Evaluation of geophysical methods for the delineation of bedrock fractures - a case history from Utengen, Hvaler, southeastern Norway

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Introduction

Researchers have used a wide variety of geophysical methods to address the problem of detecting bedrock fractures (e.g. Warrick & Winslow 1960, Zohdy & Jackson 1969, Palacky et al. 1981, Aubert et al. 1984). The location of fractures is essential in the initial stages of the investigation of water resource potential. However, very little work has been focused on the combined use of various methods for fracture location. At the Geological Survey of Norway, the applicability of several geophysical methods has been studied (Rønning 1985). These include refraction seismics, electromagnetic methods (VLF & slingram), resistivity methods and magnetic profiling. The introduction of the ground-penetrating radar has further contributed to the delineation and mapping of bedrock fractures (e.g. Davis & Annan 1989).

A test-site at Utengen, Hvaler, southeastern Norway, has been subject to geophysical investigations using several methods. The main objective of the study was to evaluate the suitability of the various methods in the mapping of bedrock fractures.

Utengen test-site

Utengen is situated on the northwestern peninsula of the island of Kjerkøy at Hvaler in southeastern Norway (Fig. 1). The lithology is dominated by the Precambrian Iddefjord Granite. Several locations in the Hvaler area have been subject to extensive hydrogeological investigations (e.g. Banks & Rohr-Torp 1990, Banks et al. 1992, 1993a, b). Utengen was one of these locations. It was chosen for detailed geophysical investigations because it lies at the intersection of several fracture lineaments, and also because the central part of the site is covered by thin Quaternary deposits, allowing us to investigate the performance of geophysical methods through such a sediment cover (Banks et al. 1993c). The geophysical results from Utengen are reported by Lauritsen & Rønning (1992) and Banks et al. (1993c).

Geophysical methods

The following is a brief outline of various geophysical methods applied to mapping of fractures.

Fig. 1. Location of the investigated area at Utengen.

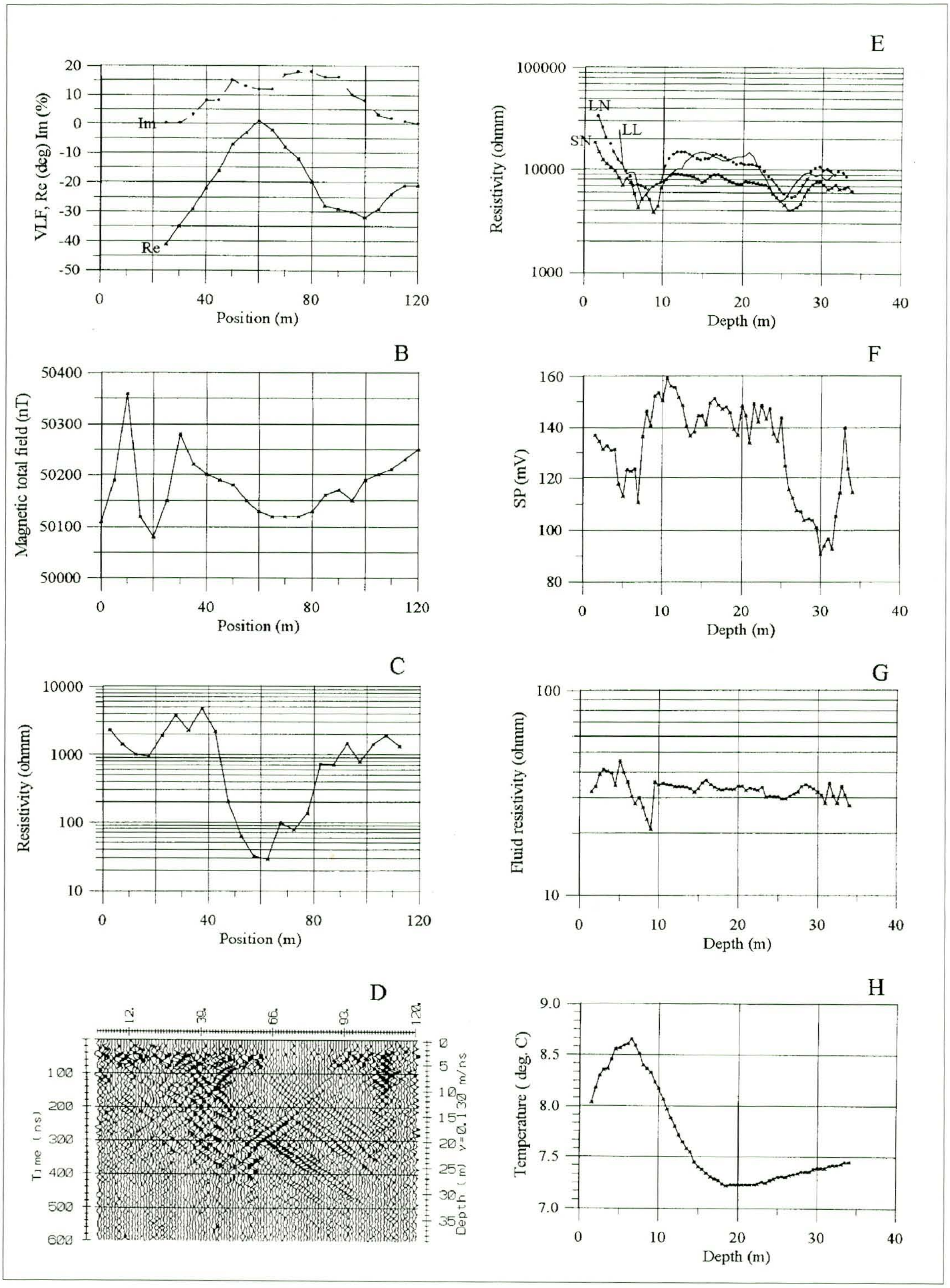

Fig. 2. Surface and borehole geophysics from the Utengen test-site. Left column: VLF (A), magnetics (B), resistivity (C), GPR (D). Right column: formation resistivity (E), SP (F), fluid resistivity (G), temperature (H).

More comprehensive descriptions of the methods can be found in standard texts, e.g. Telford et al. (1976) and Kearey & Brooks (1991).

Refraction seismics
Among other parameters, the seismic refraction method yields information about acoustic wave velocities in bedrock. Fractures are associated with velocity lows. This can be an accurate method in determining fracture position and the degree of fracturing. The method is, however, relatively expensive.

Very low frequency electromagnetic profiling (VLF)
This method utilises electromagnetic (EM) fields from military transmitters. Due to electrical conductors, a secondary field is superimposed on the primary field creating an anomaly which can be detected on a receiver. Fractures commonly act as electrical conductors due to increased porosity. A general disadvantage of the method is that spurious anomalies can be generated by numerous sources other than fractures, such as electrically conductive overburden, mineralizations, power-lines and severe topography.

Magnetic profiling
The method can only be employed in areas where the bedrock has some content of magnetite. Fractures are normally associated with magnetic lows due to oxidation and hydration of magnetite (Henkel & Guzmán 1977). The method should be used with great care in areas with overburden. Sediments are usually non-magnetic, and an increase in thickness will also give rise to magnetic lows.

Resistivity profiling
Fractures generally have lower electrical resistivity than fresh bedrock, and will appear as resistivity lows on resistivity profiles. The method offers information on fracture location and thickness. The main disadvantage with this method is the strong influence of conductive overburden which, if present, masks the response from the underlying bedrock.

Ground-penetrating radar (GPR)
GPR transmits electromagnetic pulses into the ground and records reflections from interfaces separating layers of different dielectric properties. The dielectricity increases with increasing water content. Fractures normally have a higher water content than the surrounding non-fractured bedrock, and may therefore be seen on GPR records. The method is not suitable in areas with electrically conductive overburden (e.g. marine clay) because of energy absorption.

Borehole geophysics
Several logging methods have been developed to give a great amount of downhole information. The Geological Survey of Norway applies a simple data acquisition system, measuring formation resistivity with three different electrode configurations. The system also records fluid resistivity, temperature and self potential. Recorded data can provide information on the location of fractures/fissures in bedrock and the sites of water inflow.

Results
The test profile is shown in Fig. 1. Data from each applied method are shown in Fig. 2. A rise in the VLF-Re curve (Fig. 2A) from position 20 is caused by a power-line at position -20. A steep dip in the curve from positions 60 to 80 is interpreted to be caused by a conductive zone in the ground. Small variations in the VLF-Im curve (ellipticity) indicate moderate conductivity.

Magnetic data (Fig. 2B) show irregularities from positions 0 to 30 due to the power-line. A magnetic low from positions 50 to 80 coincides with the VLF anomaly. The magnetic low is probably caused by a combination of fractured bedrock and increased soil thickness as indicated by a GPR record (not shown).

The resistivity profile (measured with gradient configuration, Fig. 2C) has a low from positions 45 to 80. This coincides with both VLF and magnetic anomalies, but also with increased soil thickness. Soil resistivity measured by a pole-dipole configuration is in the order of 30-50 ohmm, while the bedrock has a resistivity in the order of 2000-4000 ohmm. Modelling of VLF, magnetic and resistivity data (not presented here) shows that the anomalies can be explained by overburden material alone with a maximum depth of 5 m. However, from GPR profiling the soil thickness is interpreted to be less than 2 m which means that the anomalies are partly caused by bedrock fracturing. In glaciated terrain, outcropping fracture zones are commonly eroded by ice making a depression in the bedrock surface. Thus, the overburden is often thicker above fracture zones.

The GPR record is shown in Fig. 2D, and it is presented with the subtraction of neighbouring traces to enhance dipping reflectors. The record reveals reflectors dipping in both directions. The reflectors are probably representing bedrock fractures. The fractures appear most densely distributed between positions 60 and 90.

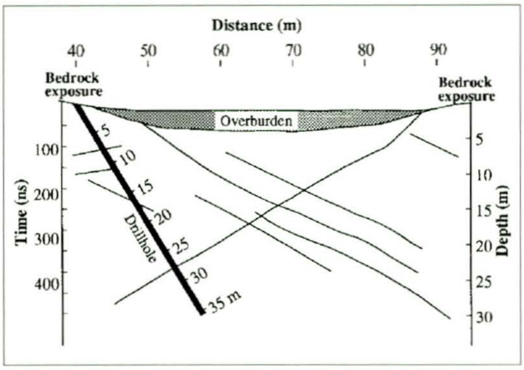

Fig. 3. Interpretation of the GPR record.

Reflectors are not as steep as they appear due to differing length and depth scale. True dips are in the order of 20-30°. The good penetration is rather surprising due to the low overburden resistivity (30-50 ohmm).

Borehole geophysics has been performed in a borehole shown in Fig. 1. A section showing the borehole on the interpreted GPR record is presented in Fig. 3. Resistivity lows (Fig. 2E) can be seen at depths of 7, 9 and 25-27 m. The first two of these correspond with reflections on the GPR record. The deepest reflector had to be migrated to match the resistivity log. The SP log (Fig. 2F) indicates porous structures at 5-7.5 and 25-33 m, coinciding with the position of resistivity anomalies. Fluid resistivity (Fig. 2G) and temperature (Fig. 2H) logs are anomalous at 7 and 9 m indicating water inflow. The largest fluid resistivity anomaly is at a depth of 9 m. There is no indication of water inflow at 26 m. Results from borehole geophysics correspond with observations made during drilling, where fractures were encountered at 7.5 and 9.3 metres.

Conclusions

At the Utengen test-site, several geophysical methods have been employed for the detection of bedrock fractures. The results are in good agreement with the location of fractures actually penetrated during drilling, and confirmed by borehole geophysics. VLF, magnetics and resistivity all gave anomalies in an area which could be explained by a combination of overburden and bedrock fracturing. Ground-penetrating radar was particularly successful at detecting low-angle fractures even with low overburden resistivity. The combined use of geophysical methods yielded most information.

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References

Aubert, M., Camus, G. & Fournier, C. 1984: Resistivity and magnetic surveys in groundwater prospecting in volcanic areas - a case- history Maar de Beaunit Puy de Dome France. *Geophys. Prosp. 32*, 554-563.

Banks, D. & Rohr-Torp, E. 1990: Hvaler-prosjektet - et integrert studium av grunnvann i fast fjell. *Geonytt 17, 4*, 25-26 & 59.

Banks, D., Rohr-Torp, E. & Skarphagen, H. 1992: An integrated study of a Precambrian granite aquifer, Hvaler, Southeastern Norway. *Nor. geol. unders. Bull. 422*, 47-66.

Banks, D., Rohr-Torp, E. & Skarphagen, H. 1993a: Groundwater resources in hard rock - do any general rules exist? Experiences from the Hvaler study, Southeastern Norway. *In* Banks, S.B. & Banks, D. (eds.). *Hydrogeology of Hard Rocks*, Proc. XXIVth Congress Int. Assoc. Hydrogeol., Ås, 39-51.

Banks, D., Rohr-Torp, E. & Skarphagen, H. 1993b: Groundwater chemistry in a Precambrian granite island aquifer, Hvaler, Southeastern Norway. *In* Banks, S.B. & Banks, D. (eds.). *Hydrogeology of Hard Rocks*, Proc. XXIVth Congress Int. Assoc. Hydrogeol., Ås, 395-406.

Banks, D., Lauritsen, T., Rohr-Torp, E., Rønning, J.S. & Skarphagen, H. 1993c: Groundwater in bedrock - Hvaler Project. Investigations at testsite Utengen. *Nor. geol. unders. Rapport 93.117*, 29 pp.

Davis, J.L. & Annan, A.P. 1989: Ground-penetrating radar for high-resolution mapping of soil and rock stratigraphy. *Geophys. Prosp. 37*, 531-551.

Henkel, H. & Guzmán, M. 1977: Magnetic feature of fracture zones. *Geoexploration 15,* 173-181.

Kearey, P. & Brooks, M. 1991: *An introduction to geophysical exploration*. Blackwell, Oxford, 254 pp.

Lauritsen, T. & Rønning, J.S. 1992: Geofysiske målinger over mulige vannførende sprekkesoner på Kjerkøy, Hvaler, Østfold. *Nor. geol. unders. Rapport 92.173*, 28 pp.

Palacky, G.J., Ritsema, I.L. & de Jong, S.J. 1981: Electromagnetic prospecting for groundwater in pre-Cambrian terrains in the republic of Upper Volta. *Geophys. Prosp.29*, 932-955.

Rønning, J.S. 1985: Geofysikk i vannprospektering fra sprekkesoner i fjell. Resultater fra et forprosjekt. *Nor. geol. unders. Rapport 85.103*, 39 pp.

Telford, W.H., Geldart, L.P., Sheriff, R.E. & Keys, D.A. 1976: Applied geophysics. Cambridge Univ. Press, Cambridge, 860 pp.

Warrick, R.E. & Winslow, J.D. 1960: Application of seismic methods to a ground-water problem in northeastern Ohio. *Geophysics 25*, 505-519.

Zohdy, A.A.R. & Jackson, D.B. 1969: Application of deep electrical soundings for ground-water exploration in Hawaii. *Geophysics 34*, 584-600.