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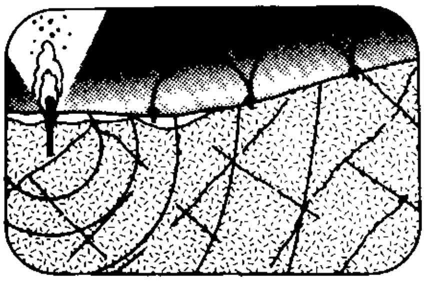
Article abstract

A program of integrated geophysical surveys has been developed within the Department of Energy, Mines and Resources in response to requests from Atomic Energy of Canada Ltd. for assistance in verifying the concept of deep underground storage of radioactive waste and in selecting suitable sites for a disposal vault. Both well established and innovative airborne, ground and borehole techniques are being tested for their usefulness in determining overall structure, lithological variations, rock quality, the character of specific fracture systems and long term stability of selected areas. Preliminary results from the Chalk River Nuclear Laboratories property illustrate the use of electrical, seismic and other methods in analysing complex fracture systems.



The Use of Geophysics in the Canadian Radioactive Waste Disposal Program, with Examples from the Chalk River Research Area

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Summary
A program of integrated geophysical surveys has been developed within the Department of Energy, Mines and Resources in response to requests from Atomic Energy of Canada Ltd. for assistance in verifying the concept of deep underground storage of radioactive waste and in selecting suitable sites for a disposal vault. Both well established and innovative airborne, ground and borehole techniques are being tested for their usefulness in determining overall structure, lithological variations, rock quality, the character of specific fracture systems and long term stability of selected areas. Preliminary results from the Chalk River Nuclear Laboratories property illustrate the use of electrical, seismic and other methods in analysing complex fracture systems.

Introduction
The current emphasis on deep underground vaults for the disposal of radioactive waste in Canada presents a distinctive challenge to geophysicists. Geophysics clearly has a role to play in establishing criteria that must be met by any acceptable disposal site, in developing approaches and techniques for evaluating sites under consideration and in monitoring selected locations during and following waste disposal.

The program that has been developed by the Department of Energy, Mines and Resources in response to requests from AECL is a joint undertaking involving approximately equal effort by the Earth Physics Branch and the Geological Survey of Canada (Scott, 1979). It has grown in parallel with the geological activities within the GSC and with rock property studies which involve CANMET as well as the other two branches. While much of the development work to date has been carried out by government scientists, to an increasing extent both surveys and laboratory measurements have been contracted out to industry and university groups. This trend will undoubtedly continue as the program develops, bringing many more minds to bear on the special requirements of site evaluation.

For the most part the Canadian program has focused on the potential for disposal in crystalline rocks, largely because of the abundance in Ontario of areas underlain by rocks of the Canadian Shield (Aikin *et al.*, 1977). The preliminary specifications for a disposal vault place it on the order of one km underground and give it horizontal dimensions of two to three km. This has been taken as requiring a rock body with uniform composition over approximately twice the depth and lateral dimensions of the vault and lacking major fracture zones or important variations in rock quality. The geophysics tasks thus have been directed at a combination of traditional roles, such as determining the size and shape of selected rock masses, and less familiar applications of seismic, electrical and other surveys to the mapping and characterization of fractures and related structures. Commonly this has required an attention to small scale features generally treated as part of the background of standard geophysical surveys. It has also generated a renewed awareness of the dependence of rock properties on flaws at all scales from microcracks to major fracture systems. Geophysical systems have to be tuned accordingly and efforts made to extend the range, penetration and discrimination of geophysical exploration methods.

In addition there is a need to assist the hydrogeologists in their determinations of the flow of water through fractured rock media. Emphasis is thus being given to geophysical methods of determining water flows and regional aquifer characteristics as well as evaluations of the nature of fractures intersected by drill-holes. A further concern, the long term stability of the southern Canadian Shield, has been addressed by a program to investigate regional seismicity and determine possible risk from earthquakes or other geodynamic effects (Berry and Hasegawa, 1979).

Thus, as their contribution to the evaluation of the concept of deep burial in crystalline rocks, geophysicists have been concerned with both broad regional considerations and methods of studying specific sites. It is some of the work for the latter purpose that we outline here.

The Geophysical Program
In effect, geophysical activities directed at determining the characteristics of specific areas have developed along two parallel lines. One has been concerned with the design of an integrated program to be carried out at areas specified for detailed study; the other with the development of new or refined techniques which may be included in future surveys within the program.

The integrated approach is planned to proceed in several stages. Initially, potential sites are assessed geologically, first by perusal of the literature and aerial photography, then by preliminary ground work at areas under active consideration. Regional aeromagnetic and gravity data would be included in the preliminary assessment, but, as soon as an area has been selected for detailed study, these data would be augmented by reconnaisance airborne geophysical surveys.

Methods selected for this phase include the airborne magnetic gradiometer developed by P. J. Hood and associates at the Geological Survey of Canada, and airborne electromagnetic surveys to be carried out under contract. The contracted work would also include reconnaissance gravity traverses and supply any topographic control required. A selection of ground follow up surveys would then be chosen on the basis of the airborne and geological results. In a typical case the ground work would include further magnetic, electromagnetic and gravity surveys as well as seismic reflection and refraction profiling. This work is all provided for in a comprehensive master contract which has been developed to expedite the use of these standard exploration methods.

The following phase of geophysical work will normally be concentrated on borehole logging and the use of drill holes for geophysical tests. Their aim will be to help assess the hydrological properties of the rock body and give subsurface extension to geologic observations. Again, a combination of standard and innovative procedures is to be applied, with the particular aim of developing hole-to-hole and hole-to-ground techniques to give a comprehensive, three-dimensional picture of the entire body and of significant fracture zones that may cut it.

Inevitably the geological character of each area will dictate the exact combination of methods that can usefully be applied. This is well illustrated by the work carried out to date which has largely been confined to the two AECL properties at Chalk River, Ontario and Whiteshell, near Pinawa, Manitoba. At the latter, extensive conductive clay overburden averaging approximately 20 m thick has inhibited the application of many electrical and electromagnetic methods, while the lack of outcrop prevents sampling of bedrock except at a few drill sites. Consequently activities there have concentrated on borehole studies, with emphasis on hydrogeologic tests and borehole logging techniques. At Chalk River the bedrock geology has proved extremely complex with considerable variation in lithology and degree of fracturing over short distances. Nevertheless sufficient work has been done with a broad spectrum of techniques to justify using the area as a case history study of a strongly fractured rock body. Some preliminary results illustrate the directions being pursued in this work.

Chalk River Area

The research area under study lies within the property of AECL's Chalk River Nuclear Research Establishment, approximately 200 km west of Ottawa along the Ottawa River. The entire region is underlain by complexly folded crystalline rocks of the Grenville Province of the Canadian Shield, covered to a considerable extent by sand and gravel deposits of the Champlain Sea. The hilly terrain is typical of the Upper Ottawa Valley, and has a relief of the order of 100 m. Near Maskinonge Lake, one of a chain marking a former channel of the Ottawa River, the rock exposures are relatively numerous and access by existing bush roads quite satisfactory. Work has thus centred on an area approximately three by two km on the east side of the lake, though some profiles and aerial surveys have been more extensive.

As was appreciated from the inception, the Chalk River area is typical of the Grenville province in its lithologic heterogeneity and structural complexity. Surface sampling and drilling has shown that there are marked changes in lithology on a scale of centimetres to hundreds of metres. The main rock unit is a folded sheet of garnetiferous quartz monzonite which includes granitic, monzonitic and syenitic phases, and is overlain and underlain by paragneisses and discontinuous pods of metagabbro. The rocks are at high amphibolite to granulite regional metamorphic grade. There are numerous cross-cutting faults and fractures as befits the area's situation within the Ottawa Valley fault zone. Several directions of fracturing have been mapped (Brown *et al.*, 1979) and drilling programs, now amounting to nine holes from 150 to 700 m deep, have been designed to provide hydrologic and geophysical tests of the various fracture systems.

Geophysical Results

Most comprehensive of the activities to date have been the airborne and ground electromagnetic (EM) surveys (Dighem, 1979). These have been conducted in both north-south and east-west directions on lines 100 m apart, and have shown interesting direction dependant properties. The magnetic measurements made during the EM survey show that the weakly magnetic character of the country rocks results in an almost featureless magnetic field except for a strong set of east-west trending anomalies (Fig. 1). These are interpreted as due to post-Grenville diabase dikes. Diabase of high magnetic susceptibility has been intersected in drill holes CR-6 and CR-9, which cut across the anomalies, but has not yet been recognized in outcrop.

The airborne EM surveys showed a system of weak anomalies following east-west and north-south trends. Most are interpreted as water-bearing fracture zones, though some under the lakes may be due to conductive lake-bottom sediments. The ability of EM methods to map fracture systems of preferred orientation has been most clearly demonstrated by very low frequency (VLF) land surveys using the transmitters at Cutler, Maine, to the east and Annapolis, Maryland, to the south (Fig. 2). Fractures oriented in the approximate azimuth of the transmitters are preferentially detected, a result attributed to the little-studied phenomenum of current channelling. This results from currents returning in the direction of the transmitter being locally concentrated in zones of relatively high conductivity. To check for the presence of fractures in other orientations and to develop the capability for similar studies in areas where distant transmitters are not favourably located, a local mobile transmitting loop system is being tested. Consideration is also being given to theoretical and experimental studies of current channeling in terms of the quantitative information it may yield about fracture systems. These developments complement other electrical survey methods such as magnetotelluric (Redman and Strangway, 1978; Redman, 1979) and electrical resistivity studies carried out or under consideration at Chalk River.

The use of seismic methods to determine rock properties has also been extensively tested at Chalk River. Overburden thicknesses and bedrock velocities have been obtained by

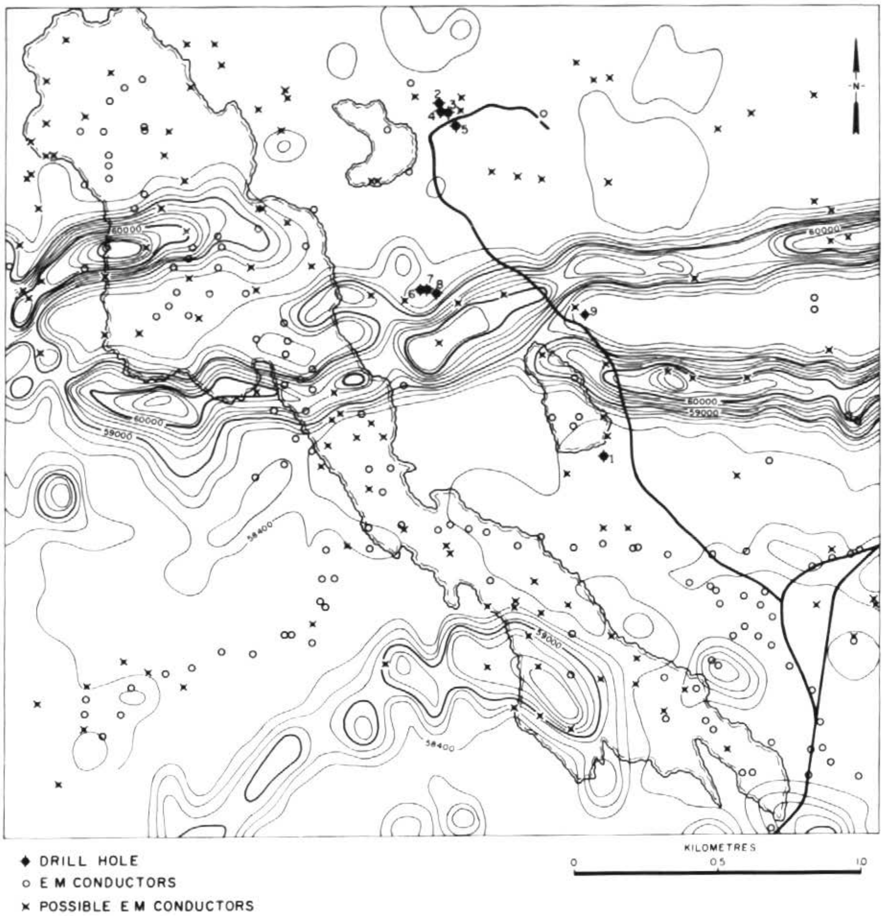

Figure 1

Electromagnetic (EM) conductors and magnetic anomalies in the vicinity of Maskinonge Lake, Chalk River area, as obtained by a helicopter-borne survey by Dighem Ltd. Priniciple roads are shown by a solid line. Total field magnetic anomalies, contoured at 200 nT spacing, have been enhanced by downward continuation to approximately 1/20th of bird height. Drilll holes CR-1 to-9 are numbered. Main magnetic anomalies are attributed to diabase dykes, and EM anomalies to fracture zones.

standard shallow refraction profiling (Gagné, 1979) which has shown that both vary strongly in the vicinity of major fractures. The sandy nature of the drift cover has permitted extensive use of radar as a tool to determine depth to bedrock and bedrock quality (Davis and Annan, 1979), and good agreement between seismic and radar results has been recorded (Fig. 3). In turn these data have been used in the reduction of microgravity profiles measured to investigate the change in residual Bouguer anomalies and the vertical gradient of gravity across fracture zones (Liard, 1979). To test the properties of the Chalk River rocks to greater depths, seismic lateral and reflection profiles were measured at distances of a kilometre or more from drill hole CR-1. Strong lateral variations in P and S wave velocity were found (Lam and Wright, 1979; Wright *et al.*, 1979) but processing the reflection data to enhance the effect of sub-horizontal reflectors produced no evidence of significant changes to depths of several kilometres (Mair and Lam, 1979) (Fig. 4). The lateral variations are thus attributed to the influence of sub-vertical diabase dikes, as defined in the aeromagnetic survey, or to low velocity fracture zones. Additional data are coming from downhole seismic surveys and hole-to-hole surveys are planned. Perhaps the most striking result of the downhole surveys has been the evidence for tube wave generation at open fractures, where compressional waves force water from fracture zones into the borehole (Huang and Hunter, 1979). These results are now being examined to determine what additional information they contain on the characteristics of the fracture zones.

The seismic results are also being compared closely with laboratory measurements on drill cores in which velocity and strain is being measured as a function of pressure (Simmons *et al.*, 1978). These results are being analysed in terms of microcrack porosity and the influence of crack characteristics on other physical properties of the rocks.

Brief mention should be made of two other aspects of the geophysical use of boreholes at Chalk River. Temperature logging has been carried out repeatedly at all available drill holes (Fig. 5) and has proved to be a simple and rapid means of determining the location and rate of water flow in each hole (Judge, 1978, 1979). Plans are underway to extend this technique by measurements at much closer spacing than the conventional 3 to 8 m through the use of a micrologger. The response of the goundwater aquifer to loading by earth tides, major earthquakes and similar transient stresses is being measured by monitoring the level of the water in drill holes at Chalk River. The response to earth tide loading is evident in all records, with some being in phase and others responding as much as several hours later (Bower, 1979). Future work on this method will probably involve close collaboration with hydrogeologists to record the response to earth tides of specific fracture zones.

Conclusions

Many additional measurements are being made at Chalk River and much remains to be done in producing a comprehensive correlation of airborne, ground, borehole and laboratory data. Instrument development of downhole radar is in an advance stage and will be tested in the drill holes clustered around fracture zones. Detailed gamma ray spectral logging is also being tested for the information it can give on fracture fillings and as an adjunct to hydrological tracer tests. Acoustic logging devices such as those pioneered by W. Scott Keys (Keys *et al.*, 1979) and King (King *et al.*, 1974) are

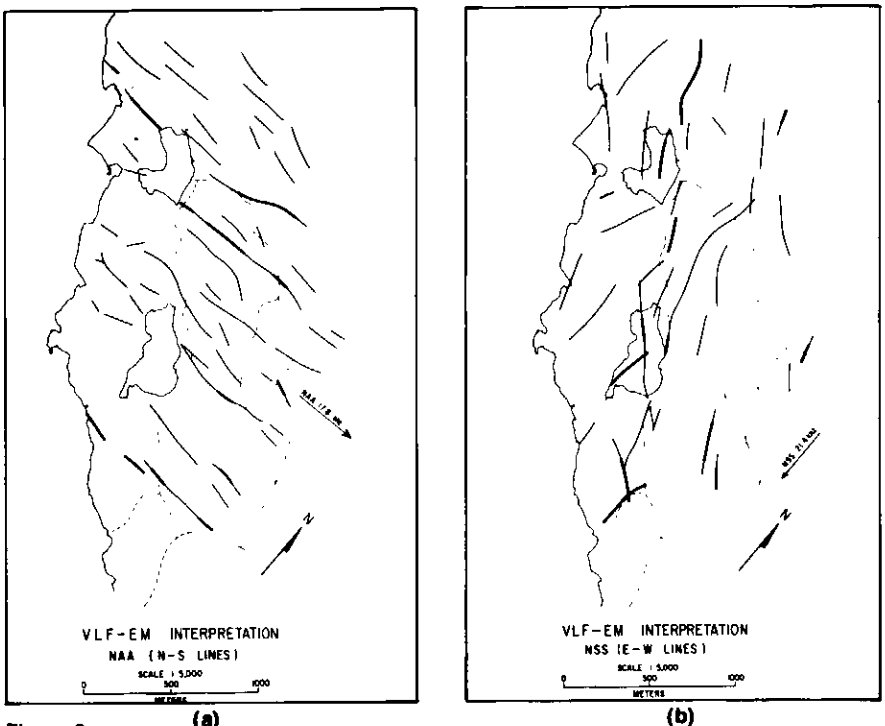

Figure 2
VLF-EM anomalies obtained by ground surveys on the east side of Maskinonge Lake. (a) Traverses on N-S lines used transmission from NAA, 17.8 khz, Cutler, Maine, and (b) E-W lines used NSS, 21.4 khz, Annapolis, Maryland. Weight of lines indicates relative strength of anomalies. Roads are shown by dotted lines.

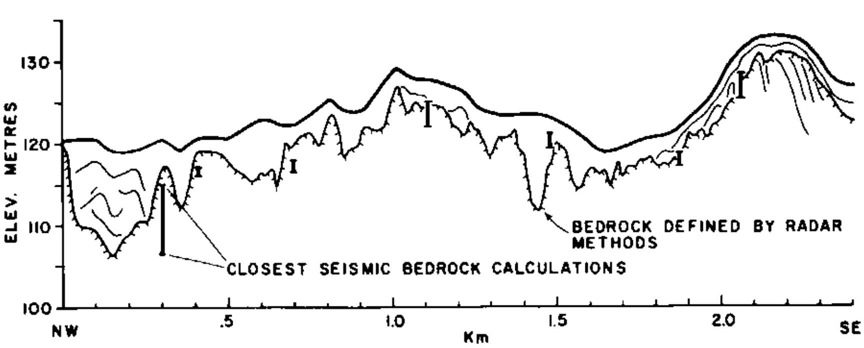

Figure 3
Comparison of depth to bedrock obtained by radar and seismic refraction methods (after Gagné, 1979). The traverse is along the road shown on Figure 1 between Drill holes CR-2 to-5 and the junction to the southeast. Note the complexity of the sandy drift at the NW end of the traverse and indications of fractures in bedrock at the SE end, where there are significant EM anomalies (Fig. 1).

being applied to the program as they become available. Parallel developments are taking place in the theory and experimental study of rock properties in terms of fractures and microcracks and will undoubtedly influence the future course of surveys and the choice of survey methods.

While the geophysics contribution to the waste disposal program is being made at all scales, probably the greatest challenge is, and will continue to be, the need to bridge the gap between the detailed borehole and ground observations of the geologists and hydrogeologists and the rock mass as a whole. Borehole information must needs remain selective and limited in extent. Our endeavour, therefore, will be specifically directed at methods which show promise of increasing our ability to assess rock quality and homogenity and to detect major fracture zones over lateral and vertical distances of hundreds of metres. It will require the applied ingenuity of geophysicists of all specialities and a much broader experience with fractured rock masses to produce an effective response.

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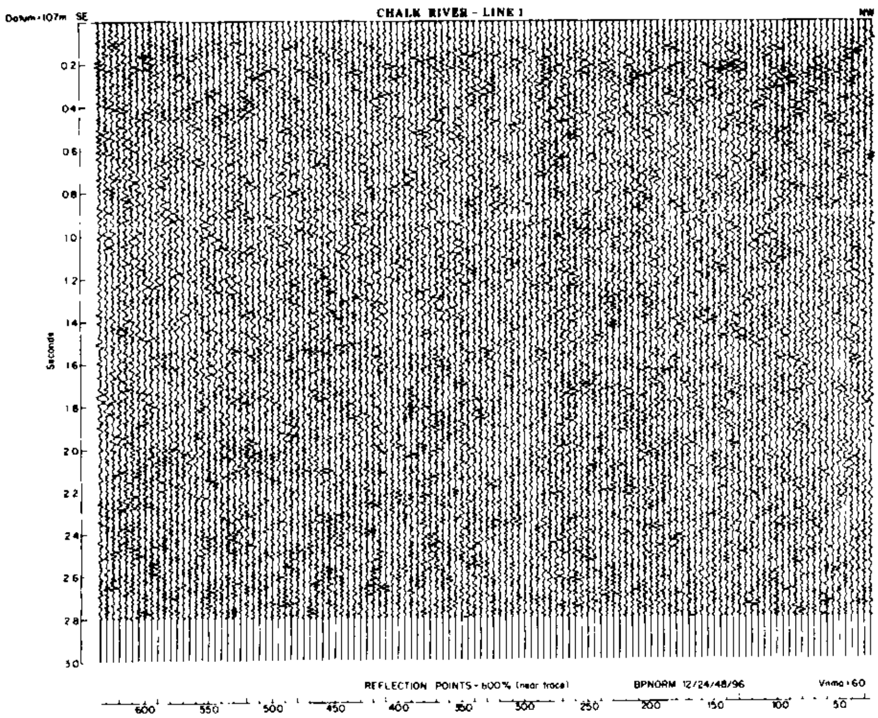

Figure 4
High resolution seismic reflection survey along the same profile as in Figure 3 (after Mair and Lam, 1979). The method uses a thumper source and traces are stacked to bring out common reflection points The lack of distinct reflections in this 600% stack indicates no sub-horizontal discontinuities with dimensions of approximately 120 m or more to depths of as much as 8 km.

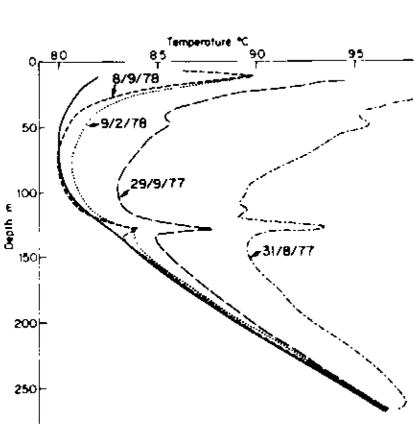

Figure 5
Successive temperature logs of drill hole CR-1 at Chalk River. The first log taken within 24 hours of the cessation of drilling shows a number of strong perturbations which fade with successive logs as the hole approaches the predicted equilibrium profile (solid line). Perturbations are thus attributed to drilling fluid entering open fractures rather than significant water flows from them (after Judge, 1979).

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