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Comparison of geoelectrical imaging and tunnel documentation at the Hallandsås Tunnel, Sweden

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ABSTRACT

For construction in rock a thorough pre-investigation is important in order to avoid unforeseen conditions which may delay the work. It is crucial to remember the results from this investigation in the further work, and use the experience from the construction to update the geological prognosis and reduce the uncertainties. Different geophysical methods have proved valuable tools in such investigations. In this work the electrical imaging is evaluated with regards to the method's applicability. The evaluation is done qualitatively by comparing the electrical imaging with tunnel documentation from a tunnel in Southern Sweden. By evaluating the result continuously when making the tunnel a more detailed geological prognosis can be compiled and used in the continued work with the tunnel. The parameters used for the comparison are lithology, Q, RQD, weathering and water leakage. The result was that virtually every change in electrical resistivity image coincides with a change in rock conditions. The general trend was that high resistivity corresponded with good quality gneiss whereas low resistivity corresponds to poor quality rock e.g., high weathering, low RQD, low Q and/or several lithological contacts. The intermediate resistivity is often amphibolites or rock with water bearing fractures. The results were supported by in-situ resistivity measurements inside the tunnel and resistivity logging in a core drilling. Geoelectrical imaging proved to give valuable information for a detailed geological model, which could be compiled for a section where the tunnel had not yet been drilled as a help for planning of the continued tunnel work. As is the case other geophysical methods it is clear that for the interpretation of data a priori information about the geological setting is necessary.

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1. Introduction

Construction in rock with unforeseen quality or conditions can result in delays which in the end are expensive. Therefore a thorough pre-investigation has to be carried out in order to establish the best geological model possible. Different geophysical methods have proven to be valuable tools in the early stages of the large scale pre-investigations (Dahlin et al., 1999; Rønning, 2003; Cavinato et al., 2006; Ganerød et al., 2006). An engineering geological prognosis is based on the pre-investigation report and the purpose is to form the base for design and estimation of e.g., reinforcements and grouting (Swindell and Rosengren, 2007). By using the experience gained during construction work a more detailed interpretation of the geoelectrical data can be done, and an updated and geological prognosis with less uncertainties can be compiled. The original prognosis is optimised based on the data available when it was compiled, but with a new prognosis the construction work is better prepared for unforeseen conditions. No matter how good a prognosis is it is still an estimate of how the ground

conditions are and there will always be room for improvements. It might be that nothing is added, but the prognosis becomes more certain. Therefore it is always a good idea to learn from the parts already drilled, and use it to update the geological model and its reliability. In this way the data are used in a more optimal way and the value of the money spent on the data is higher.

The compilation of the first prognosis is bound to involve uncertainties. A traditional method for obtaining information about the rock properties is core drilling. Core drillings are considered giving very exact information about the geological properties. However they have the limitation that they only give point information. An important issue is also that, to some degree, they are interpreted, preferably by a geologist. When considering the documentation from the core drillings the human factor has to be acknowledged; the geologist can misinterpret the rock quality when it is based on core drillings. For example the scale and orientation of a sample can give a wrong impression and in addition two different persons do evaluate the classification systems differently. For compiling a useable prognosis the geologist/engineering geologist has to be certain which parameters are important for the construction work. In some cases time is used for gathering information which is not necessary for the actual work, while other information is neglected. In order to make

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the classification easier the pre-investigation has to be planned and carried out so that it gives suitable information and is decision oriented. If the desired result of the investigations is unclear it might cause unnecessary time consuming and expensive investigations (Stanfors et al., 2001). It is advisable to use multiple methods in any rock engineering investigation in order to reduce the uncertainty.

The International Society for Rock Mechanics (ISRM) has suggested the use of geophysics to obtain more information about the rock properties (Takahashi, 2004; Takahashi et al., 2006). The different geophysical methods exploit the contrast in the physical properties of the subsurface. The most commonly used geophysical method in tunnel construction is seismic refraction (Cardarelli et al., 2003; Ganerød et al., 2006). Often the method is used with advantage for locating the bedrock surface and evaluating the mechanical properties of soil and rock. In Klose et al. (2007) multi-dimensional seismic data, achieved from sidewalls of a tunnel, are used to characterize and predict engineering geological conditions. The very low frequency method (VLF) is an electromagnetic method that is often used for detecting sub-vertical electrical conductors such as fracture zones (Reynolds, 1997; Stanfors et al., 2001). The geomagnetic method measures the variation in the content of magnetic minerals in the rock. This is a fast method but a disadvantage is that the method is sensitive towards buried scrap metal and electrical installations (Stanfors et al., 2001). Geoelectrical imaging is used for measuring the spatial variation in the resistivity of the subsurface. Most rock forming minerals are insulators so the resistivity of crystalline rock depends largely on the amount and quality of water present and the degree of weathering of the rock. Therefore rock without water bearing fractures or weathering has a high resistivity whereas clay-weathered rock or rock with water bearing fractures has a considerably lower resistivity (Parasnis, 1997; Binley and Kemna, 2005). A joint interpretation of different methods with different sensitivities will produce the best result. Before deciding on a certain method, knowledge about the expected contrasts in physical properties has to be obtained from e.g., previous measurements, geological maps and geological history. Evaluations of the different geophysical methods used in connection to construction of a number of tunnels (Dahlin et al., 1999; Rønning, 2003; Cavinato et al., 2006; Ganerød et al., 2006) showed that geoelectrical imaging gave good results. In addition it was a time and cost effective method compared to other geophysical methods.

The aim of this paper is to show what the resistivity method is able to resolve by comparing the results from geoelectrical imaging and tunnel documentation. The aim is also to show how the experience can be used to update the geological prognosis. The prognosis becomes more reliable and can therefore reduce the number of uncertainties in the continued construction work. Ongoing work in a tunnel provides the opportunity to compare actual rock type, Q, RQD, weathering, water leakage and amount of grout used with the measured resistivity profiles. The resistivity values are extracted at different levels from the inverted data. This allows a good evaluation of how the resistivity model varies with depth.

In this specific case the tunnel work is already started and the pre-investigations carried out. First of all it is a good example of showing how reliable the method is and secondly it can be shown how the data can be used in the continued tunnel work. Just because the pre-investigations are finished the data should not be forgotten. Based on the experience from the finished parts of the tunnel updated geological prognoses can be made for the sections not yet built and used in the planning of the tunnel work. This can repeated more or less continuously or at regular intervals throughout the construction phase.

In this study the construction of twin track tunnels through the Hallandsås Horst in southern Sweden (Fig. 1) is used. The work was initiated in 1992 and is ongoing. Problems related to high ingress of water and difficult rock conditions have resulted in major delays to the

work. The tunnel has 100 to 150 m overburden and a high water pressure, which in combination with strict requirements on limiting the water ingress, even during the construction period, have caused problems for the project. Despite considerable pre-grouting operations a substantial amount of water has been leaking into the tunnels with a critical lowering of the groundwater table as a consequence (Banverket, 2005). The use of an advanced shielded tunnel boring machine has mitigated these problems and the tunnel is now being built with a water tight segmental lining.

Since the beginning of the project different geophysical methods have been used, e.g., geoelectrical imaging, ground based magnetic, VLF and seismic refraction. Especially geoelectrical imaging and ground based magnetic has been useful. Geoelectrical imaging has pinpointed large weak zones and magnetic measurements have located dolerite dykes.

The tunnel is constructed 100 to 150 m below the surface whereas the measured geoelectrical data has an investigation depth of maximum 160 m. The resolution of the geoelectrical method gets inferior with depth. Thus the resolution at tunnel level is not suitable for a quantitative and statistical comparison of the geoelectrical imaging and tunnel documentation. Still the qualitative comparison gives valuable information about the rock properties which are useful in the large scale pre-investigation of a tunnel construction.

2. Geological setting

The Hallandsås Horst is the most northern of the Scanian horsts. These are the result of a tectonic activity, which has been going on since Silurian time. The uplifted blocks have a NW–SE orientation and occur in the so called Tornquist Zone. This tectonic element stretches all the way to the Black Sea (Wikman and Bergström, 1987). The Hallandsås Horst is 8–10 km wide, 60–80 km long and reaches an elevation of 150 to 200 m in the tunnel area. Towards the north the slope is steep whereas it has a gentler slope towards the south (Dahlin et al., 1999).

Crystalline Precambrian rocks make up most of the bedrock, whereas sedimentary rocks cover minor areas. Gneisses of presumably intrusive origin dominate the area. Amphibolites of several generations occur and the oldest often are seen as minor layers or schlieren parallel to the layering in the gneiss. The younger amphibolites have mostly distinct contacts and cut across the structures of the older bedrock. These younger dykes often run in the NNE–SSW direction (Wikman and Bergström, 1987).

The dominant fractures are oriented in NW–SE direction corresponding to the Tornquist Line. Another important fracture system has a NNE–SSW direction and is younger than the NW-system. The bedrock is intruded by a set of younger dolerite dykes with their trend parallel to the Scanian horsts. These so-called NW-dolerites are steeply dipping dykes that can have a width up to 50 m (Wikman and Bergström, 1987). These dolerite dykes are seen as very distinct linear positive anomalies on the aeromagnetic map (Swedish Geological Survey, 1981). On the aeromagnetic maps it is even possible to see the NNE and NE fracture system because they disconnect the positive anomalies associated with the dolerite dykes (Wikman and Bergström, 1987).

The substantial deep weathering of the bedrock began during Triassic time and periodically continued during the Cretaceous. This resulted in a weathering to mainly kaolinite. The weathering is documented in core drillings from the area. In the core drillings it is also clear that there is often chlorite in the fractures (Wikman and Bergström, 1987).

The Hallandsås Horst is an important groundwater reservoir. There are two types of reservoirs; one in the soil layer (<20 m thick) and one in the bedrock. In the bedrock the water flows in a large and complex web of fractures. The tectonic activity has made it possible for
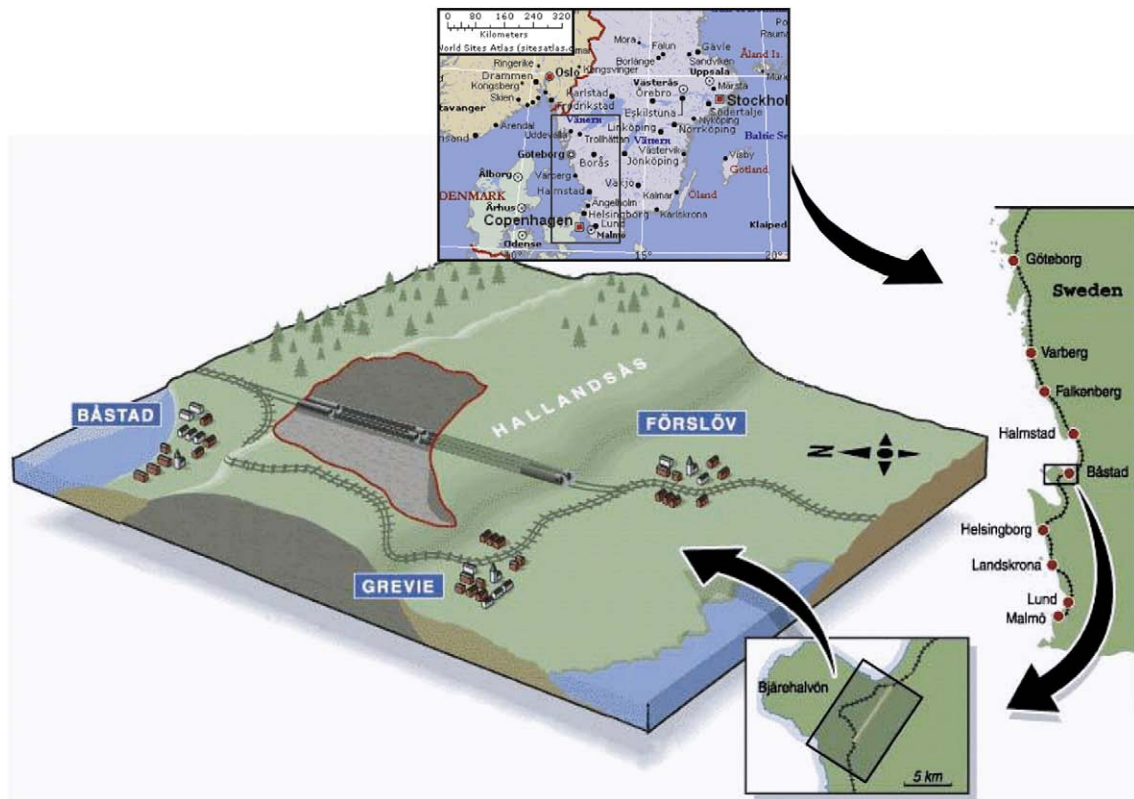
Fig. 1. Location of the Hallandsås Horst. Modified from Öhrling (2007) and Sitesatlas.com (2008).

the large amounts of water to be contained within the bedrock. At tunnel level there is a water column of 100–150 m which results in high water pressure. The groundwater level is strongly influenced by the construction of the tunnel and is therefore monitored very thoroughly (Banverket, 1996 and www.banverket.se).

3. Geoelectrical imaging

Geoelectrical imaging is used for measuring the spatial variation of resistivity of the subsurface. The resistivity of the different geological materials differs greatly from about 10^{-6} Ωm in minerals such as graphite to more than 10^{12} Ωm for dry quartzitic rocks. Most rock forming minerals are insulators so the resistivity of crystalline rock depends basically on the amount of water present and the degree of weathering of the rock. Therefore rock without water bearing fractures or weathering has a high resistivity whereas clay-weathered rock or rock with water bearing fractures has a considerably lower resistivity (Palacky, 1987; Parasnis, 1997; Binley and Kemna, 2005).

In this paper no introduction to the geoelectrical imaging is given. For more information see Binley and Kemna (2005), Reynolds (1997) and Takahashi (2004).

Generally the depth of investigation of the method increases with increasing electrode distance. The current will seek to obtain the lowest possible total resistance on the path between the two current electrodes. For example a very low resistive layer near the surface would prevent the current from penetrating deeper into the ground. In this case, the resolution of the deeper layer will be limited. By contrast, a very high resistive layer close to the surface would force the

current down to a less resistive lower layer. The depth of investigation therefore depends on the resistivity of the different layers as well as the largest electrode separation.
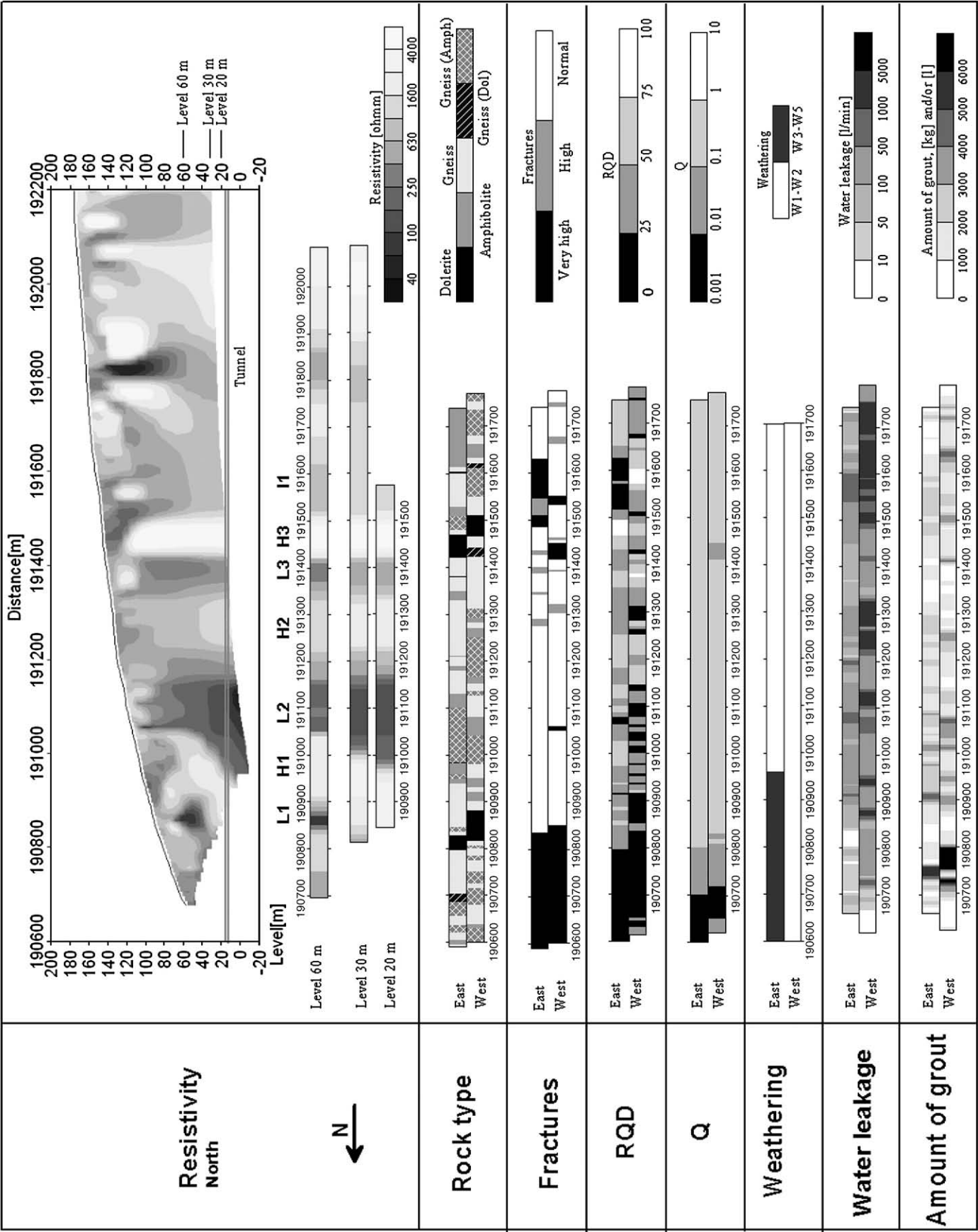
The resistivity data were measured as 2D profiles while the sub-surface is 3D. To assume a 2D earth might in some cases be problematic. This would create 3D effects in the resistivity data; especially in this particular case where the geology changes relatively fast. In order to obtain the best 2D situation the profiles should always be perpendicular to the geological structures. The Hallandsås Horst profiles are more or less perpendicular to the NW–SE structures.

3.1. Geoelectrical imaging at the Hallandsås Horst

In connection with the tunnel project almost 20 km of CVES profiles have been measured between 1995 and today using different versions of the ABEM Lund Imaging system (ABEM, 2007). During this time the measuring instruments, computers and software have developed and become faster and with better resolution. The measurements were done using the roll-along technique allowing a continuous data acquisition. For more information about the technique used at the Hallandsås tunnel, the reader is referred to Dahlin et al. (1999).

For comparison in this paper, old data of good quality has been re-processed using the newest version (ver. 3.55.77) of the software RES2DINV. This program uses a 2D finite element calculation method. For the inversion of the data the robust inversion is used which favours a blocky geology (Loke, 2004). This is done because at the Hallandsås there are often sharp boundaries and vertical structures.

Fig. 2. Visualization of resistivity and mapped data from both tunnels in the northern part of the Hallandsås tunnel. The mapped data were rock type, fractures, RQD, Q, weathering, water leakage and amount of grout. The resistivity data are shown as full model and as sub-models extracted at 60 m, 30 m and 20 m above sea level. The low resistive zones are marked with L1, L2 and L3. High resistive zones are marked with H1, H2 and H3. The area with intermediate resistivity is marked I1. Here the tunnel base is at approximately 15 m above sea level.

The resistivity data was measured using a Schlumberger electrode configuration with a cable layout of 800 m and an electrode spacing of 10 m. An exception is in the southern part of the profile where the measurements were done using a Wenner electrode configuration with cable layout of 400 m and an electrode spacing of 5 m. With the electrode layout and arrays used, the depth of investigation is 120–160 m for the long Schlumberger layout and 60 m for the short Wenner layouts. For long intervals, the tunnel is located 150 m below ground surface. To compensate for the inadequate penetration depth the full resistivity model is shown as well as sub-models extracted at different levels from the model. By showing the different sub-models a clear image of the resistivity change with depth is obtained. Instead of the commonly used colourful resistivity images, the images here are shown in grey scale. This allows an easier comparison (Fig. 2) to mapped tunnel parameters such as RQD, Q, weathering, water inflow etc. which are also presented in a similar grey scale.

4. Tunnel documentation

The long history of the Hallandsås tunnel has given rise to different types of approaches both for tunnel construction and documentation. Documentation exists from regular drill and blast at the early stages of the tunnel construction. This was done from both ends and in both tunnels more or less concurrently. However the work was stopped because of problems caused by large amounts of ground water leaking into the tunnel. Therefore this type of mapping only exists for 1 km in the north and for 800 m at the south end of the tunnel.

Use of a TBM (tunnel boring machine) has resulted in another type of documentation. The geologist can only get access for mapping the tunnel face when the TBM is stopped during mounting of the lining. This means the face is only visible every 2.2 m. So far 1200 m has been mapped in a single tunnel.

In both types of documentation the lithology is mapped. In several instances there are different types of rock present in one tunnel face. When there is more than 50% gneiss in a face but with different rock types also present, such as amphibolite, it is written as e.g., gneiss (amph).

4.1. Documentation from drill and blast

During the period when drill and blast was done the parameters mapped were rock type, fracture zones, weathering, RQD, Q, water leakage and amount of grout used. The water leakage was measured for every grouting round (fan). The weathering was classified according to ISRM 1980 (ISRM, 1980). The weathering was only divided in two intervals; W1 to W2 and W3 to W5. W1–W2 is fresh rock while W3–W5 is weathered rock. The RQD is the Rock Quality Designation as proposed by Deere et al. (1967).

Barton et al. (1974) developed the rock mass quality system (Q-system) evaluating the rock quality using six different parameters. The six parameters are: RQD, the number of joint sets (J_n), the roughness of the weakest joints (J_r), the degree of alteration or filling along the weakest joints (J_a), and two parameters which accounts for the rock load (SRF) and water inflow (J_w). In combination these parameters represent the block size, the inter-block shear strength and the active stress.

The degree of fracturing is another parameter which was observed. As a starting point the rock is all fractured, but the degree of fracturing

Table 1
The rock class defined exclusively for the Hallandsås tunnel.

Rock class	RQD	Block size (cm)	Weathering
1	75–100	>60	W1
2	50–75	20–60	W1
3	25–50	5–20	W1
4	0–25	0–5	W1
5	25–50	5–20	W2
6	0–25	0–5	W2
7a	25–50	5–20	W3
7	0–25	0–5	W3
8	25–50	5–20	W4
9	0–25	0–5	W4
10	0–25	0–5	W5

Based on Banverket (2002).

increases at several places. Thus the fracturing is divided into three different categories; normal, high and very high fracturing.

During the tunnel construction the fractures are grouted to water from leaking into the tunnel. The amount of grout is stated with the unit of kg and/or l. This is done because there were used two different types of grout; cement and chemical grout. The first has the unit kg and the latter has the unit litres.

4.2. Documentation from the TBM

For the use with the TBM, a site specific classification system was developed exclusively for the Hallandsås. The rock masses were divided into 11 different classes based on RQD, block size and weathering. The classification can be seen in Table 1.

Thus the parameters mapped are rock type, weathering, block size and rock class. Based on the weathering and block size the RQD can be assessed (see Table 1). For several probe drilling ahead of the TBM the water flow was measured. The measured water flow is a mean value for the whole probe length of 10 to 40 m. The exact position of the water bearing fractures is therefore not distinguished in this analysis. In the zones where the water leakage is less than 10 it shall be regarded as if there were no probe drillings or no flow measurements and not that there was no water leakage.

5. Comparison of resistivity data and tunnel documentation

In order to evaluate the results from the resistivity method the data are compared with the existing tunnel documentation. The comparison is done merely by visual evaluation because of the difference in the scale of the data and the inadequate penetration depth. The resolution of the tunnel documentation is in decimetres whereas the resistivity data are in tens of metres. Because of the inadequate penetration depth of the resistivity data the sub-models at different levels are primarily used for the comparison in order to give an impression of how the structures changes with depth. This is possible because of the vertical structures in the area.

All data is plotted in grey scale in order to give a rapid impression of the rock quality. Dark colours are poor rock mass quality while light colours are good quality. The only exception is rock type where the colour does not have any significance with regards to the mechanical quality of the rock.

The coordinate system used is the chainage system used by the Swedish National Rail Administration.

Fig. 3. Visualization of resistivity and mapped data from both tunnels in the southern part of the Hallandsås tunnel. The mapped data were rock type, fractures, RQD, Q, weathering, water leakage and amount of grout. The resistivity data are shown as full model and as sub-models extracted at 60 m, 40 m and 20 m above sea level. The low resistive zones are marked L4, L5 and L3. The zones with intermediate resistivity are marked I2 and I3. Here the tunnel base is at approximately 15 m above sea level.
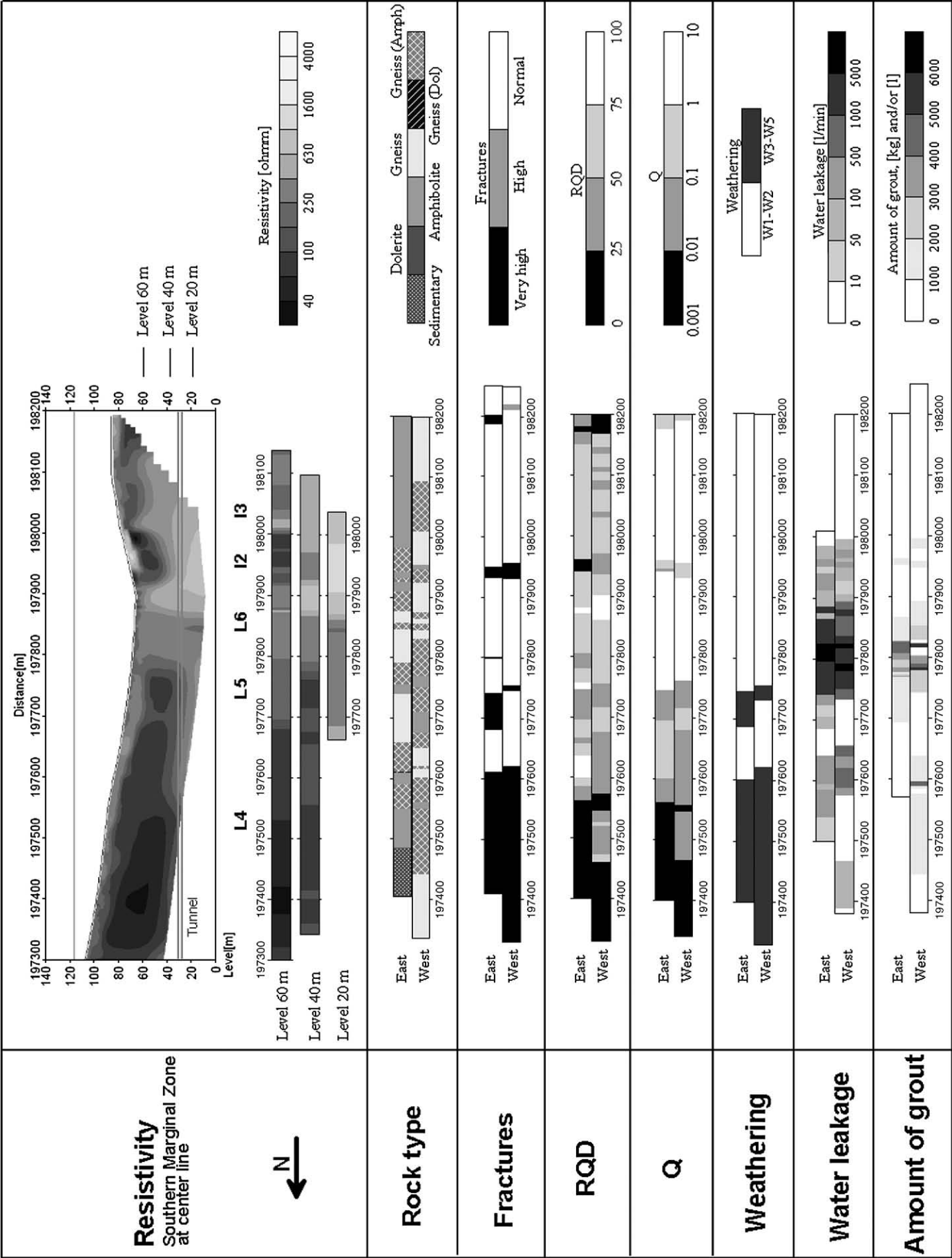
6. Results

The comparison between resistivity and the mapped data is done for three different sections of the tunnel here referred to as North, South and TBM. The distance between the centrelines of the two tunnels is 25 m.

To make the evaluation of the results easier different resistivity zones are marked with a letter and number. The resistivity data are divided into three types e.g., low (L), high (H) and intermediate (I). The dividing into the different resistivity zone is done so that it covers the same resistivity intervals in all three tunnel sections. The intervals can be disputed and discussed.

6.1. North

Fig. 2 shows the resistivity and the mapped data from the northern part of the twin track tunnel. The mapped data are rock type, fracture zones, RQD, Q, weathering, water leakage and amount of grout. What is obvious when evaluating the water leakage from the two parallel tunnels is that the amount of water in the western tunnel is much higher than in the eastern tunnel (~factor 10). This is probably due to the fact that the western tunnel was constructed prior to the eastern. Therefore the ground water reservoir was drained by the first tunnel and there was not the large amount of water accessible for leaking into the second tunnel. Furthermore, considerable pre-grouting was carried out for the west tunnel which may influence also the east tunnel. As a consequence the water leakage data for the eastern tunnel is biased.

The mapping of the lithology in the two parallel tunnels shows that the dolerite dykes are striking NE–SW following the structural trend.

The sub-models of the resistivity data shows three zones with low resistivity along the part with tunnel documentation, but only two, L2 and L3, are clearly seen in all three depth slices. Interesting zones in the resistivity data can also be areas with very high resistivity. Three areas with high resistivity (~4000 Ωm) are visible in the depth slices.

6.2. South

Fig. 3 shows the resistivity data and the tunnel documentation for the southern part of the Hallandsås tunnel. This part of the tunnel is dominated by poor rock quality. The resistivity data was measured with Wenner array and had a maximum layout on 400 m. This might have implications for the resolution at the tunnel level. In a later field campaign resistivity was measured from chainage 190800 to 197600 using the Schlumberger array and layouts of 800 m. The southernmost part of this can be seen in Fig. 4. Thus there is an overlap between the resistivity sections shown in Figs. 3 and 4. The deeper model in Fig. 4 confirms that the resistivity at tunnel level between chainage 197300 and 197950 is low.

In this part of the resistivity section three areas are categorized as low resistive zones and two as intermediate zones. In Table 2 the dominant observations from the tunnel documentation are summarized.

6.3. Tbm

In Fig. 4 the tunnel documentation from the use of a TBM is compared with the resistivity data from the same section. The mapped data were rock type, RQD, block size, weathering, rock class and water leakage. The resistivity data are shown as the full model and as sub-models extracted at 60 m and 25 m above sea level.

In this part of the resistivity section three low resistive zones are identified. Only L7 and L9 are visible in both levels. Two high resistive areas and three areas with intermediate resistivity are visible. In Table 4 the corresponding properties from the tunnel documentation are summarized.

7. Discussion

The comparison shows that a change in resistivity in most cases is related to some kind of change in the rock conditions. High resistivity corresponds well with good quality gneiss as the dominant rock type. For the northern part this is seen at H2 and H3, Fig. 2 (Table 3). In the part drilled with a TBM, Fig. 4 (Table 4), it is observed at H4 and H5. In general low resistivity corresponds to a varying lithology with fractured contacts or merely rock with very poor quality (RQD < 25). This is very clear in large areas of the southern part of the tunnel, Fig. 3. The intermediate resistivity often coincides with areas of amphibolite with an average RQD of 25–75 (fair quality). An example of this is in Figs. 3 and 4 where the I3, I4 and I6 all are amphibolites. But in some cases the intermediate resistivity corresponds to increased water content. The presence of water can decrease the resistivity of a rock with an otherwise fair rock quality. This is the case in the northern part, Fig. 2 (Table 3) at I1 where there is an increased amount of water.

For reference, in-situ measurements of the resistivity were performed on some representative samples of the different rock types in the tunnel. For this purpose a special device was made for measuring the resistivity using a Wenner-configuration with spacing between the electrodes equal to 0.05 m and to 0.1 m. The measured apparent resistivities are shown in Fig. 5. It is seen that the resistivity of the amphibolite is between 800 and 4000 Ωm, whereas for gneiss it is scattered between 1000 and 11,500 Ωm. This emphasises the difficulty in distinguishing between these two lithologies. But it is quite clear that the amphibolite does not attain the same high resistivity as the gneiss. High resistivity is clearly an indication of gneiss whereas an intermediate resistivity is often amphibolite that to some degree may be mixed with gneiss. This supports the observations from comparing tunnel documentation with the resistivity data.

This is also confirmed by geophysical logging of the core drilling KB6105. The position of the drill-hole is marked with a line in Fig. 4. The drill-hole is positioned 30 m west of the tunnel line inclined at an angle of 20° from vertical. From the full resistivity section it is seen that the drill-hole passes through a low resistivity zone (250–600 Ωm), L7. In Fig. 6 the lithology is plotted together with the resistivity log and natural gamma log. The core drilling is dominated by gneiss but with two layers of dolerite at 37 m and 47 m. From 85 m to 92 m the lithology is amphibolite. It is interesting that the resistivity of these three zones is as low as 2000 Ωm, whereas the gneiss has a resistivity of 4000 to 10,000 Ωm. In addition they give low gamma readings. In the gneiss there is a thin layer with a very high gamma count which is seen neither in the lithology log nor the resistivity log. The low resistive zone L7 is well explained in the tunnel documentation by several lithology contacts. Thus the disagreement between the resistivity seen in the profile and in the resistivity log might be explained by the fact that the geology is very complex and that the drilling is made 30 m from the resistivity profile. The different scale of resolution of the methods is also essential for the result.

Although in most cases there is a correlation between resistivity and rock conditions, there are also exceptions. The example from the northern part of the tunnel is at H1, Fig. 2 (Table 3). There is a high resistivity and therefore it is expected to be good quality rock without weathering and water. The rock in the eastern tunnel is highly weathered whereas the western tunnel is fresh. On the other hand the RQD is lower in the western than in the eastern tunnel. In agreement with the expectation there is gneiss, mixed with amphibolite in some places. The result from the investigation at L3 is also difficult to interpret. There is increased water leakage but the RQD is not as low as expected. Thus the low resistivity here might be an effect of the inversion or 3D effects. Lack of resolution can also cause a low resistive body at a shallower depth to apparently extend
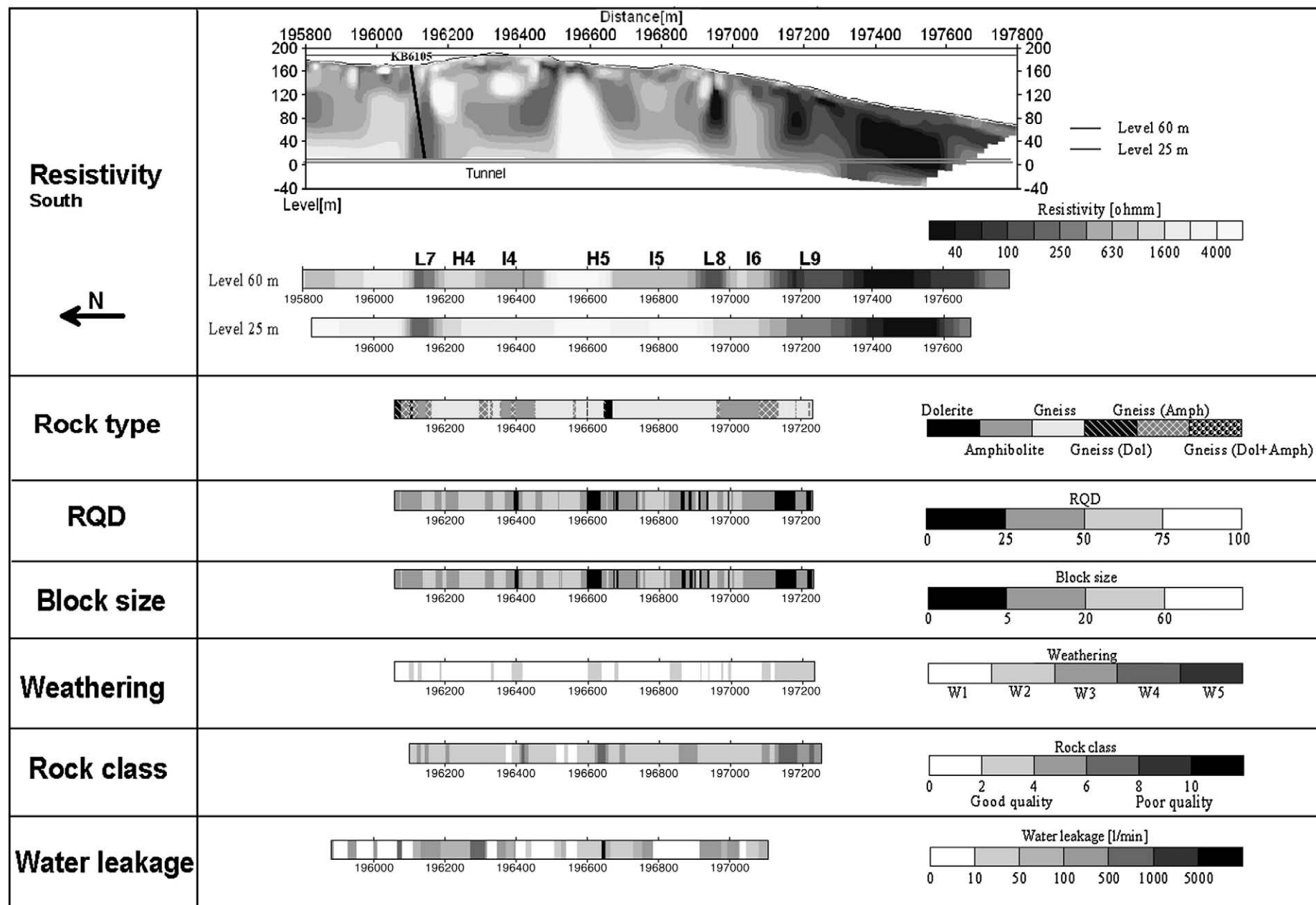
Fig. 4. Visualization of resistivity and mapped data from the southern part of the Hallandsås tunnel. The mapping is done in front of the TBM at every operational stop. The mapped data were rock type, RQD, block size, weathering, rock class and water leakage. The resistivity data are shown as full model and as sub-models extracted at 60 m and 25 m above sea level. The low resistive zones are marked with L7, L8 and L9. High resistive zones are marked with H4 and H5. The areas with intermediate resistivity are marked I4, I5 and I6. Here the tunnel base is at approximately 15 m above sea level. The position of core drilling KB6105 is marked with a line.

Table 2
Summation of the dominating properties of the rock in the intervals based on the resistivity data for the southern part of the tunnel.

Resistivity	Rock type	Fracturing	RQD	Q	Weathering	Water
L4	Gneiss/amphibolite	*Very high*	*0–25*	*<0.01*	*W3–W5*	E: Int. W: Low
L5	E: gneiss W: gneiss (amph)	E: very high W: normal	25–50	*0.01–0.1*	*W3–W5*	E: Int. W: Low
L6	E: gneiss W: gneiss (amph)	Normal	50–75	1–10	W1–W2	*High*
I2	E:gneiss (amph) W: gneiss	*Very high*	E: 0–25 W: 25–50	0.1–1	W1–W2	*Int.*
I3	E: *amphibolite* W: gneiss(amph)	Normal	50–75	1–10	W1–W2	Low

L is low, H is high and I is intermediate resistivity. The most likely explanation to the resistivity value in the interval is indicated with bold and italic.

Table 3
Summation of the dominating properties of the rock in the intervals based on the resistivity data for the northern part of the tunnel.

Resistivity	Rock type	Fracturing	RQD	Q	Weathering	Water
L1	Dolerite	*Very high*	*0–25*	0.1–1	E: *W3–W5* W: W1–W2	E: Low W: *High*
L2	Gneiss(amph)	Normal	E: 25–50 W: *0–25*	0.1–1	W1–W2	E: Low W: *High*
L3	Gneiss	Normal	E: *25–50* W: 50–75	0.1–1	W1–W2	Med.
H1	*E: Gneiss W: Gneiss/Amph*	Normal	E: 25–50 W: *0–25*	0.1–1	E: *W3–W5* W: W1–W2	E: *Low* W: *High*
H2	*E: Gneiss W: Gneiss(amph)*	Normal	E: 25–50 W: *0–25*	0.1–1	*W1–W2*	E: Low W: *High*
H3	*Dolerite/Gneiss*	Normal	E: *75–100 W: 25–50*	0.1–1	*W1–W2*	*Low*
I1	E: Gneiss W: Gneiss(amph)	*E: Very high W: Normal*	*E: 0–25 W: 75–100*	0.1–1	W1–W2	*High*

L is low, H is high and I is intermediate resistivity. The most likely explanation to the resistivity value in the interval is indicated with bold and italic.

down to tunnel level. For I1 the documentation, especially for the eastern tunnel, shows that the rock has a low RQD (0–25) and is very highly fractured. On the other hand the western tunnel has a very high RQD (78–100). Additionally there is a large amount of water in the western tunnel. A low RQD is expected to give low resistivity while the high amount of water is expected to give an intermediate resistivity. But in this case it is also interesting to see that the rock is fresh. Therefore in this instance it has an intermediate resistivity due to increased water content.

In the documentation from the TBM, Fig. 4, the RQD at H5 shows a relatively large area with a value of less than 25 and a very high water leakage in an otherwise fair rock quality. It is expected that such a large area with poor rock quality and very high water leakage would give low resistivity. Instead there is quite high resistivity. The water might flow in few fractures and the high water leakage may be caused by the high pressure. The nature of the fractures cannot be evaluated in the type of flow measurement performed in the probe drillings. The conclusion is that the zone most likely is too small to create an anomaly in high resistivity gneiss with good quality. Another example is at L8 in the same section where the RQD shows many narrow zones with values lower than 25. The water leakage shows an intermediate flow that is slightly increased. There is no clear indication of this problematic area because the resistivity data at tunnel level does not show any low resistivity whereas at 60 m.a.s.l. it does. Here the problem might be that 20 m.a.s.l. is deeper than the resistivity method can resolve with the layout and electrode array used.

A probable reason for the divergence between the tunnel documentation and the resistivity data might be the 3D effects in data. The tunnels are separated by 25 m and still there is a large difference between the lithology and rock properties in the eastern and western tunnels, emphasising the high variability in the rock mass properties.

Another issue is the difference in the scale of the data. The tunnel documentation shows every small change in the rock conditions. For the resistivity method to be successful a zone has to be sufficiently large and have large enough contrast in the physical properties. A complicating factor in this particular tunnel project is that the tunnel is situated at a large depth giving poor resolution at tunnel level. The resistivity data are measured at the ground surface 120–150 m above the tunnel. Therefore these data have a lower resolution at tunnel level than the detailed tunnel documentation. Thus a zone can be too narrow to be visible in the resistivity data if the resistivity contrast with the surrounding rock is not sufficiently large. The scale of resolution is tens of metres.

In the mapping of the tunnel there is the human factor to acknowledge. The mapping of RQD, weathering and lithology is a subjective assessment done by geologists at the tunnel site. There is not a big difference in the rock properties if the rock has a RQD of e.g.,

Table 4
Summation of the dominating properties of the rock in the intervals based on the resistivity data for the TBM drilled part of the tunnel.
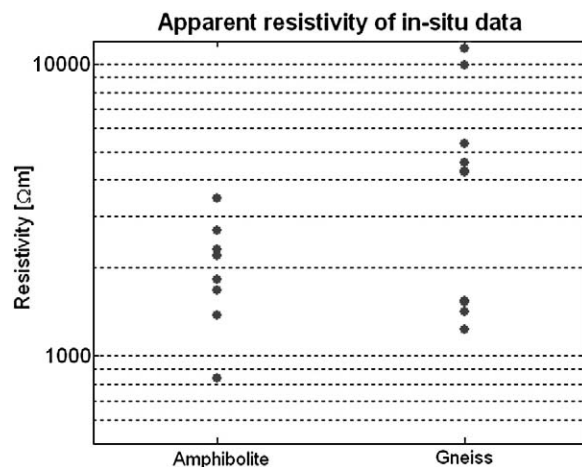
| Resistivity	Rock type	RQD	Weathering	Water
L7	*Several contacts*	25–50	W1	*Intermediate but increased*
L8	Gneiss/amph.	*25–50*	W1	*Intermediate*
L9	Gneiss	*0–25*	W2	No values
H4	*Gneiss*	25–50	W1	*Low*
H5	*Gneiss*	*50–75*	W1	*Low/Very high*
I4	*Amphibolite*	*25–50*	W1	*Int./high*
I5	Gneiss	*25–75*	W1	Intermediate/no values
I6	*Amphibolite*	*25–75*	W1	*Intermediate*

L is low, H is high and I is intermediate resistivity. The most likely explanation to the resistivity value in the interval is indicated with bold and italic.

Fig. 5. The apparent resistivity of amphibolite and gneiss measured at different locations in the tunnel.
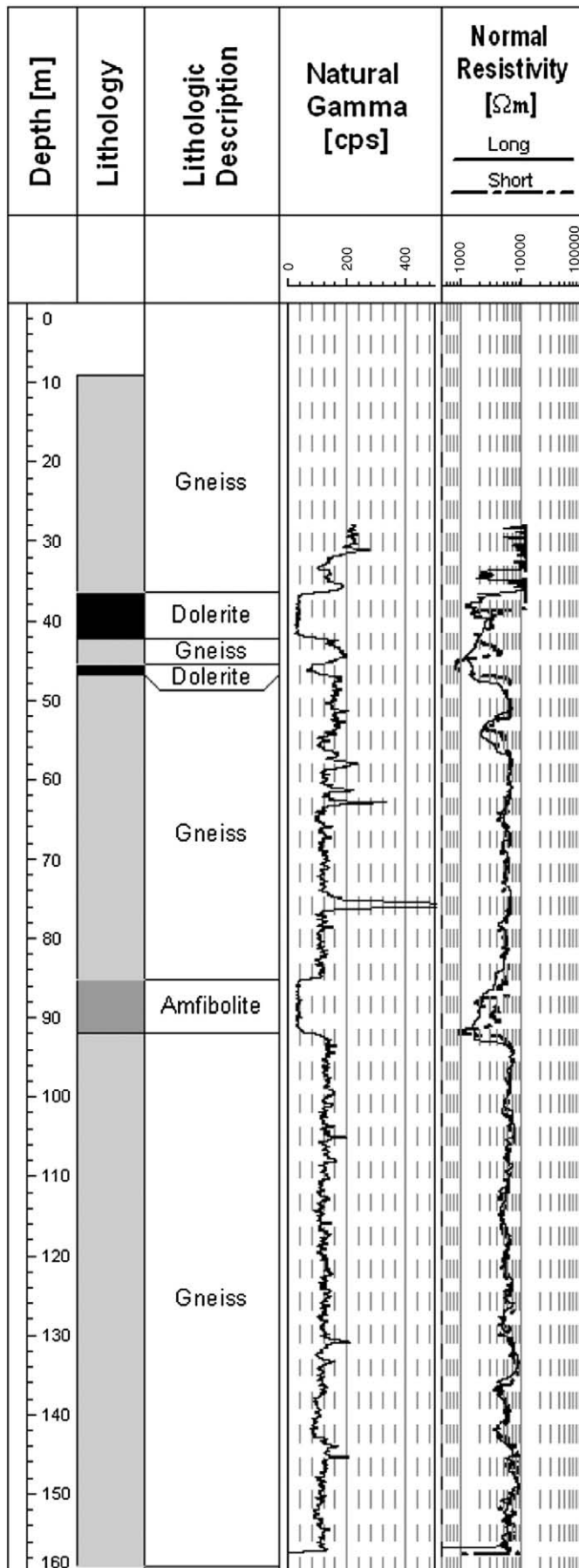
28 or 23 but it means that the conditions look more serious in the plot. So the mapping is somewhat subjective and might bias the results of this study in some parts.

By using the experience from the evaluation made in this paper a new geological prognosis can be compiled and used in the further work with the TBM. Fig. 7 shows a part of a new prognosis for a part of the tunnel. In Fig. 7a the resistivity profile for the whole tunnel is seen. Fig. 7b shows a close-up of a 1200 m long section in the central part where the TBM had not yet drilled through when this study was finished. In Fig. 7c the rock type, RQD and weathering is estimated based on the resistivity data and ground based magnetic data (not shown). The dolerite in the southern part of the selected section is pinpointed by the magnetic data. The low RQD and high weathering in the contact zone between the dolerite and the gneiss is based on general knowledge about the rock conditions in such zones. The old prognosis showed that from 194400 to 194650 there should be rock with a RQD lower than 25. This is to some extent confirmed in the updated version of the model where the RQD is between 25 and 50. In the old model there are several dolerite dykes between 194100 and 194400 with a poor rock quality in the contact zones. This is not confirmed by the resistivity data. In the old model, as well as in the updated version, the dolerites are pinpointed by ground based magnetic surveys. It was noted in the first version that the magnetic anomalies might be due to noise, and because they are not indicated in the resistivity data they are left out of the updated model. The next step for the prognosis would be to estimate its reliability. This brings up a lot of new issues and will therefore not be discussed in this paper.

8. Conclusion

For the Hallandsås tunnel project in southern Sweden several kilometres of resistivity measurements (CVES) have been made. Therefore the tunnel documentation gives a good opportunity to perform an evaluation of the resistivity data. It has previously been shown that three large zones with problematic rock conditions could be identified using geoelectrical imaging (Dahlin et al., 1999). In this case the contrast in resistivity between rock of good quality and rock of poor quality is sufficiently large to be resolved beyond any doubt. It is probable that more information can be extracted from the remaining part of the 2D profile and used in the construction work.

The ability of geoelectrical imaging to indicate changes in rock conditions by means of varying resistivity makes it a valuable tool in the pre-investigation. With the tunnel drilled 150 m beneath the surface and in an area with this type of geology, the scale of resolution is tens of metres. Thus in this example the method cannot resolve bodies smaller than this. The comparison of the tunnel documentation and the geoelectrical imaging showed that a change in resistivity often corresponds to some kind of change in the rock mass properties. The resistivity can be divided into three categories, i.e., high, low and intermediate resistivity. These three categories can generally be correlated to certain types of rock mass conditions. The high resistivity corresponds well with gneiss with a good quality. Intermediate resistivity is most likely amphibolite with a relatively good rock quality. This is also supported by in-situ measurements in the tunnel where the only rock with very high resistivity is gneiss. Also the resistivity log showed that amphibolite has lower resistivity than gneiss. In some cases the intermediate resistivity can also be water bearing rock. The low resistivity is rock of a poor quality which is deeply weathered or has many contacts between different lithologies.

Fig. 6. The lithology from the core drilling KB6105 plotted together with the natural gamma and long/short normal resistivity log.
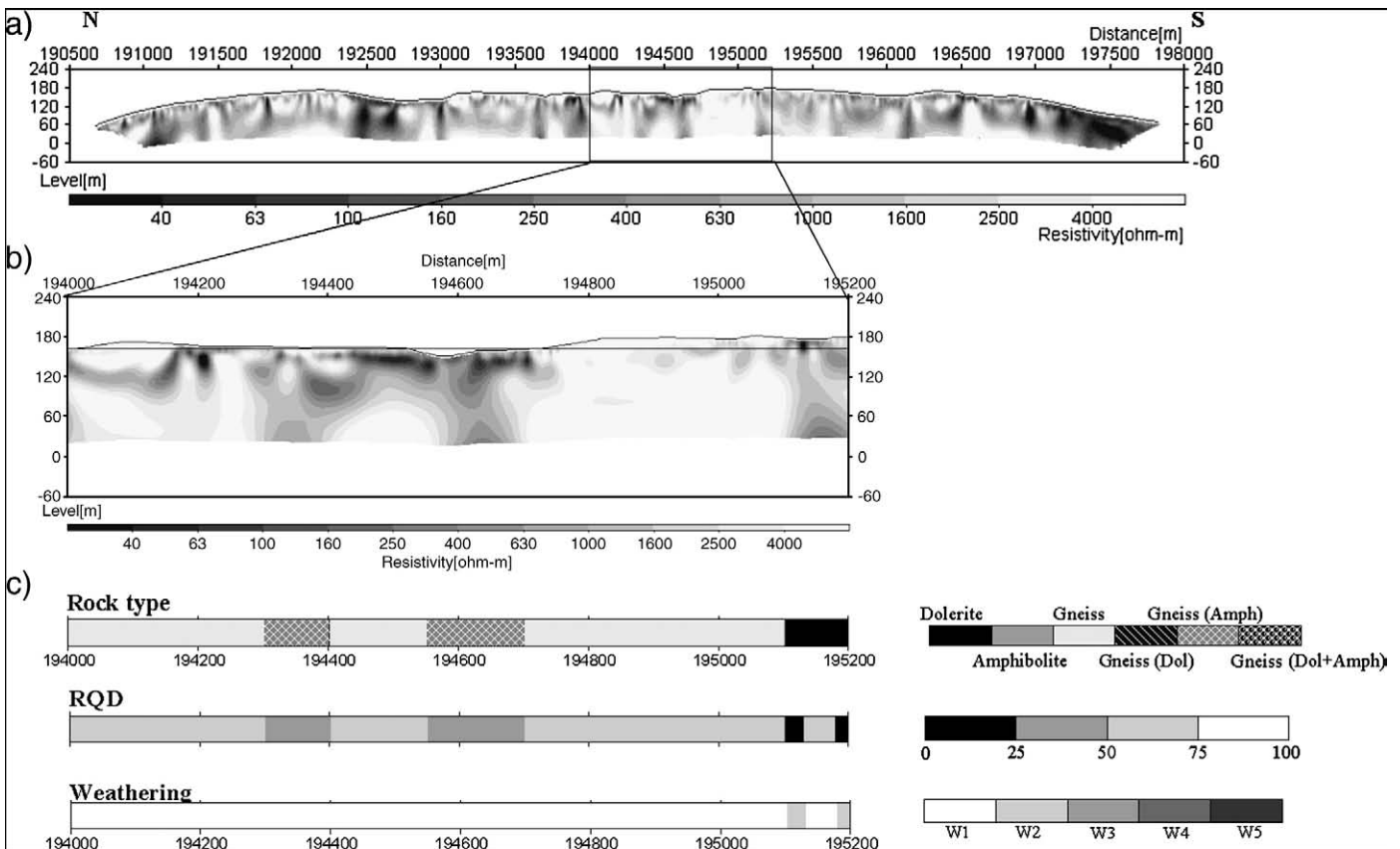
Fig. 7. a) The full resistivity section for the Hallandsås tunnel in grey scale. b) Close-up on 1200 m in the central part of the tunnel section. c) Estimated rock type, RQD and weathering for the 1200 m long section.

However it is not always possible to relate the changes in resistivity to a specific rock condition or property. This may be caused by differences in the scale of the compared data. The resistivity data has a much lower resolution than the tunnel documentation. Another reason can be 3D effects in the 2D resistivity profiles. In addition a certain amount of bias can occur in the mapping of the tunnel parameters because different geologists may interpret the conditions differently.

The decision makers can use the changes in resistivity as an indication of the need for caution when planning for example an underground rock construction. The experience from the Hallandsås tunnel construction can be used to improve the interpretation capability of the resistivity image. Previously there has been a focus on low resistivity zones in order to identify poor rock conditions. The comparison has shown that the high resistivity zones tend to indicate good quality rock. This is as important for the contractor to know as the location of poor quality rock. Even though the resistivity method is not able to interpret every change in the conditions it still contributes with important information within the limitations of its resolution. Geoelectrical imaging contributes to reduce the number of uncertainties. In combination with other investigations the ambiguity and uncertainty might be further reduced.

As a tool for pre-investigations, resistivity imaging has the advantage that it is more time and cost efficient than other alternatives, e.g., seismic refraction. It has to be stressed that the method should not stand alone. A priori information about the geological setting is crucial and the results have to be followed up by additional measurements, i.e., with other types of geophysical methods exploiting other physical parameters or by 3D resistivity measurements. The measurements can then be used as a base for deciding where to perform geotechnical drillings.

When the resistivity data has been used for the pre-investigations they should never be put aside. It is important to make a dynamic geological prognosis and always use new information and experience to update the interpretation of the data. No matter how good a prognosis is, it is still an estimate of the ground conditions and there will always be room for improvements. It might be nothing is added, but the model becomes more certain. By performing a comparison as in this paper the value of the time and money spent on the investigations becomes higher and the tunnel projects might be better prepared for unforeseen rock conditions.

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