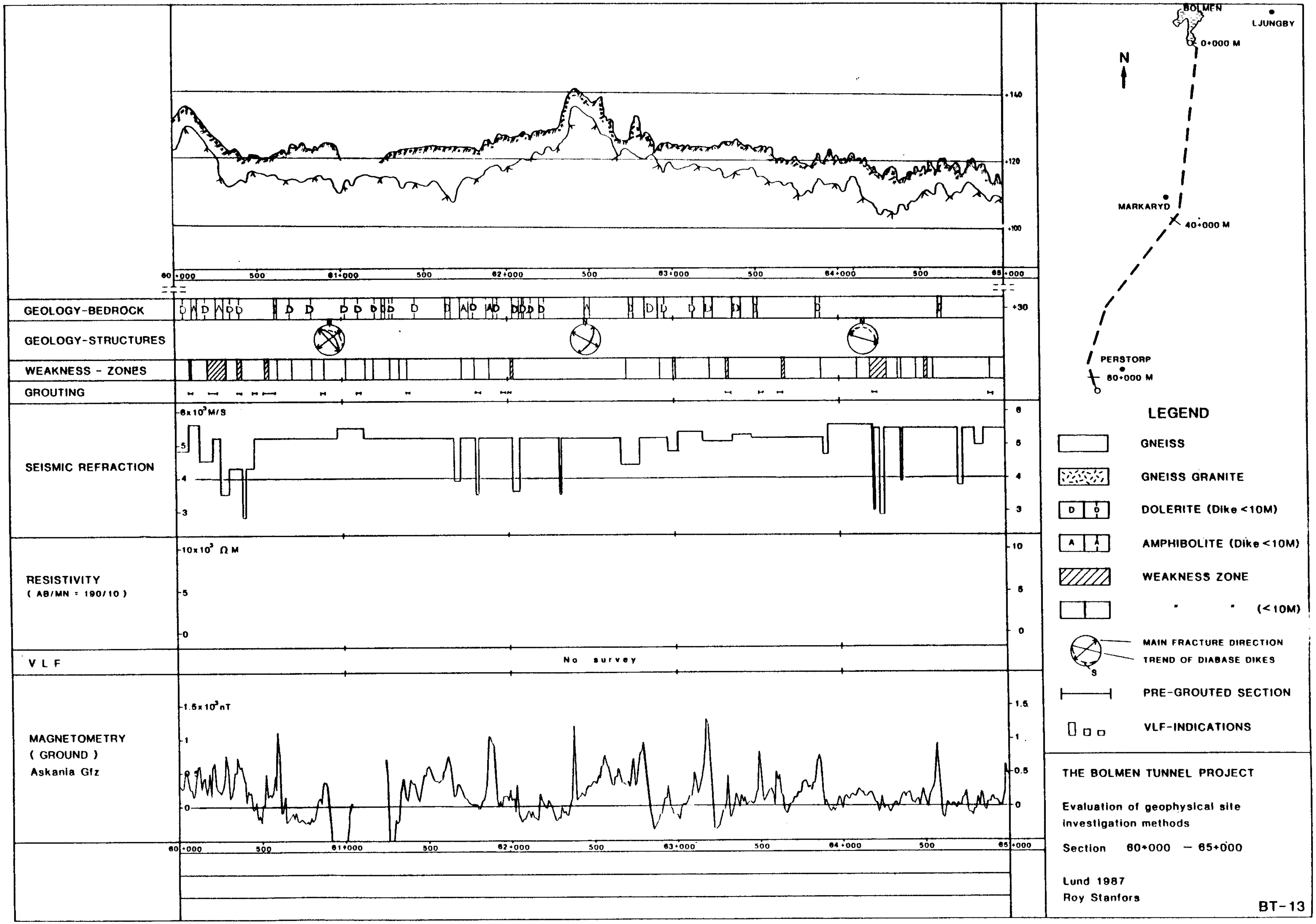


BOLMEN
LJUNGBY
0+000 M
N
MARKARYD
40+000 M
PERSTORP
60+000 M
LEGEND
GNEISS
GNEISS GRANITE
DOLERITE (Dike <10M)
AMPHIBOLITE (Dike <10M)
WEAKNESS ZONE
(<10M)
MAIN FRACTURE DIRECTION
TREND OF DIABASE DIKES
PRE-GROUTED SECTION
VLF-INDICATIONS
GEOLOGY-BEDROCK
GEOLOGY-STRUCTURES
WEAKNESS - ZONES
GROUTING
SEISMIC REFRACTION
6x10³M/S
RESISTIVITY
(AB/MN = 190/10)
10x10³ Ω M
V L F (55+000 - 57+300)
MAGNETOMETRY
(GROUND)
Askania Gfz
1.5x10³nT
55+000
500
56+000
57+000
58+000
59+000
60+000
+140
+120
+100
+40
THE BOLMEN TUNNEL PROJECT
Evaluation of geophysical site investigation methods
Section 55+000 – 60+000
Lund 1987
Roy Stanfors
BT-12



GEOLOGY-BEDROCK
GEOLOGY-STRUCTURES
WEAKNESS - ZONES
GROUTING
SEISMIC REFRACTION
6x10³M/S
RESISTIVITY
(AB/MN = 190/10)
10x10³ Ω M
V L F
No survey
MAGNETOMETRY
(GROUND)
Askania Gfz
1.5x10³nT
60+000
500
61+000
62+000
63+000
64+000
65+000
+140
+120
+100
+30
BOLMEN
LJUNGBY
0+000 M
N
MARKARYD
40+000 M
PERSTORP
60+000 M
LEGEND
GNEISS
GNEISS GRANITE
DOLERITE (Dike <10M)
AMPHIBOLITE (Dike <10M)
WEAKNESS ZONE
" " (<10M)
MAIN FRACTURE DIRECTION
TREND OF DIABASE DIKES
PRE-GROUTED SECTION
VLF-INDICATIONS
THE BOLMEN TUNNEL PROJECT
Evaluation of geophysical site investigation methods
Section 60+000 – 65+000
Lund 1987
Roy Stanfors
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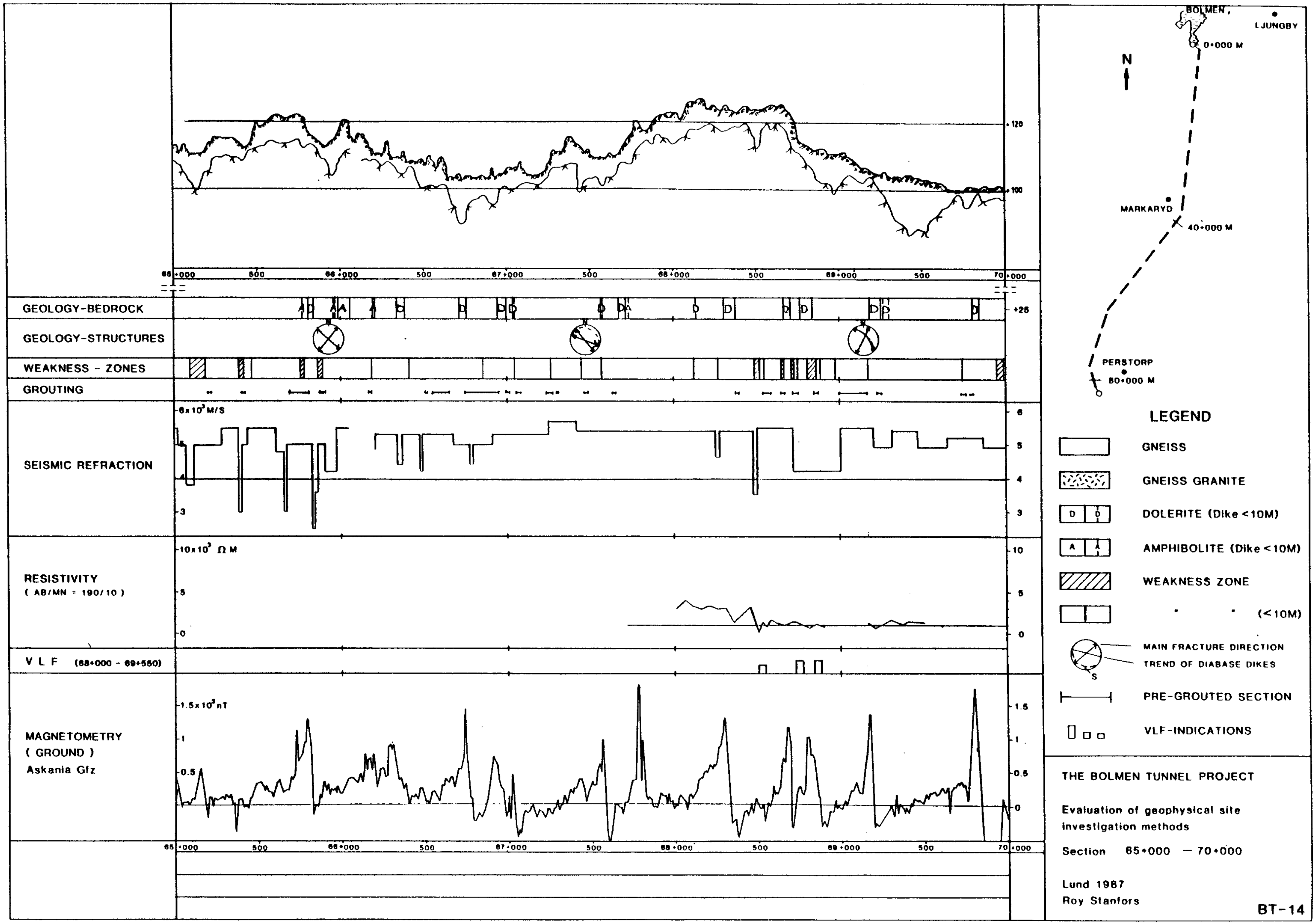

GEOLOGY-BEDROCK
GEOLOGY-STRUCTURES
WEAKNESS - ZONES
GROUTING
SEISMIC REFRACTION
6x10³ M/S
RESISTIVITY
(AB/MN = 190/10)
10x10³ Ω M
V L F (68+000 - 69+550)
MAGNETOMETRY
(GROUND)
Askania Gfz
1.5x10³ nT
65+000
500
66+000
500
67+000
500
68+000
500
69+000
500
70+000
120
100
+25
BOLMEN
LJUNGBY
0+000 M
N
MARKARYD
40+000 M
PERSTORP
80+000 M
LEGEND
GNEISS
GNEISS GRANITE
DOLERITE (Dike <10M)
AMPHIBOLITE (Dike <10M)
WEAKNESS ZONE
(<10M)
MAIN FRACTURE DIRECTION
TREND OF DIABASE DIKES
PRE-GROUTED SECTION
VLF-INDICATIONS
THE BOLMEN TUNNEL PROJECT
Evaluation of geophysical site investigation methods
Section 65+000 — 70+000
Lund 1987
Roy Stanfors
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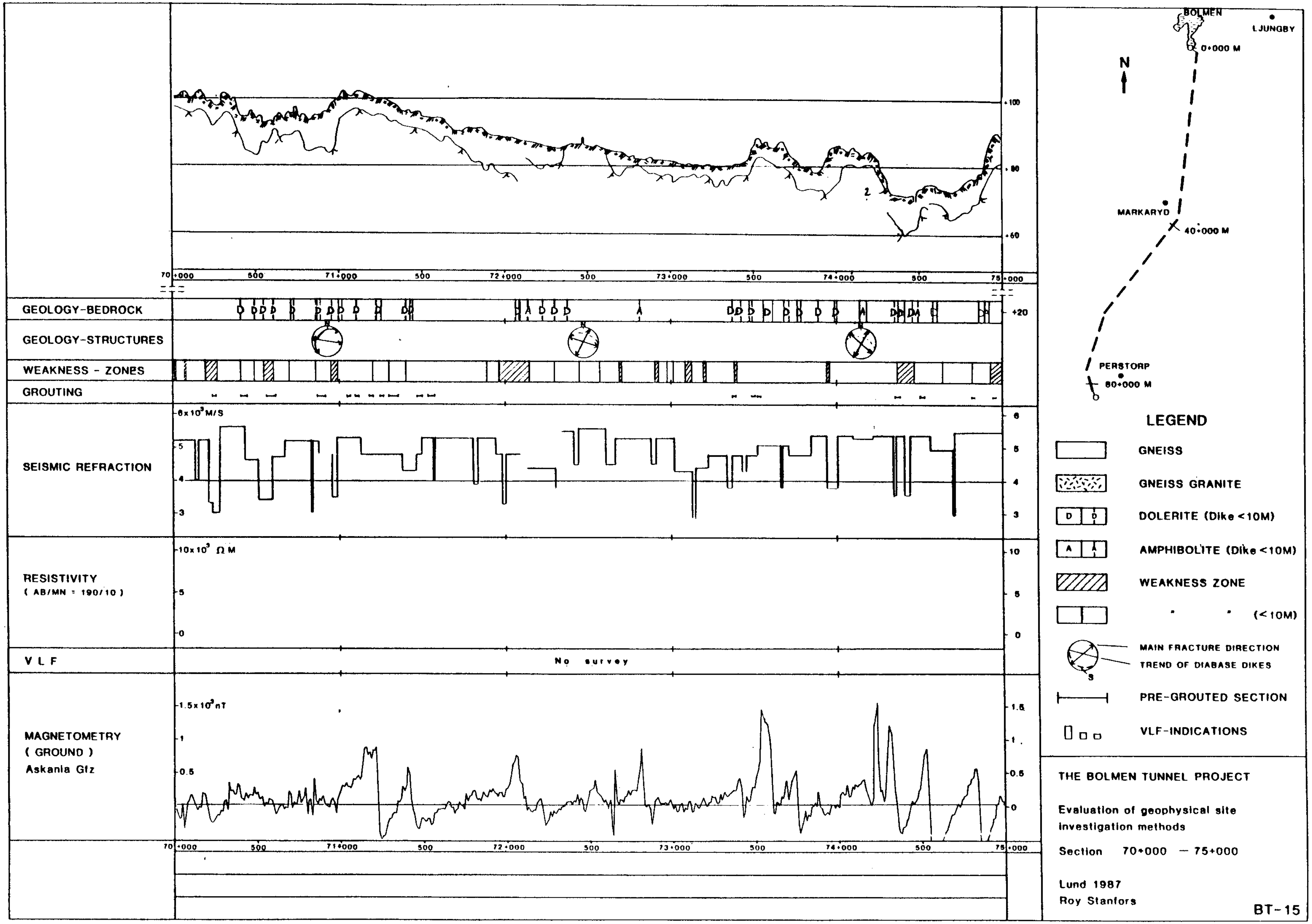
GEOLOGY-BEDROCK
GEOLOGY-STRUCTURES
WEAKNESS - ZONES
GROUTING
SEISMIC REFRACTION
6x10³M/S
RESISTIVITY
(AB/MN = 190/10)
10x10³ Ω M
V L F
No survey
MAGNETOMETRY
(GROUND)
Askania Gfz
1.5x10³nT
70+000
500
71+000
72+000
73+000
74+000
75+000
+100
+80
+60
+20
BOLMEN
LJUNGBY
0+000 M
N
MARKARYD
40+000 M
PERSTORP
80+000 M
LEGEND
GNEISS
GNEISS GRANITE
DOLERITE (Dike <10M)
AMPHIBOLITE (Dike <10M)
WEAKNESS ZONE
(<10M)
MAIN FRACTURE DIRECTION
TREND OF DIABASE DIKES
PRE-GROUTED SECTION
VLF-INDICATIONS
THE BOLMEN TUNNEL PROJECT
Evaluation of geophysical site investigation methods
Section 70+000 — 75+000
Lund 1987
Roy Stanfors
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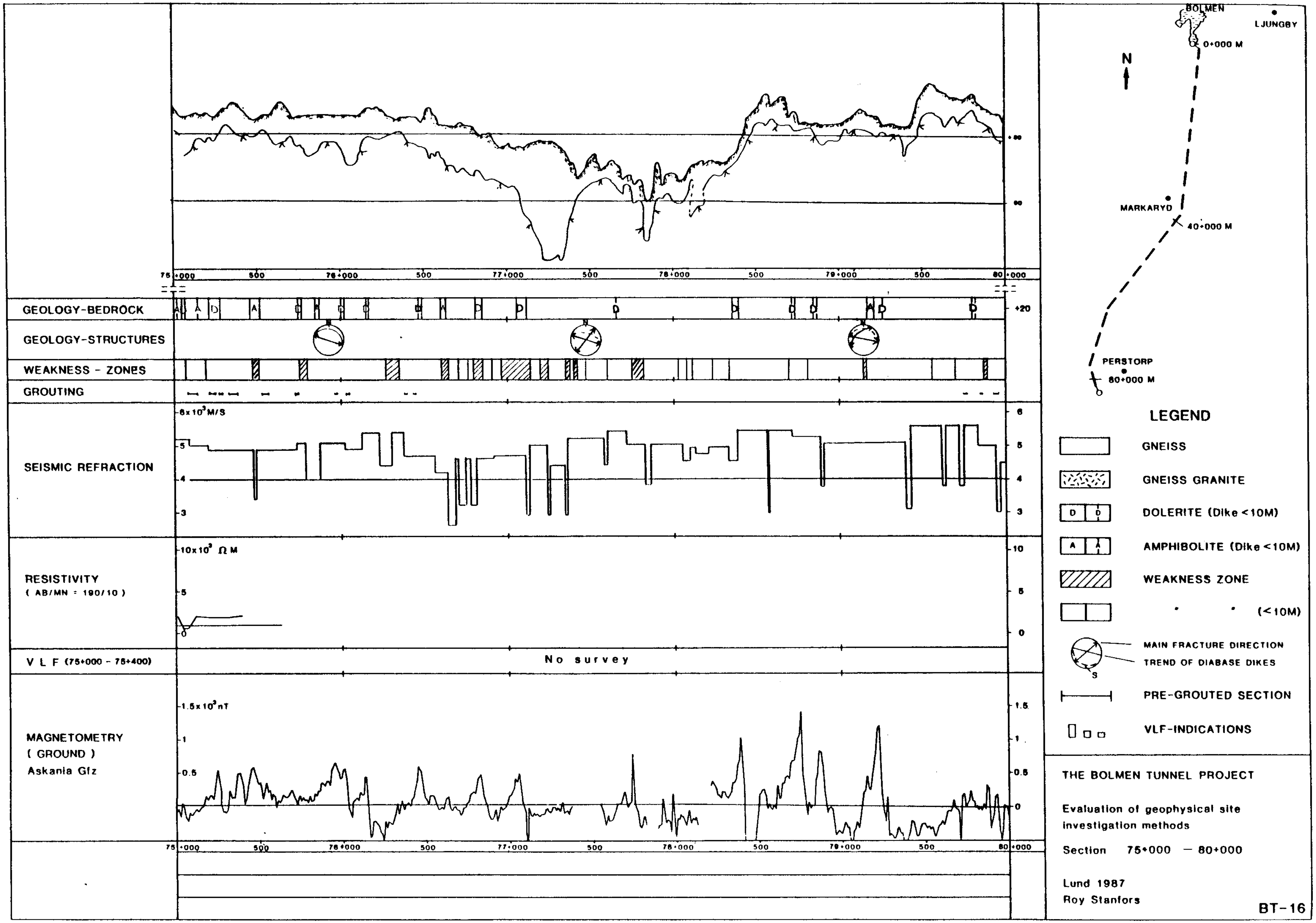

BOLMEN
LJUNGBY
0+000 M
N
MARKARYD
40+000 M
PERSTORP
80+000 M
GEOLOGY-BEDROCK
GEOLOGY-STRUCTURES
WEAKNESS - ZONES
GROUTING
SEISMIC REFRACTION
RESISTIVITY
(AB/MN = 190/10)
V L F (75+000 - 75+400)
No survey
MAGNETOMETRY
(GROUND)
Askania Gfz
75+000
500
76+000
77+000
78+000
79+000
80+000
+20
6×10^3 M/S
10×10^3 Ω M
1.5×10^3 nT
LEGEND
GNEISS
GNEISS GRANITE
DOLERITE (Dike <10M)
AMPHIBOLITE (Dike <10M)
WEAKNESS ZONE
(<10M)
MAIN FRACTURE DIRECTION
TREND OF DIABASE DIKES
PRE-GROUTED SECTION
VLF-INDICATIONS
THE BOLMEN TUNNEL PROJECT
Evaluation of geophysical site investigation methods
Section 75+000 — 80+000
Lund 1987
Roy Stanfors
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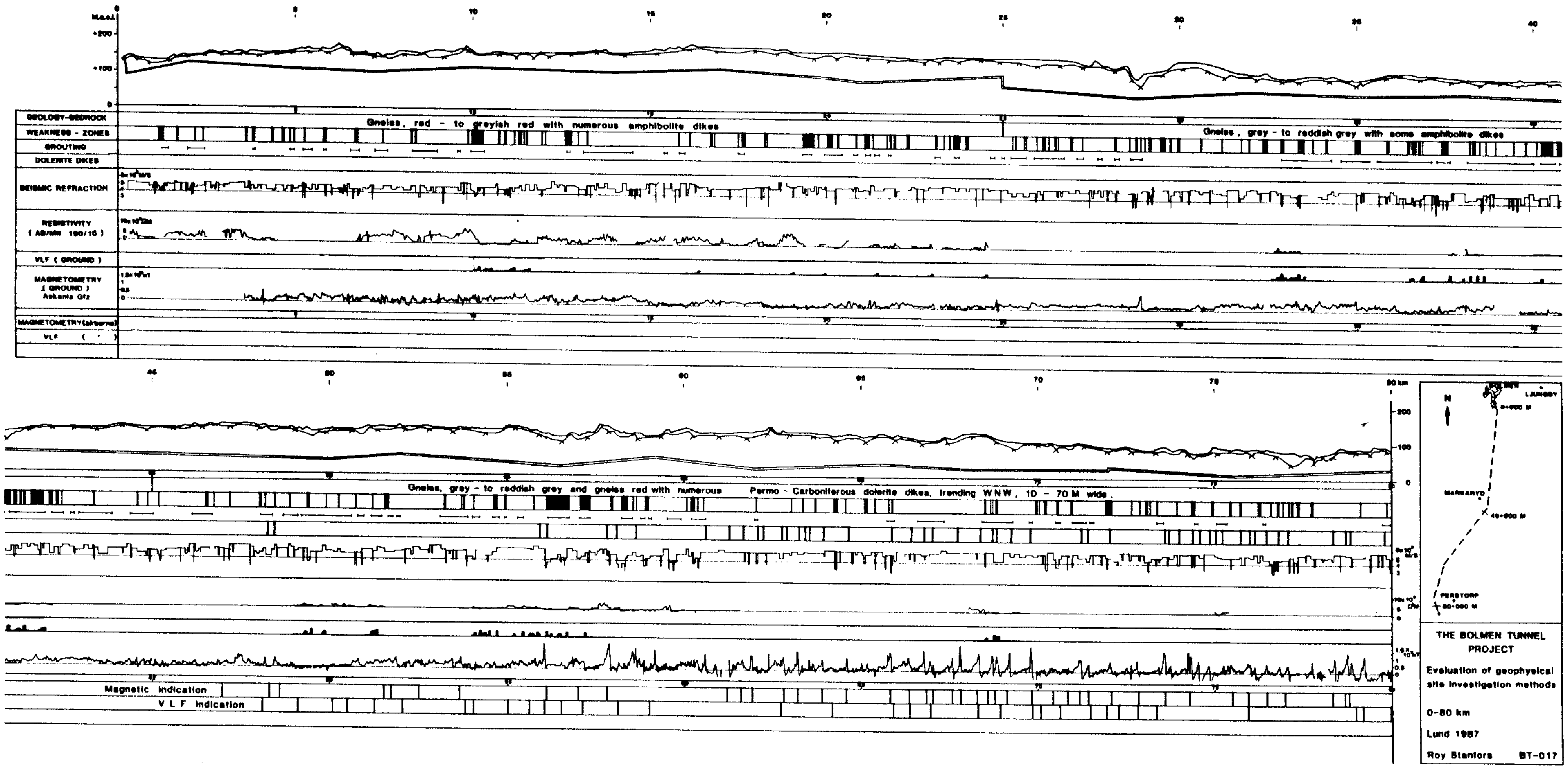

M.a.s.l.
+200
+100
0
GEOLOGY-BEDROCK
WEAKNESS - ZONES
GROUTING
DOLERITE DIKES
SEISMIC REFRACTION
RESISTIVITY
(AB/MN 180/15)
VLF (GROUND)
MAGNETOMETRY
(GROUND)
Askania Gfz
MAGNETOMETRY(airborne)
VLF
Gneiss, red - to greyish red with numerous amphibolite dikes
Gneiss, grey - to reddish grey with some amphibolite dikes
Gneiss, grey - to reddish grey and gneiss red with numerous Permo - Carboniferous dolerite dikes, trending WNW, 10 - 70 M wide.
Magnetic indication
V L F indication
80 km
N
LJUNGBY
MARKARYD
PERSTORP
THE BOLMEN TUNNEL PROJECT
Evaluation of geophysical site investigation methods
0-80 km
Lund 1987
Roy Stanfors
BT-017

List of SKB reports

Annual Reports

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TR 121
KBS Technical Reports 1 – 120.
Summaries. Stockholm, May 1979.

1979
TR 79–28
The KBS Annual Report 1979.
KBS Technical Reports 79-01 – 79-27.
Summaries. Stockholm, March 1980.

1980
TR 80–26
The KBS Annual Report 1980.
KBS Technical Reports 80-01 – 80-25.
Summaries. Stockholm, March 1981.

1981
TR 81–17
The KBS Annual Report 1981.
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Summaries. Stockholm, April 1982.

1982
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KBS Technical Reports 82-01 – 82-27.
Summaries. Stockholm, July 1983.

1983
TR 83–77
The KBS Annual Report 1983.
KBS Technical Reports 83-01 – 83-76
Summaries. Stockholm, June 1984.

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TR 85–01
Annual Research and Development Report 1984
Including Summaries of Technical Reports Issued during 1984. (Technical Reports 84-01– 84-19)
Stockholm June 1985.

1985
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Annual Research and Development Report 1985
Including Summaries of Technical Reports Issued during 1985. (Technical Reports 85-01-85-19)
Stockholm May 1986.

1986
TR86-31
SKB Annual Report 1986
Including Summaries of Technical Reports Issued during 1986
Stockholm, May 1987

Technical Reports

1987

TR 87-01
Radar measurements performed at the Klipperås study site
Seje Carlsten, Olle Olsson, Stefan Sehlstedt, Leif Stenberg
Swedish Geological Co, Uppsala/Luleå
February 1987

TR 87-02
Fuel rod D07/B15 from Ringhals 2 PWR: Source material for corrosion/leach tests in groundwater
Fuel rod/pellet characterization program part one
Roy Forsyth, Editor
Studsvik Energiteknik AB, Nyköping
March 1987

TR 87-03
Calculations on HYDROCOIN level 1 using the GWHRT flow model
Case 1 Transient flow of water from a borehole penetrating a confined aquifer
Case 3 Saturated-unsaturated flow through a layered sequence of sedimentary rocks
Case 4 Transient thermal convection in a saturated medium
Roger Thunvik, Royal Institute of Technology, Stockholm
March 1987

TR 87-04
Calculations on HYDROCOIN level 2, case 1 using the GWHRT flow model
Thermal convection and conduction around a field heat transfer experiment
Roger Thunvik
Royal Institute of Technology, Stockholm
March 1987

TR 87-05
Applications of stochastic models to solute transport in fractured rocks
Lynn W Gelhar
Massachusetts Institute of Technology
January 1987

TR 87-06
Some properties of a channeling model of fracture flow
Y W Tsang, C F Tsang, I Neretnieks
Royal Institute of Technology, Stockholm
December 1986

TR 87-07
Deep groundwater chemistry
Peter Wikberg, Karin Axelsen, Folke Fredlund
Royal Institute of Technology, Stockholm
June 1987

TR 87-08
An approach for evaluating the general and localized corrosion of carbon steel containers for nuclear waste disposal
GP March, KJ Taylor, SM Sharland, PW Tasker
Harwell Laboratory, Oxfordshire
June 1987

TR 87-09
Piping and erosion phenomena in soft clay gels
Roland Pusch, Mikael Erlström,
Lennart Börgesson
Swedish Geological Co, Lund
May 1987

TR 87-10
Outline of models of water and gas flow through smectite clay buffers
Roland Pusch, Harald Hökmark,
Lennart Börgesson
Swedish Geological Co, Lund
June 1987

TR 87-11
Modelling of crustal rock mechanics for radioactive waste storage in Fennoscandia—Problem definition
Ove Stephansson
University of Luleå
May 1987

TR 87-12
Study of groundwater colloids and their ability to transport radionuclides
Kåre Tjus* and Peter Wikberg**
*Institute for Surface Chemistry, Stockholm
**Royal Institute of Technology, Inorganic Chemistry Stockholm
March 1987

TR 87-13
Shallow reflection seismic investigation of fracture zones in the Finnsjö area method evaluation
Trine Dahl-Jensen
Jonas Lindgren
University of Uppsala, Department of Geophysics
June 1987

TR 87-14
Combined interpretation of geophysical, geological, hydrological and radar investigations in the boreholes ST1 and ST2 at the Saltsjötunnel
Jan-Erik Andersson
Per Andersson
Seje Carlsten
Lars Falk
Olle Olsson
Allan Stråhle
Swedish Geological Co, Uppsala
1987-06-30

TR 87-15
Geochemical interpretation of groundwaters from Finnsjön, Sweden
Ignasi Puigdomènech[1]
Kirk Nordstrom[2]
[1]Royal Institute of Technology, Stockholm
[2]U S Geological Survey, Menlo Park, California
August 23, 1987

TR 87-16
Corrosion tests on spent PWR fuel in synthetic groundwater
R S Forsyth[1] and L O Werme[2]
[1]Studsvik Energiteknik AB, Nyköping, Sweden
[2]The Swedish Nuclear Fuel and Waste Management Co (SKB), Stockholm, Sweden
Stockholm, September 1987

TR 87-17
The July — September 1986 Skövde aftershock sequence
Conny Holmqvist
Rutger Wahlström
Seismological Department, Uppsala University
August 1987

TR 87-18
Calculation of gas migration in fractured rock
Roger Thunvik[1] and Carol Braester[2]
[1]Royal Institute of Technology
Stockholm, Sweden
[2]Israel Institute of Technology
Haifa, Israel
September 1987

TR 87-19
Calculation of gas migration in fractured rock – a continuum approach
Carol Braester[1] and Roger Thunvik[2]
[1]Israel Institute of Technology
Haifa, Israel
[2]Royal Institute of Technology
Stockholm, Sweden
September 1987

TR 87-20
Stability fields of smectites and illites as a function of temperature and chemical composition
Y Tardy, J Duplay and B Fritz
Centre de Sédimentologie et de Géochimie de la Surface (CNRS)
Institut de Géologie Université Louis Pasteur (ULP)
1 rue Blessig, F-67084 Strasbourg, France
April 1987

TR 87-21
Hydrochemical investigations in crystalline bedrock in relation to exesting hydraulic conditions: Klipperås test-site, Småland, Southern Sweden
John Smellie[1]
Nils-Åke Larsson[1]
Peter Wikberg[3]
Ignasi Puigdomènech[4]
Eva-Lena Tullborg[2]
[1]Swedisch Geological Company, Uppsala
[2]Swedisch Geological Company, Göteborg
[3]Royal Institute of Technology, Stockholm
[4]Studsvik Energiteknik AB, Nyköping
September 1987

TR 87-22
Radionuclide sorption on granitic drill core material
Trygve E Eriksen and Birgitta Locklund
The Royal Institute of Technology
Department of Nuclear Chemistry
Stockholm
November 1987

TR 87-23
Radionuclide co-precipitation
Jordi Bruno and Amaia Sandino
The Royal Institute of Technology
Department of Inorganic Chemistry
Stockholm
December 1987

TR 87-24
Geological maps and cross-sections of Southern Sweden
Karl-Axel Kornfält[1] and Kent Larsson[2]
[1]SGU, Lund
[2]Softrock Consulting, Genarp
December 1987