INTEGRATED GEOPHYSICAL CHARACTERIZATION OF A HARD ROCK SITE FOR NUCLEAR WASTE DISPOSAL

N. ENESCU[1], T. AHOKAS[2], E. HEIKKINEN[3], C. COSMA[1]
[1] *Vibrometric Oy, Sitratori 3, FIN-00420 Helsinki, Finland*
[2] *Posiva Oy, FIN-27160 Olkiluoto, Finland*
[3] *JP-Fintact, Jaakonkatu 3, FIN-01620 Vantaa, Finland*

ABSTRACT

Geological characterization aimed initially to select the site for final disposal from a series of candidate sites, and later to support the positioning and design of the repository facilities. Airborne and ground level geophysical mapping and soundings, geological mapping, core logging, detailed geophysical logging and surface and borehole reflection studies, hydrological and hydrochemical investigations in 28 deep boreholes, over 7 square kilometers, were used to date for building a comprehensive hydrogeological model of the Olkiluoto site. Geophysical data has provided information on anomalous locations, and valuable orientation and continuity information, as well as petrophysical knowledge of the rock mass. It is believed that the use of the 3D seismic borehole reflection imaging (maily by multi-offset, multi-azimuth VSP) has been crucial for the site modelling.

INTRODUCTION

The Finnish programme for final disposal of high-level nuclear waste has chosen to build a deep repository into the Precambrian crystalline bedrock in Finland. Posiva Oy carries out the research and development tasks. The work focuses in the Eurajoki Olkiluoto site placed on a peninsula in western Finland. The construction of an underground investigation facility, ONKALO, will commence in July 2004. This will facilitate the detailed characterization of the planned repository host rock as well as the development and testing of various tools, techniques and processes to be used for the construction of the repository. The Olkiluoto area has been comprehensively characterized since 1987 by extensive geological and geophysical investigations, [2], [3], [4], [5], [6].

A modelling exercise implies a simplification of the physical reality. This simplification is done by adopting a set of constraints, which seem reasonable in a certain context. The context itself depends on the intended use of the model. For instance, it is recognized now that attempts to use for geology a seismic model intended e.g. for hydraulics are doomed to fail. Therefore, a joint effort is required to integrate different independent survey data at all stages of developing a complex site model.

Detailed site characterization and model compilation [6] has been recently focussed into the central site area, where the access tunnel for underground facilities will be build. For this purpose, a joint modelling exercise was done recently, to combine the trends that were observed from some of the existing geophysical magnetic and EM mapping data, which has been reprocessed and interpreted with map trend analysis, and those observed from the VSP data in the same region. The main drive of this study was that no reliable supporting information on the magnetic and EM trends detected from surface data could be gathered independently from borehole logging, in spite of quite dense drilling. It was suspected that the anomalies interpreted from the magnetic and EM data were mainly caused by vertical or sub-vertical structures. Archive VSP data measured [2] in borehole KR4, placed in the middle of the ONKALO area was reprocessed and jointly interpreted with data from two other adjacent boreholes, KR10 & KR14. Newly developed techniques made possible the 3D interactive joint interpretation of these various VSP data sets, acquired in 1990, 1995, 1997 and 2001, using external trend constraints derived from borehole logging and magnetic and EM data.

GROUND GEOPHYSICAL IMAGING

Ground magnetic and electromagnetic Slingram (HLEM) measurements, surveyed in 1989, were reassessed in 2003. The data has been originally interpreted in a single campaign [1], when the interpretation was focused to a general view of regional and site scale features, being done in a non-systematic manner, using an early fracture zone conceptual model.

With the new re-interpretation, on regional and site scales, linear or near-linear discontinuity indications in the magnetic data were gathered and are shown in *Figure 1*. It has been determined that the same indications can be found also in the Slingram map available in the area. These features control behaviour of magnetized or conductive zones, like alignment or discontinuity of the anomalous zones, being evidences on possible displacements by shearing and faulting. They could be generated by either fracture zones or lithological contacts, and could reflect large scale fold structures or fault displacements.

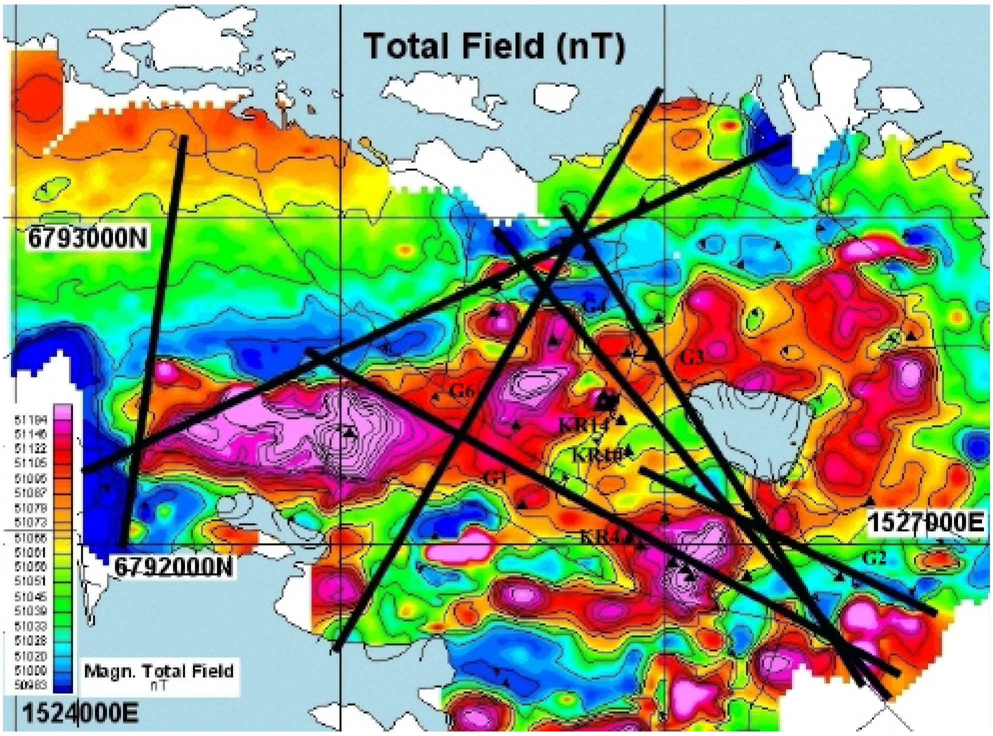


Figure 1. Magnetic map of the Olkiluoto area. Map contains interpretations based on visual assessment of the data (black lines). Definition of their absolute locations would require model calculations. Black triangles show the locations of the drilled holes.

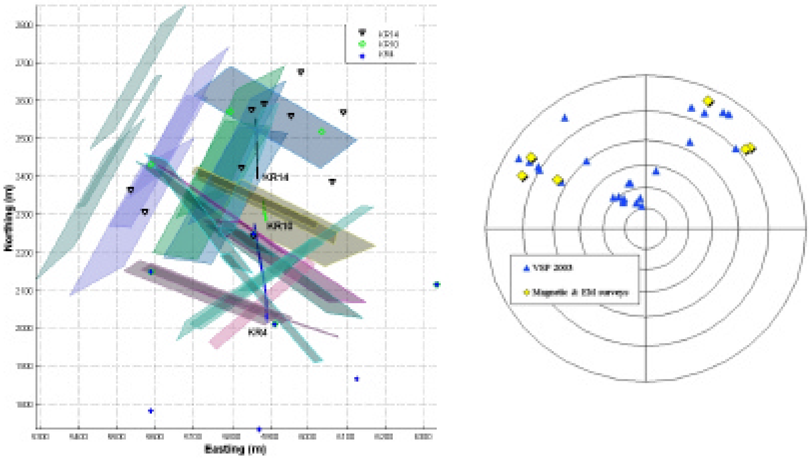
MULTI-OFFSET, MULTI-AZIMUTH VERTICAL SEISMIC PROFILING

The penetration of investigation methods has to be larger than distances between boreholes, which at Olkiluoto ranges from 500 to 1000 m. For an accurate characterization, the resolution has to be better than the typical transverse dimension of relevant site features, i.e. in the order of 1 to 2 m. Seismics is deemed to be the only geophysical method to accommodate both.

With the preferred seismic investigation method used at Olkiluoto, Vertical Seismic Profiling (VSP), the receivers located close to targets, dense drilling not being needed. Over 100 VSPs [5] showed that this method permits the mapping of both steeply and gently dipping features while avoiding near-surface loss of resolution. With multi-offset VSP it is possible to map in the 3D volume covered by the investigation sub-horizontal and inclined features intersecting the boreholes; sub-horizontal features below the bottom of the boreholes and inclined features not intersecting the boreholes but dipping towards the boreholes. Most of the VSPs were performed using 3-component receivers, permitting wave polarization to aid in estimating the azimuth of the reflectors.

Figure 2a displays a top view of the sub-vertical fractures that were derived by combined interpretation of the VSP data recorded over 10 years from 24 source points by receivers placed in boreholes KR4, KR10 and KR14. A good match was found between sub-vertical features interpreted from the magnetic and EM surface data and those interpreted from the VSP data. This may be observed by comparing *Figures 1* and *2a* or inspecting *Figure 2b*.

Figure 2.
(a) VSP Investigation boreholes and shot points, together with interpreted subvertical reflectors
(b) Stereographic projection of reflectors suggested by magnetic and EM surveys (yellow squares) and interpreted from VSP data (blue triangles).



Further consistency was noted by joint analysis of events observed from detailed borehole logging and from 3D VSP imaging. This is exemplified in *Figure 3*, where anomalies in the borehole logs are paired with seismic reflecting surfaces. An important crushed shear zone, which produced strong variation on all logs, was interpreted as a gently dipping reflector, while a potential sub-vertical fault, visible on several VSP profiles, would not be directly observable from the borehole logs.

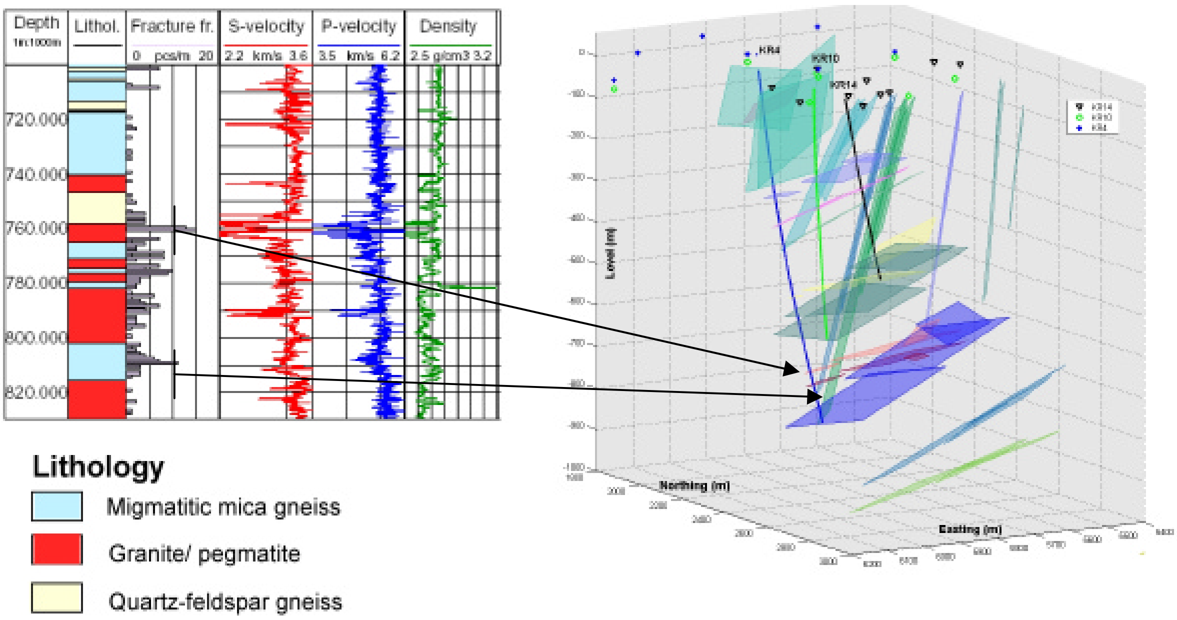


Figure 3. Site scale presentation of the VSP reflectors from boreholes KR4, KR10 and KR14, and an example of lithologies, fracture frequency and sonic and density logs from KR4 depth level 700-780 m (a gently dipping reflector 760 m, a sub-vertical 810 m, and location shown with an arrow).

DETAILED BOREHOLE LOGGING

Further to borehole reflection soundings, characterizing a large volume, there has been performed a comprehensive set of detailed borehole investigations, [4]. The purpose of these has been to describe the host rock, hydrochemical properties, deformation, and the fracture zone properties. Core logging has covered rock types, deformation and orientations. Image logging has provided oriented fracture and foliation data comparable to seismic orientation in detailed scale, *Figure 4*. Hydraulic conductivity has been measured in detail. The geophysical logging data, e.g. sonic and density logs in *Figure 3*, was used to derive properties of the host rock and its alteration and fracturing. A comparison of these with the seismic investigations highlighted the petrophysical and geological connection between features interpreted at different scales to form an integrated network of lithological contacts and fractures.

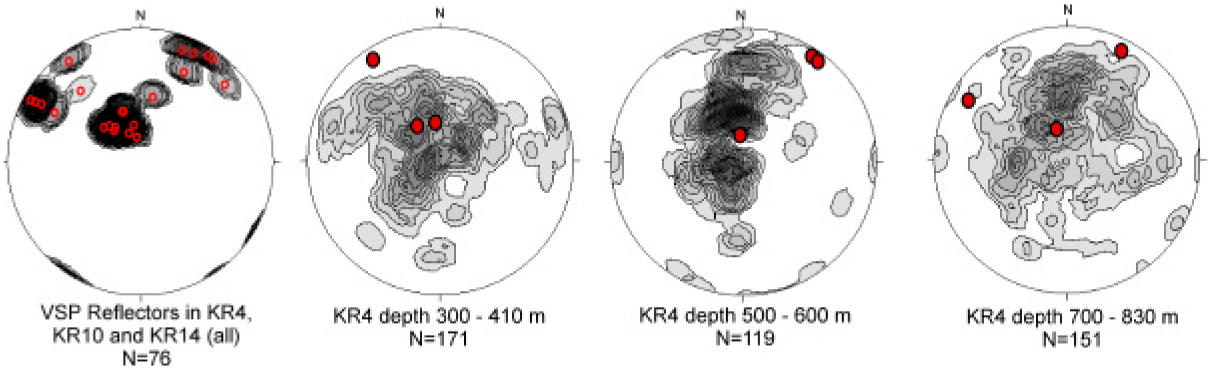


Figure 4. The VSP reflectors of KR4, KR10 and KR14 (all, on the left those found from KR4 are denoted with red dots) and the fracture orientation of KR4 short sections A (300-410 m), B (500-600 m) and C (700-830 m) with reflector orientations from same depth level. Lower hemisphere, area-equal projection.

INTEGRATION

With characterisation of a hard rock site such as the one at Olkiluoto, the importance of integrating independent borehole and surface geophysical data over a range of scales and shading geological understanding on the seismic interpretations became clear at an early stage. A new view and concept were introduced into the site detailed model by re-interpretation of the existing magnetic and EM data. Good correspondence of the features interpreted independently from different data sets generated support and insured needed continuity of the site model at different resolution scales. This has been deemed as an essential gain. Whenever possible, interpretation should focus on proving clear experimental hypotheses, instead of attempting head-on complex reconstructions. A result infirming the experimental hypotheses is equally useful.

CONCLUSIONS

The integrated approach presented here generated confidence in the Olkiluoto site model, being therefore deemed as a successful one. Because of the lack of a common theory, interdisciplinary models are a collection of sub-models linked by logical inference. The whole construction is as valid as these weak links. It is advisable that subjective interpretation be left to the last stage of the modelling exercise, when it provides the basis for the understanding of the model. If subjective interpretation stages are intercalated with hard data processing, biased results may be produced.

REFERENCES

[1] Paananen, M. & Kurimo, M. 1990. Interpretation of geophysical airborne and ground survey data on the Olkiluoto study site, Eurajoki, southwestern Finland. TVO Work Report 90-19, 41 p.

[2] Cosma, C., Heikkinen, P., Honkanen, S. & Keskinen, J. 1996. VSP-survey at Olkiluoto in Eurajoki, borehole OL-KR8 and extended parts of boreholes OL-KR2 and OL-KR4. Work report 96-11e, 86 p.

[3] Heikkinen, E. & Saksa, P. 1998. Integrating geophysical data into bedrock model in site characterization for nuclear waste disposal. EAGE 60th Meeting and Technical Exhibition, Extended Abstract 4-49. Leipzig, Germany, June 8- 12, 1998.

[4] Anttila, P., Ahokas, H., Front, K., Hinkkanen, H., Johansson, E., Paulamäki, S., Riekkola, R., Saari, J., Saksa, P., Snellman, M., Wikström, L. & Öhberg, A. 1999. Final disposal of spent nuclear fuel in Finnish bedrock – Olkiluoto site report. Report POSIVA-99-10, 206 p. ISBN 951-652-065-0.

[5] C. Cosma, P. Heikkinen, J. Keskinen, 2003. "Multi-azimuth VSP for rock characterisation of deep nuclear waste disposal sites in Finland" in SEG publication Hardrock Seismic Exploration, edited by D. W. Eaton, B. Milkereit and M. H. Salisbury, ISBN 0-931830-41-9.

[6] Vaittinen, T., Ahokas, H., Heikkinen, E., Hellä, P., Nummela, J., Saksa, P., Tammisto, E., Paulamäki, S., Front, K. & Kärki, A. 2003. Bedrock model of the Olkiluoto site, version 2003/1. Posiva Working report 2003-43, 266 p.