TWO DECADES OF EVOLUTION OF HARDROCK SEISMIC IMAGING METHODS APPLIED TO NUCLEAR WASTE DISPOSAL IN FINLAND

C. COSMA[1] and N. ENESCU[1]

[1] *Vibrometric Oy, Sitratori 3, FIN-00420 Helsinki, Finland*

ABSTRACT

The Finnish Site Investigation Programme for the Final Disposal of Spent Nuclear Fuel started over two decades ago. The Eurajoki-Olkiluoto was selected for building the planned repository. Based on the large number of surveys performed and the ample direct and indirect verifications, the multi-azimuth multi-offset VSP is considered an effective method for determining the positions and orientations of fracture zones in crystalline rock. This has been continuously developed and used extensively for general to detailed hardrock site characterization in Finland.

BACKGROUND INFORMATION

Seismic techniques have been used for the prospecting of oil and gas for most of the 20th century. Nonetheless, unlike many sedimentary formations, fractured bedrock cannot be described accurately by models with less than three dimensions and the surveying routines and data processing techniques developed for oil exploration find only limited use with deep focused bedrock investigations.

As a natural host for the radioactive waste, the bedrock is meant to prevent the migration of radioactive nuclides from the repository to the biosphere. In crystalline rock essentially all groundwater transport takes place in fractures and fracture zones, hence the need of determining their location and extent and of evaluating their transport capacity. The investigations for high level nuclear waste repositories are generally focused on deep and relatively small volumes of rock, which limits the relevance of the studies conducted from ground surface, especially in areas covered by water and thick overburden. The alternative to surface studies is the use of boreholes. Following analyses and feasibility tests, VSP has been chosen, in Finland, as the main method for deep seismic imaging of the rockmass.

Five sites were initially selected from a shortlist of potential candidate areas in Finland and preliminary investigations were conducted at these sites during 1986 – 1992. Subsequently, three areas were selected for detailed characterization, which concluded in 1999. The Olkiluoto site has been selected in 2000 and further investigations have been performed in the region of the planned repository. The bedrock at the Eurajoki-Olkiluoto site consists of gneisses, tonalite and granite, as shown in *Figure 1*. Borehole OL-KR4, is placed in the center of the investigation area and hosted seismic subsequent seismic investigations through all the stages of the site characterization programme.

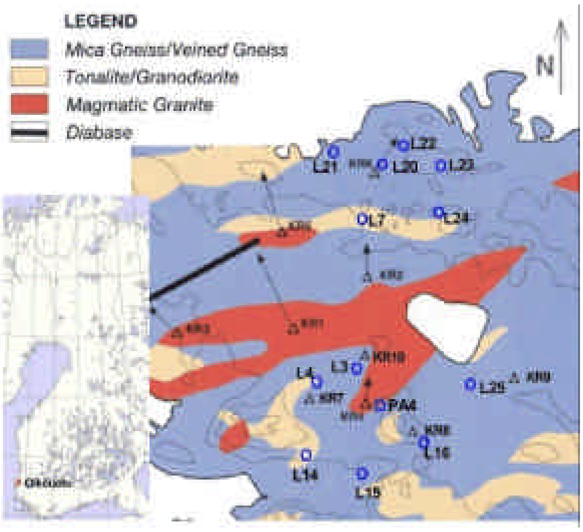


Figure 1. *The Eurajoki-Olkiluoto test site in SW Finland.*

SEISMICS FOR HARDROCK SITE CHARACTERISATION

OL-KR4 was drilled to a depth of 500m as a part of the preliminary site investigations and VSP data were acquired in 1990 by means of 60-90g dynamite charges at five shot points placed at diverse azimuths and distances up to 500 m around the borehole collar. The charges were placed in shot holes 5-15m deep, cased through the overburden and reaching into the bedrock.

With the preliminary investigations, the main targets were rock features that could possibly jeopardize the use of a site for disposal purposes. These features would include major fracture zones and faults, extend through large portions of the site and be essentially planar, which lead to a processing scheme tuned to identify and emphasize planar targets. No limiting condition or preference was set with respect to their possible orientations, as all orientations were deemed possible. Likewise, no particular attention was given at that time to determining their actual spatial extent; as such targets would be extensive, by definition. The result was a 3D geometrical model, presented in *Figure 2*, consisting of planes extending throughout the investigation volume. This constrained geometrical formulation of the problem allowed the information contained in the recorded data to be effectively used for identifying and enhancing the targets complying with the assumptions made, i.e. planar and extensive. Specialist multi-channel filtering methods (e.g. the IP transform) were designed for this purpose [2]. This investigation strategy served well the purpose of ascertaining the non-existence of structural impediments to the potential construction of a deep repository and succeeded in identifying and locating the major structures of the site.

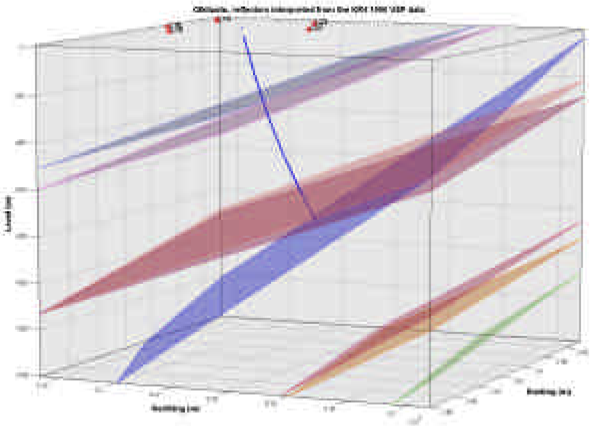


Figure 2. *Simplified geometrical fracture model compiled from OL-KR4 in 1990.*

OL-KR4 was extended to 900m in 1995 and another round of VSP investigations was carried out from seven shot points, the five old ones being used only from 400 to 900m, and the two new all the way from 40 to 900m. The objective of the detailed investigations was to detect also smaller scale hydraulically transmissive zones (normally fracture zones and faults) and to determine their geometry. Such features, whilst conserving local planar attributes, would not necessarily extend throughout the site and it became necessary to determine where in the rock volume seismic reflections actually occurred. A single VSP profile is not sufficient to determine the 3D position and orientation of a reflector associated with an event identified in the said profile. Therefore, seismic events consistent with the same reflector orientation were identified in profiles shot from various shot points to the same borehole. This was done by a procedure somewhat similar to the one used for the 1990 data, except that the planarity of the reflectors was assumed only within limited regions. The elements of surface on which the reflections would actually occur were computed for each reflector orientation deemed probable, as displayed in *Figure 3*. A new orientation set, roughly perpendicular to the previously interpreted one, was identified in the 1995 campaign. It can also be noticed that, as the assumption of throughout planar extensiveness of the seismic features was dropped, the region effectively covered by a single multi-azimuth VSP survey becomes relatively small, more so for features nearly perpendicular to the borehole.

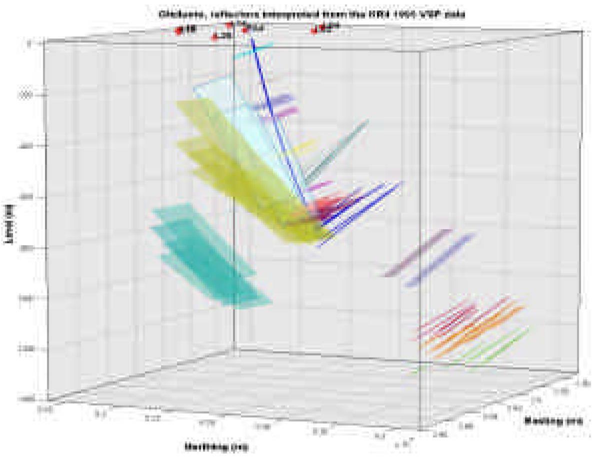


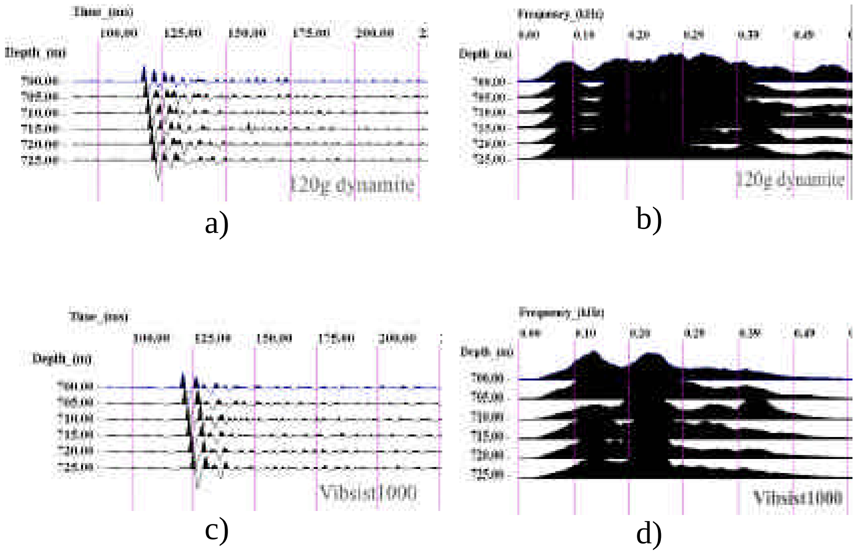
Figure 3. *Detailed structural model compiled from OL-KR4 in 1996.*

TECHNOLOGYCAL DEVELOPMENT

Coverage gaps from one investigated borehole to another had to be bridged to assure the continuity of the seismic interpretations of gently dipping reflectors. The intention was to conserve as much as reasonable the survey and processing routines used with VSP, but use horizontal layouts instead of the nearly vertical ones deployed previously in boreholes. Three lines of sources, each approximately 1 km long, were shot in 2003 with chains of eight 3-component receivers placed in four boreholes at depths of 65-100m and 700-735m. The receivers were kept at the same depths for all shots along each line. The important increase in the number of shot positions, with respect to previous VSP investigations, brought the need of a new source, to replace the explosive charges, as the drilling of a few thousands of shot holes was not deemed practical.

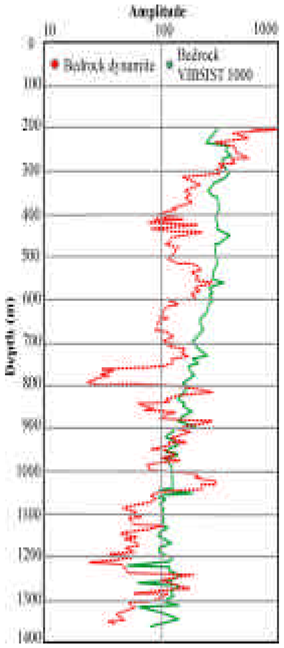
The VIBSIST-1000 is a time-distributed swept impact source [4], which produces seismic signals as coded sequences of impacts delivered by a hydraulic hammer. Seismic records are obtained by correlation. This source is environmentally friendly, requires virtually no shot preparation and a much faster shot cycle can be achieved than explosives. The repeatability and amplitude consistency of the shots is also much better than with explosives. To illustrate this, *Figure 4e* depicts (according to [3]) the amplitude vs. depth dependencies for the VIBSIST-1000 source actuated on an outcrop (green) and 70g dynamite charges exploded in 1 m deep shot holes (red).

The VIBSIST-1000 source uses a tractor/excavator-mounted hydraulic rock-breaker, powered through a computer controlled flow regulator. As the energy is built up from a large number of low-power impacts, the VIBSIST-1000 maintains – compared with other engineered sources – relatively high frequencies while achieving a significant depth penetration. The frequency content of the VIBSIST signals is somewhat lower but comparable with the one of dynamite charges fired in shot holes, if the overburden is hard and thin. *Figures 4a* and *4b* show a group of traces and their spectra recorded in borehole OL-KR4 at 700-725m depth, from a 120 g dynamite charge fired in a borehole reaching 5m into the bedrock and damped with water. *Figures 4c* and *4d* show the corresponding graphs for the VIBSIST-1000 source actuated near the dynamite shot hole on 1m thick overburden. Whilst the frequency band of the VIBSIST-1000 is somewhat lower, the overall appearance of the signals is actually better. On the other hand, in areas with overburden over 10m thick, the frequencies obtained with the VIBSIST1000 fired at surface fell abruptly at about 120 Hz.



a) b) c) d)

Figure 4. *Comparison of explosive and Vibsist1000 seismic sources. Shot gathers recorded in OL-KR4.*



e)

Picked amplitudes from near offset source points, [3].

COHESIVE INTEGRATION OF FEATURES IMAGED BY SEISMICS

As the geometrical conditions were gradually relaxed to permit the inclusion to the model of more local and possibly folded features, the number of eligible targets increased significantly.

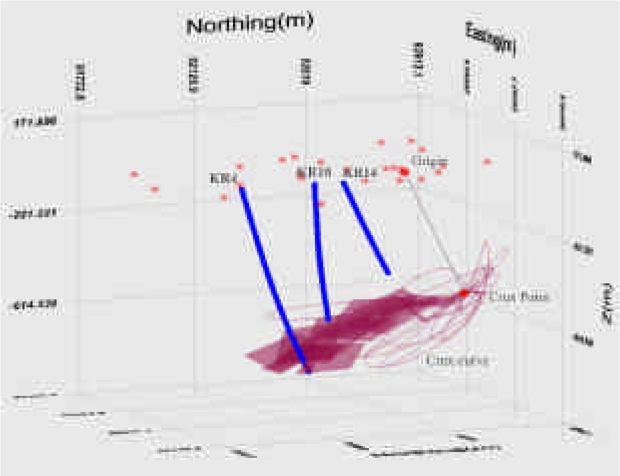


Figure 5. *Crux point diagram for a subhorizontal feature identified from three boreholes in Olkiluoto.*

To facilitate the interpretation and integration of a cohesive site model from several types and vintages of data sets, three classes of objects were created: events, elements and features. An event is an outstanding pattern recognized in a time-depth profile as a potential image of a reflector. By itself, a seismic event does not possess all the geometrical information needed for defining completely the position and orientation of the associated reflector. This is achieved by the simultaneous analysis and fitting of groups of events appearing in several profiles. With the procedure exemplified in *Figure 5*, the 'Crux Point' is defined as the foot of the perpendicular descended on a given plane from an origin common for all profiles, measured in the same borehole, in different boreholes, or on surface. It becomes then possible to investigate whether events observed in different data sets can be images of the same feature. As the orientation of a reflector cannot be completely resolved within a single profile, the crux points would describe loci, represented by closed curves. The most probable orientations are then given by the regions where groups of curves get closest to each other. This formulation makes the problem resolvable by clustering analysis. An associative procedure is used, able to reduce and categorize reflection elements likely to belong to the same site feature. Elements of area where reflections actually occur for each data profile are then computed and a fine fitting procedure is used to resolve local folds or shifts of the site feature thus inferred. The resulting model is exemplified in *Figure 6*.

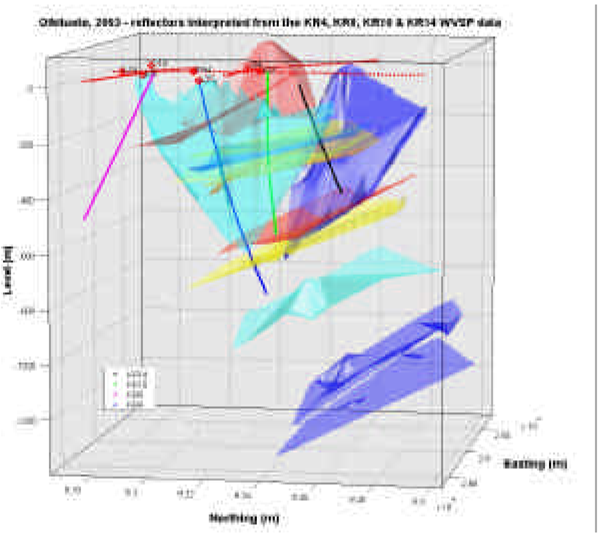


Figure 6. *Cohesive structural site model compiled from both VSP and HSP data acquired in Olkiluoto from 1990 to 2003.*

This extended seismic interpretation would include the majority of the hydraulically significant features, but only a relatively small part of the seismic features were found to bear consequences relevant to the hydraulic properties of the rockmass. The continuity and consistency of features inferred independently from several seismic profiling surveys constitutes an internal verification of the model. The result is a comprehensive model of the fracture zones throughout the site.

REFERENCES

[1] 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.

[2] 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.

[3] Juhlin, C., Bergman, B., Cosma, C. and Enescu, N., 2002. "Vertical seismic profiling and integration with reflection seismic studies at Laxemar, 2000", SKB TR-02-04.

[4] Cosma, C. and Enescu, N. 2001. Characterization of Fractured Rock in the Vicinity of Tunnels by the Swept Impact Seismic Technique. Intl. J. of Rock Mechanics and Mining Sciences, 38, 6,815 – 6,821.