Geological Survey of Canada
Commission géologique du Canada

PAPER 88-13

A REVIEW OF GEOPHYSICAL INVESTIGATIONS AT THE SITE OF CHALK RIVER NUCLEAR LABORATORIES, ONTARIO

M.D. Thomas
J.G. Hayles

Canada

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Energy, Mines and Resources Canada
Énergie, Mines et Ressources Canada

Available in Canada through

authorized bookstore agents and other bookstores

or by mail from

Canadian Government Publishing Centre
Supply and Services Canada
Ottawa, Canada K1A 0S9

and from

Geological Survey of Canada offices:

601 Booth Street
Ottawa, Canada K1A 0E8

3303-33rd Street N.W.,
Calgary, Alberta T2L 2A7

100 West Pender Street,
Vancouver, B.C. V6B 1R8

A deposit copy of this publication in also available for
reference in public librairies across Canada

Cat. No. M44-88/13E
ISBN 0-660-12874-8

Canada: $ 5.00
Other countries: $ 6.00

Price subject to change without notice

Critical reader
R.A. Gibb

Original manuscript submitted: 1987-2-16.
Final version approved for publication: 1988-03-02.

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A REVIEW OF GEOPHYSICAL INVESTIGATIONS AT THE SITE OF CHALK RIVER NUCLEAR LABORATORIES, ONTARIO

Abstract

The site of the Chalk River Nuclear Laboratories was one of the first research areas located on crystalline rocks to be extensively investigated under the Canadian Nuclear Fuel Waste Management Program. A large contribution to meeting the geoscientific objectives of the program has been made using a suite of geophysical techniques. Many of them are standard, though sometimes modified in terms of instrumentation and/or experimental and/or analytical procedures, to meet the particular needs of the waste management program. Relatively new techniques have also been employed. Much of the early evaluation and development of the various techniques took place at the Chalk River site.

Standard methods such as gravity, magnetics and seismic sounding have been used to investigate bedrock structure, and the seismic method has also been used to estimate overburden thickness. Standard geophysical borehole logging has been used to obtain in situ estimates of physical properties, to locate fracture zones and to make hole to hole correlations that have helped define local structure. Several standard electrical (e.g. resistivity) and electromagnetic (e.g. VLF-EM) techniques have proven successful in identifying water-filled fractures and faults.

Relatively new techniques introduced into the geophysics program at Chalk River were: ground probing radar, to investigate overburden; borehole TV and acoustic televiewer and VLF-EM, to locate fractures; studies of seismic tube-waves, well tides and temperature logs, to investigate fracture location and permeability. Most of these methods have been very successful and are now routinely employed at other research sites.

Résumé

Le site des Laboratoires nucléaires de Chalk River est un des premiers endroits en sol cristallin où des études approfondies ont été menées aux termes du programme canadien de gestion des déchets radioactifs. L'utilisation de différentes techniques géophysiques a largement contribué à l'atteinte des objectifs géoscientifiques de ce programme. Ces techniques sont en bonne partie d'usage courant, bien que les instruments, le déroulement des essais ou les méthodes analytiques aient été parfois adaptés aux besoins particuliers du programme de gestion des déchets. D'autres techniques plus récentes ont aussi été utilisées. Une grande partie des travaux de premières évaluations et de mise au point de ces techniques ont été effectués au site de Chalk River.

La structure du socle rocheux a été étudiée à l'aide de méthodes courantes telles la gravimétrie, la magnétométrie et la sismique; on a aussi utilisé cette dernière afin d'évaluer l'épaisseur des dépôts meubles. La diagraphie géophysique des trous de forage a servi à évaluer des propriétés physiques in situ, à repérer des zones de fracture et à corréler les données provenant de différents forages, dans le but d'établir la structure locale. Plusieurs méthodes électriques (la résistivité, par exemple) et électromagnétiques (comme la technique VLF-EM) de prospection ont permis de déceler des fractures et failles remplies d'eau.

Des techniques plus nouvelles ont été employées à Chalk River, dans le contexte du programme géophysique, soit: le géoradar, employé dans l'étude des dépôts meubles; la caméra de télévision et la sonde de reconstitution acoustique de fond ainsi que la méthode électromagnétique VLF-EM, qui servent à repérer les fractures; et l'étude des ondes sismiques de tube, des variations du niveau hydrostatique et l'enregistrements de température, qui fournit des renseignements sur l'emplacement et la perméabilité des fractures. Pour la plupart, ces méthodes ont bien réussi et sont maintenant utilisées couramment à d'autres sites d'étude.

SUMMARY

A geophysics program carried out at the Chalk River property of Atomic Energy of Canada Limited has followed three main directions: (1) measurement of rock properties, (2) investigation of overburden thickness and layering, and (3) characterization of bedrock, with particular emphasis on the detection of fractures. The accomplishment of these various tasks has required considerable innovation in techniques and instrumentation in order to help achieve the particular objectives of the Nuclear Fuel Waste Management Program. A significant amount of technical and related skills has thus been acquired through the research at Chalk River. The geophysical programs currently being applied at other research areas are to a large extent built on this foundation.

Information on physical properties has been obtained primarily from laboratory measurements of rock samples. It has been used in the interpretation of data acquired in geophysical surveys and in hydrogeological and engineering studies. In addition, the rock properties program has yielded information indicating that porosity in the Chalk River rock mass is in the form of narrow cracks, that such cracks may be completely closed at depths of 3 km and largely closed at depths of about 1.5 km, and that the diffusion mechanism of transporting fluids may play a significant role in crystalline rocks.

The characterization of superficial deposits has been achieved using seismic refraction surveys and ground probing radar; both methods have provided comparable estimates of depth to bedrock and limited borehole control suggests that the depths are reasonably accurate. Advantages of the radar method are that it also provides information on the water table and internal layering of the overburden. A disadvantage, however, is that the depth of penetration is limited to about 30 m, in spite of the fact that the generally coarse grained overburden at Chalk River is very transparent to radar.

A picture of the gross crustal architecture has been provided by gravity studies. Magnetic studies have also provided structural information in the form of models of diabase dykes, but, apart from these features, correlations of the geology with the magnetic field are not obvious. A variety of seismic techniques has provided qualitative information regarding the probable presence of gabbro at depths below an orthogneiss unit and has indicated the locations of major faults.

Several electromagnetic and electrical techniques have been used to delineate linear conductors. In spite of problematical overburden effects, many conductors can be confidently attributed to bedrock fractures as evidenced by comparison of patterns of VLF-EM conductors and airphoto lineaments. Information on fractures at depth is uncertain because of overburden effects. A rapid means of identifying conductors is by airborne EM and VLF-EM surveys.

SOMMAIRE

Des travaux de recherche ont été effectués au site de Chalk River, appartenant à Énergie Atomique du Canada Limitée, aux termes d'un programme géophysique visant principalement à (1) mesurer les propriétés de la roche; (2) étudier la stratification des dépôts de surface et évaluer l'épaisseur de ces derniers; et (3) caractériser le socle rocheux, en s'intéressant particulièrement à la détection des fractures. L'accomplissement de ces diverses tâches a exigé la création de techniques et d'instruments nouveaux, afin d'atteindre les objectifs particuliers du programme de gestion des déchets radioactifs. Une part considérable de savoir-faire technique et autre a donc été acquise par le biais des recherches effectuées à Chalk River, sur lesquelles sont largement basés les programmes géophysiques en cours à d'autres sites.

Les propriétés physiques de la roche ont été déterminées principalement par l'analyse d'échantillons en laboratoire. Ces renseignements ont servi à l'interprétation de données provenant de levés géophysiques et d'études hydrogéologiques ou techniques. De plus, les travaux portant sur les propriétés de la roche ont indiqué que d'étroites fissures donnent à la masse rocheuse de Chalk River sa porosité, que ces fissures peuvent être complètement fermées à une profondeur de 3 km et fermées dans une grande mesure à une profondeur d'environ 1.5 km, et que le transport des fluides par diffusion pourrait jouer un rôle important dans la roche cristalline.

Les dépôts de surface ont été caractérisés par sismique réfraction et à l'aide du géoradar. Ces méthodes ont produit des évaluations comparables de la profondeur jusqu'au socle rocheux; quelques vérifications effectuées dans les trous de forage corroborent l'exactitude relative des approximations. Le géoradar a pour avantage de fournir également des renseignements sur la nappe phréatique et sur la stratification interne des dépôts de surface. La profondeur d'investigation est malheureusement limitée à 30 m environ, quoique les dépôts de surface de Chalk River, dont les grains sont généralement grossiers, soient très perméables au radar.

Les études gravimétriques ont permis d'obtenir une idée générale de la structure de la croûte. Les études magnétométriques ont également fourni des renseignements sur la structure, c'est-à-dire qu'elles ont servi à l'élaboration de modèles décrivant les dykes de diabase. Sauf pour ce cas, cependant, la géologie et le champ magnétique ne sont pas corrélés de façon évidente. La présence probable de gabbro sous une formation d'orthogneiss a été étudiée de façon qualitative à l'aide de techniques sismiques, qui ont aussi servi à déterminer l'emplacement de failles importantes.

Plusieurs techniques électriques et électromagnétiques ont été utilisées dans le but de délimiter les axes conducteurs. En dépit des problèmes causés par les effets qu'engendrent les dépôts meubles, on a pu établir avec certitude que de nombreux conducteurs correspondent à des fractures dans le socle rocheux, comme en témoigne une comparaison de la forme des conducteurs VLF-EM et des alignements structuraux décelés par photographie aérienne. Il est difficile de se prononcer sur les fractures en profondeur, à cause des effets créés par les dépôts de surface. Les études électromagnétiques aéroportées utilisant les ondes à fréquence normale EM et les ondes VFL-EM servent à reconnaître rapidement les conducteurs. On peut par la suite effectuer

Detailed follow-up studies can then be carried out using ground VLF-EM, resistivity or audio-frequency magnetotelluric surveys.

A number of borehole techniques yield subsurface information on fracture patterns. One method that provides visual information on the locations of both fractures and veins and, significantly, on their dip and strike is the borehole TV camera; the acoustic televiewer provides similar information. Neither method provides information on the extent of the fractures. The borehole VLF-EM method provides indirect, i.e. interpreted, information on fracture locations and also may detect fractures that do not intersect the borehole, but occur within about 10 m of it; fracture orientation is claimed to be estimated within ± 45°. Well tides can also provide indirect evidence for fracture locations and estimates of fracture dip and strike; however, in an open borehole, tidal changes may respond to the effects of several fractures so that the result is an averaging effect. Where a single fracture is packed off, the method has the potential of providing information on the fracture to a distance of a few hundred metres from the borehole. The seismic tube-wave method yields information about fracture location and fracture permeability; tube-wave studies have indicated that some fractures identified as closed by the TV method permit the flow of water. Temperature studies can locate fractures, provide information on the connectivity of a fracture with flow systems, and in some cases, determine the flow direction. Standard logs have proven useful for locating fractures, determining lithological boundaries and for hole to hole correlations up to distances of a few hundred metres. Together, the various borehole techniques provide a good picture of subsurface fracture patterns and related information on fracture permeability and connectivity and directions of groundwater flow.

des études plus détaillées au sol, en faisant appel à la méthode VLF-EM, à la résistivité ou à la méthode magnéto-tellurique.

Un certain nombre de techniques d'exploration des forages fournissent des renseignements sur la répartition géométrique des fractures sous la surface. La caméra de télévision de fond permet de situer visuellement les fractures et les filons et, fait important, d'obtenir des renseignements sur leur pendage et leur direction. La sonde de reconstitution acoustique donne des résultats semblables, mais ni l'une ni l'autre technique ne permet d'établir l'étendue des fractures. On peut aussi situer les fractures à l'aide de la méthode VLF-EM, quoique de façon indirecte (par interprétation des données). Cette méthode peut aussi détecter des fractures qui ne recoupent pas le trou de forage, mais qui sont présentes dans un rayon d'environ 10 m autour de celui-ci, apparemment, l'orientation d'une fracture peut être évaluée à plus ou moins 45°. Les variations du niveau hydrostatique peuvent aussi fournir, de façon indirecte, des renseignements portant sur l'emplacement, le pendage et la direction des fractures; dans le cas d'un trou de forage ouvert, cependant, ces variations peuvent refléter l'effet produit par plusieurs fractures, de sorte qu'on n'observe que l'effet moyen. Cette méthode peut nous renseigner sur une seule fracture colmatée, et ce jusqu'à quelques centaines de mètres du trou. L'étude des ondes sismiques de tube informe les chercheurs au sujet de l'emplacement et de la perméabilité des fractures; ces études ont indiqué que des fractures que la caméra de télévision montrait fermées permettent en fait à l'eau de s'écouler. Par des études de la température, on peut situer les fractures, obtenir des renseignements sur le raccordement d'une fracture au réseau d'écoulement et, dans certains cas, déterminer la direction de l'écoulement. Les diagraphies ordinaires sont utiles lorsqu'il s'agit de situer des fractures, d'établir les limites des unités lithologiques et de comparer des trous de forage distants l'un de l'autre jusqu'à quelques centaines de mètres. Lorsqu'elles sont utilisées ensemble, les différentes techniques d'exploration des forages donnent aux intéressés une bonne idée de la répartition géométrique des fractures sous la surface et fournissent des renseignements complémentaires sur la perméabilité et le raccordement des fractures, de même que sur la direction de l'écoulement des eaux souterraines.

INTRODUCTION

A geoscience program directed primarily to the safe geological disposal of radioactive wastes in crystalline rocks was initiated in 1977 at the site of the Chalk River Nuclear Laboratories of Atomic Energy of Canada Limited. The Department of Energy, Mines and Resources (EMR) and Environment Canada, in conjunction with Atomic Energy of Canada Limited (AECL), were responsible for implementing research in geology-geophysics and hydrogeology, respectively.

The objective of the geophysics activity was to characterize the structural geology with emphasis on determining the distribution and nature of potential pathways of fluid flow, i.e., faults and fractures. Detection of these features using conventional geophysical methods has required an innovative approach to instrumentation, field methods and interpretation. Consequently, much of the research effort in geophysics was devoted to testing and modifying established techniques and developing and experimenting with new instruments and techniques. The Chalk River site thus became a test area for geophysical instrumentation and techniques, and at the same time its geology became progressively better characterized. The Chalk River site will not be used for the storage of high-level waste, however, an assessment of its potential to accommodate low – and intermediate-level waste is in progress. The present information on the Chalk River site will therefore be utilized in this assessment (Heystee and Dixon, 1987).

One opinion on the ideal conditions for storage of radioactive wastes in crystalline rock is that the rock should be isotropic, situated in a seismically stable region, and be free of fluids (Wallach and Poliscuk, 1979), the latter condition presumably being equated with a fracture-free condition. Access of groundwaters to radioactive waste and the possible subsequent movement of radionuclides into the biosphere is, therefore, a major concern in the selection of a site for a disposal vault. For this reason close attention is given to the hydrological characteristics of a site. In terms of the crystalline rocks being investigated in the Canadian Shield this translates essentially into a knowledge of fractures.

Because of the importance of fractures, much of the geophysical effort has been directed towards their detection and characterization, and this has presented new challenges. The geophysical activities can be subdivided into three categories: (1) characterization of overburden, (2) characterization of crustal structure, and (3) detection and characterization of fractures. The scale of investigation ranges from regional to site specific.

Geophysics is but one of the many geoscience disciplines that are used together to characterize potential nuclear fuel waste disposal sites. The results of geophysical investigations are useful to hydrogeologists concerned with groundwater flow patterns in the vicinity of such a site, and to engineers concerned with the integrity, strength and elasticity of the host rock. In this report, which follows earlier progress reports on geophysical studies at Chalk River (Dence and Scott, 1979; Hayles, 1982), the capabilities of the various techniques are described and some of the main results of the studies are presented. More information on the techniques and their methodologies is given in Gibb and Scott (1986). Units of measurement in this report are as quoted by the various researchers. Where the units do not conform to the international system of units (SI), the SI conversion factor is provided following the first occurrence of a unit.

Acknowledgments

The authors thank the following people for various forms of assistance in preparing this report: M.R. Dence and R.A. Gibb (Geological Survey of Canada (GSC)) and N.M. Soonawala (AECL) for critical reviews of the manuscript, S.H. Whitaker (AECL) and M.J. Drury (GSC) for additional comments, R.W.D. Killey and C.F. Huang (AECL) for providing diagrams, A. Rafeek (AECL) for drafting the bulk of the diagrams and S. Davis (GSC) for drafting the remainder and M. Whissell (GSC) for word-processing the manuscript.

GEOLOGICAL SETTING

The Chalk River research area is located in the Grenville Structural Province of the Canadian Shield (Fig. 1), a region that experienced its last major orogeny approximately 1000 Ma ago (Stockwell, 1982). Since then the region has been relatively stable except for two episodes of abortive rifting that superimposed the large fracture systems defining the Ottawa, Nipissing and Timiskaming grabens of the St. Lawrence Rift System (Kumarapeli, 1976); the Chalk River area is located close to the northern margin of the Ottawa graben. The first episode of rifting, marked by tensional faulting and emplacement of east-southeast-trending diabase dykes, occurred 700 to 600 Ma ago and was probably related to opening of a proto-Atlantic Ocean with the Ottawa graben developing as a failed arm of a triple-junction. A second episode of tensional tectonics, again thought to be related to opening of the Atlantic Ocean, took place in the mid-Mesozoic (about 150 to 90 Ma ago) and this phase may be largely responsible for the present form of the rift system, although the movements were probably superimposed on faulting produced during the first episode (Kumarapeli, 1976).

The rocks in this part of the Grenville Province are dominated by gneisses (Lumbers, 1976) metamorphosed to amphibolite and granulite facies (Brown et al., 1979) that have been mapped as two main units designated as paragneiss and monzonitic orthogneiss in the Chalk River research area; a third unit of limited extent is metagabbro (Fig. 1). The prevailing structural trend, reflected in foliations and fold axes, is northwest-southeast. In the research area, the gneisses have been folded about northwest-southeast axes into a series of isoclinal antiforms and synforms overturned towards the southwest. The orthogneiss unit is downfolded into the paragneiss unit with the metagabbro lying close to, or along, the folded contact. A later phase of folding along east-west axes is much gentler.

Brown et al. (1979), on the basis of regional studies of aerial photographs and more localized outcrop mapping, have demonstrated that the pattern of faults and fractures

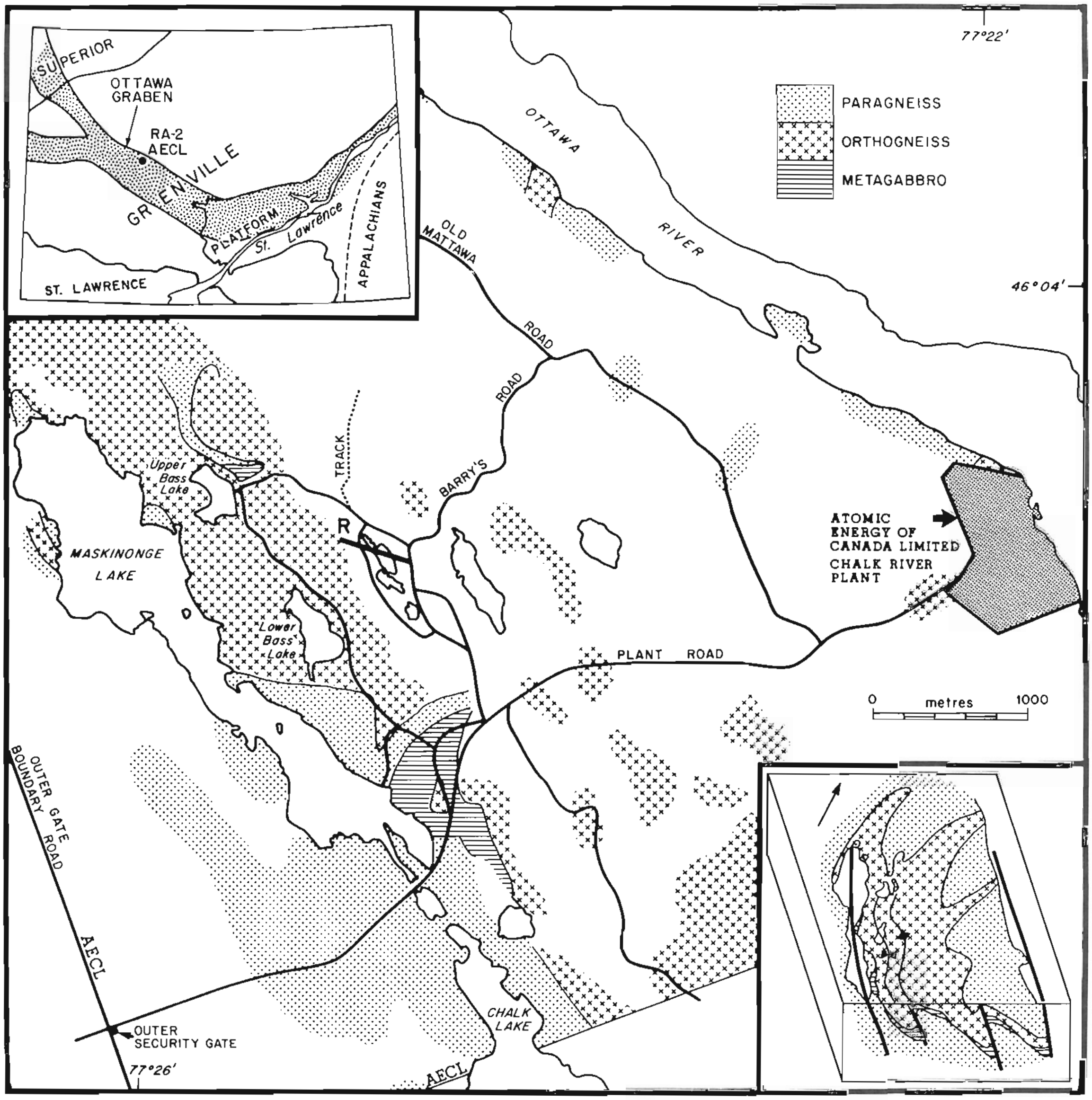

Figure 1. Geological map of AECL Research Area 2 (RA2), Chalk River, based on Lumbers (1976) with modifications after Brown et al. (1979); blank regions denote superficial cover. Inset in upper left-hand corner shows regional geological setting of RA2. Inset in lower right-hand corner illustrates an isometric interpretation of the folded and faulted geological structure between Maskinonge Lake and the Ottawa River (after Brown et al., 1979). Line R marks radar profile illustrated in Figure 8.

in the region is extremely complex, with as many as 13 fracture sets developed. Northwest-trending faults related to the Ottawa graben are numerous. One of the most prominent is the Mattawa River—Ottawa River fault defining the northern margin of the graben. Brown et al. (1979) considered that this may have originated at the time of isoclinal folding. Another major fault zone runs along Maskinonge Lake (Fig. 1, lower right inset).

Much of the region is covered by a veneer of Quaternary superficial deposits that include marine clays and silts deposited in the Champlain Sea during an interglacial phase, glacial till, glaciofluvial gravels, and post-glacial aeolian sands and channel sands (Catto et al., 1987).

REGIONAL SEISMICITY

A map of historical (since 1850) seismic events within areas of Quebec and Ontario lying adjacent to the Ottawa River (after Forsyth, 1981) is shown in Figure 2. Forsyth (1981) noted that most epicentres were located within the Grenville Province, many of them clustering in the Central Metasedimentary Belt to the north of the Ottawa River; in contrast, the portion of the belt lying south of the river was apparently aseismic. In spite of the greater occurrence of earthquakes in terrane of Grenvillian age, Forsyth (1981) observed that the two largest earthquakes were associated with the younger grabens. The influence of the St. Lawrence Rift System on the siting of earthquakes may be

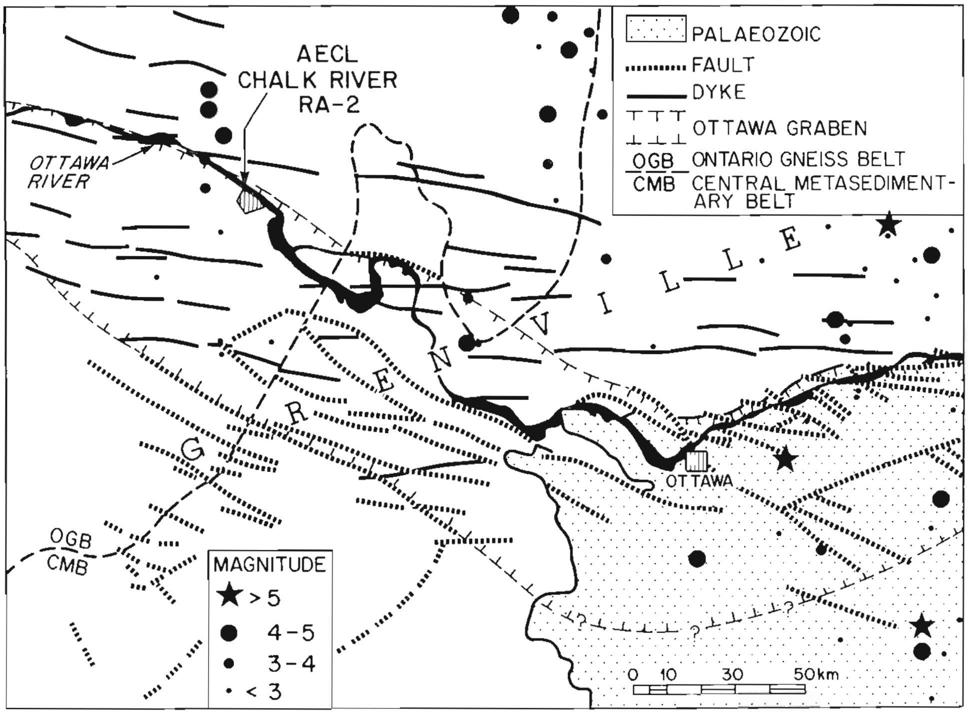

Figure 2. Seismicity within and adjacent to the Ottawa graben in the region between Chalk River and Ottawa (modified from Forsyth, 1981). Earthquake locations are indicated by star and dot symbols; earthquake magnitudes are indicated in the lower inset.

significant because, as Forsyth has indicated, one area of earthquake concentration lies near the junction of rift structures associated with the Ottawa Valley, St. Lawrence River and Lake Champlain.

A small group of earthquake epicentres occurs just northwest of Chalk River. All epicentres are positioned within 40 km of the research area, close to the northern border of the Ottawa graben; most of them occur just outside the structure. The largest earthquakes had magnitudes of 4.1 and 4.2; they have not been correlated with any specific geological feature. The possibility of the research area being affected by an earthquake must, therefore, be regarded as significant. Basham et al. (1985) have recently subdivided Canada into a number of seismic source zones for earthquake risk calculation, and have calculated a cumulative recurrence relation for each, based on estimated rates of past earthquakes. The Chalk River region lies within the Western Quebec Zone for which the upper bound magnitude is 7; the recurrence relation predicts that a magnitude 5 earthquake will occur approximately once every 10 years within this zone. Probabilistic seismic ground motion maps prepared by Basham et al. (1985) show that the Chalk River research site has a 10 % chance of being subjected to peak horizontal accelerations in the range of 16 to 23 % g (g = gravitational acceleration) every 50 years. A region characterized by such accelerations is regarded, to a certain degree, as high risk.

PHYSICAL PROPERTIES OF ROCKS BASED ON LABORATORY MEASUREMENTS

Physical properties of rocks from Chalk River have been measured with three main objectives: (1) to provide constraints in the modelling and interpretation of geophysical survey data, (2) to obtain fundamental information on the mechanical properties of the rocks, principally for engineering purposes, and (3) to obtain information on the volume, interconnectivity and configuration of cracks and fractures for use in hydrogeological studies. A list of properties measured or derived for rocks from Chalk River is given in Figure 3.

Physical properties for geophysical surveys

Rock density has been measured on a routine basis in gravity studies of the area (Liard, 1980; Thomas and Tomsons, 1987). It is the fundamental parameter controlling gravity anomalies and is an essential input into gravity modelling. Rock densities have been determined for surface samples and drill core from boreholes CR1 through CR9 sampled at an average interval of roughly 3 m (Thomas and Tomsons, 1987). Rock densities have been obtained also in conjunction with thermal studies in boreholes; measurements have been made on samples selected at intervals of approximately 5 m in CR1 and CR9, and at much greater intervals in CR6, 7 and 8 (Drury, 1981). Density is required for the computation of many mechanical properties.

Magnetic susceptibility is a fundamental parameter used in the interpretation of magnetic data and, to a lesser extent, is important in electromagnetic interpretation. Coles et al. (1987) summarized the results of 3708 measurements made on drill core from holes CR1 through CR9; core samples were selected in groups of three, spaced 0.1 m apart, located at intervals of about 2 m along the core. Most susceptibilities from the "granitic" gneisses are very low, of the order of 5×10^{-4} S.I.; in fact, the average susceptibility for these rocks is near the limit of resolution (10^{-5} S.I.) of the measuring instrument. Coles

		GEOPHYSICAL STUDIES						
APPLICATION	ROCK PROPERTY	GRAVITY	MAGNETIC	EM and ELECTRICAL	GEOTHERMAL	SEISMIC	WELL TIDES	ENGINEERING
GEOPHYSICAL STUDIES	DENSITY	●						●
	MAGNETIC SUSCEPTIBILITY		●	●				
	ELECTRICAL RESISTIVITY			●				
	DIELECTRIC CONSTANT			●				
	THERMAL CONDUCTIVITY				●			●
	THERMAL DIFFUSIVITY							●
ENGINEERING	COMPRESSIONAL WAVE VEL.					●		
	SHEAR WAVE VELOCITY					●		
	COMPRESSIVE STRENGTH							
	YOUNG'S MODULUS						●	
	BULK MODULUS							
	SHEAR MODULUS							
	POISSON'S RATIO						●	
	VOLUMETRIC STRAIN							
	THERMAL EXPANSION							
PATHWAYS ANALYSIS	POROSITY							
	PORE SIZE DISTRIBUTION							
	POROSITY SURFACE AREA							
	PERMEABILITY							
	TORTUOSITY							

Figure 3. Some rock properties measured for geophysical, engineering and pathways analysis (hydrogeological) studies. Some specific uses of the properties, not necessarily limited to the application in which they are grouped, are indicated by the dots in the relevant columns.

et al. (1987) correlated zones of increased susceptibility in some otherwise low susceptibility borehole profiles to borehole fluid temperature anomalies reported by Judge (1979) and interpreted as indications of permeable fractures or of possible water movement. They suggested that the increase may be related to the production of small amounts of secondary magnetic minerals by alteration of ferromagnesian silicates in the gneisses, or by deposition from fluid circulating in the fractures.

The susceptibility signatures of mafic rocks in CR6 and CR9 are consistent with the identification of two different rock types: a relatively unmetamorphosed diabase dyke and a metagabbro, which have susceptibilities of the order of 5×10^{-2} and 5×10^{-3} S.I., respectively. The susceptibility data also suggest layering in the metagabbro unit.

Electrical resistivity and dielectric constant are two important parameters that aid the interpretation of electrical and electromagnetic data. Electrical resistivity, in particular, has been measured for samples from a number of holes: CR6 (Chernis et al., 1979a), CR1 (Katsube, 1978) and CR7 (Katsube et al., 1978). Dielectric constant has also been measured for CR1 samples (Katsube, 1978). Related parameters are complex resistivity, which is a function of the chemical and physical properties of pores and fractures, and formation factor, which is a function mainly of pore configuration (Chernis et al., 1979b). These parameters provide information on permeability, porosity, pore structure and chemical parameters (Chernis et al., 1979b).

Thermal conductivity has been reported for several boreholes (Drury, 1981). It is used in the modelling of geothermal data and also for thermal modelling of the rock mass in connection with vault design, and in studies of thermal expansion (e.g., Bell and Lemieux, 1980). Thermal diffusivity has also been measured for Chalk River samples (M.J. Drury, pers. comm., 1984).

Mechanical properties

Stress analysis is an important facet of engineering investigations related to the design of waste disposal vaults and requires a knowledge of mechanical properties and models for rock deformation and failure (Annor et al., 1979). Annor et al. (1979) proposed that two models of deformation and failure are needed for each lithological unit: one for the matrix and one for the joint systems. Because the models must apply over ranges of temperatures and pressures that might be encountered by an underground vault, experimental measurements are conducted under pressures ranging from 0 to 35 MPa and temperatures ranging from 20 to 200°C. Annor et al. (1979) reported values of dilatational velocity (km/s), compressive strength (MPa), Young's modulus (MPa), dynamic Young's modulus (MPa) and Poisson's ratio.

Stesky (1980) measured compressional (Vp) and shear (Vs) wave velocities on dry rock cylinders at various confining pressures of up to 200 MPa. Using the velocity data and measured densities, Stesky was able to obtain estimates of the following elastic properties useful for engineering evaluations: adiabatic bulk modulus, shear modulus, adiabatic Young's modulus and Poisson's ratio. Measurements of volumetric strain (not entirely satisfactory because of equipment problems) were used to estimate isothermal bulk modulus.

The seismic velocity experiments gave the following results. All the rock samples exhibited an increase in velocity with increase in confining pressure, a relationship attributed to closure of cracks and pores. It was noted that at lower pressures the low-aspect-ratio (long and narrow) voids closed first, causing a marked increase in velocity, whereas at higher pressures, where more equant voids closed, the increase was more gradual. Velocities, and hence elastic moduli, determined at 200 MPa were close to the intrinsic values, and most of the porosity was closed by the application of 200 MPa pressure: these results suggested that most of the porosity was in the form of narrow cracks.

On the basis of (1) theoretical models that relate effective compressibility or its reciprocal, effective bulk modulus, to the number of cracks per unit volume and the average length of the cracks and (2) his estimates of elastic properties and measurements of strain, Stesky (1980)

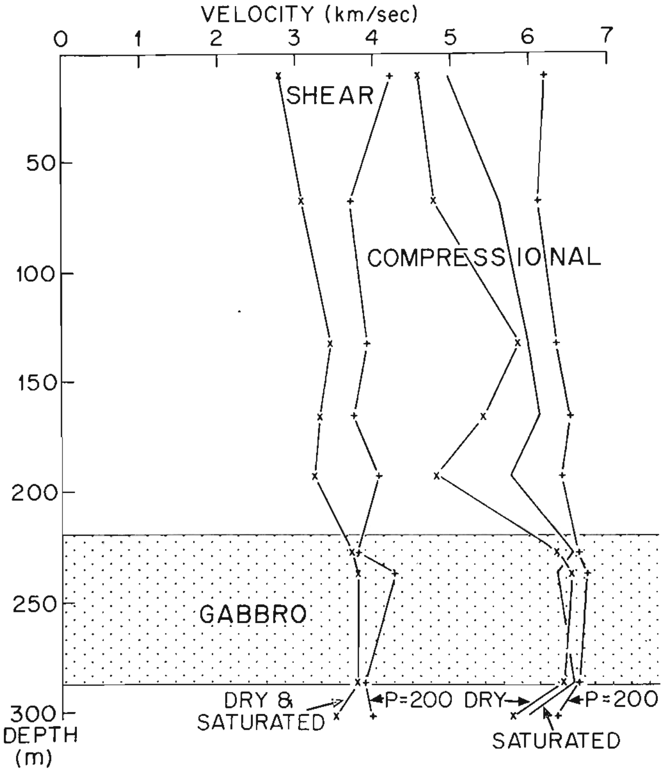

Figure 4. Plots of seismic wave velocities versus depth for core samples from CR6 and CR7. The plots labelled P = 200 are based on measurements made on dry rock cylinders subjected to a confining pressure of 200 MPa. Plots labelled DRY and DRY & SATURATED are derived by measuring the velocity of the dry core samples at the lithostatic pressure corresponding to the sample depth. The plot labelled SATURATED has been calculated from equations (after Stesky, 1980). Crustal section labelled GABBRO is now identified as diabase (Dugal and Kamineni, 1987).

calculated a crack density parameter assuming a model of penny-shaped cracks. For this model, ε (crack density parameter) equals $N\overline{c^3}$ where N = number of cracks/unit volume and $\overline{c^3}$ = average of the cube of the crack length, c. Three examples from CR6 yielded mean values for ε (based on determinations using two different theoretical models) ranging from 0.11 to 0.52. A further parameter, mean crack aspect ratio (width/length) of the cracks, was estimated on the basis of ε and measured values of the porosity of the rock: for the CR6 samples this ratio ranges from 2.9×10^{-4} to 8.7×10^{-4}.

A seismic velocity model for the rock mass to a depth of about 300 m, near CR6 and CR7, was derived using seismic velocities measured on dry core samples at the lithostatic pressure corresponding to the depth of each sample. A general trend of increasing velocity with increasing depth was obtained for both compressional and shear waves (Fig. 4). High velocities in the depth range of 220 to 280 m were obtained on gabbro (later identified as a diabase (Dugal and Kamineni, 1987)), which has the lowest values of ε calculated for any of the cores examined by Stesky (1980), including examples from Whiteshell, Manitoba. Stesky noted that fractures in dry rocks could lower seismic velocity, but, if water was introduced into a rock, the effects of cracks on compressional wave velocity was almost completely suppressed, whereas shear wave velocity was relatively unaffected. The compressional wave velocity of wet rocks may be calculated from equations, such as those derived by O'Connell and Budiansky (1974, 1977). A plot of saturated compressional velocities, calculated on this basis, versus depth for samples in CR6 and CR7 is shown in Figure 4. The velocities are generally intermediate between the corresponding dry velocities and those calculated at 200 MPa, assumed to be close to the intrinsic values. According to Stesky (1980), the results for Chalk River indicate that the in situ compressional velocity should increase from about 5 km/s at the surface to about 6 km/s at a depth of 300 m; fluid-filled fractures may reduce these values. Other laboratory measurements of compressional and shear wave velocities have been reported by Chernis et al. (1979a), Katsube (1978), Katsube et al. (1978), and Simmons et al. (1978).

The property of thermal expansion has been reported by Bell and Lemieux (1980). This property has been measured dynamically between room temperature and 500°C in a vertical tube-type dilatometer. Thermal expansions of Chalk River rocks range from 0.45 to 0.8 %.

Rock properties relating to hydrogeology

Of prime importance to hydrogeological studies is a knowledge of the reservoir characteristics of a rock. These include such parameters as permeability, pore (and/or crack) size and shape, interconnectivity of pores, pore size distribution, porosity surface area and other related parameters, e.g., formation factor and tortuosity.

Chomyn (1980) reported porosities for CR9 core samples ranging from 0.1 to 0.5 %. Katsube (1978) measured porosities for CR1 samples ranging from 0.0 to 2.7 %, with the vast majority being less than 1 %: he noted a close positive correlation between porosity and chlorite content. For CR6, 7, 8 and 9, Drury (1981) obtained values of porosity ranging from 0.1 to 2.6 %, with one exceptional value of 8.8 %; however, the vast majority are less than 0.5 %. Chernis et al. (1979c), using mercury porosimetry, were able to obtain estimates of porosity, porosity surface area and pore size distribution for samples from CR6 and 7. Porosities were consistently 0.2 % or less, with the exception of one sample that attained 3 %.

Determinations of permeability to water for core samples from CR6 and 7 have been documented by Cooley and Butters (1979). When CR6 samples were measured under ambient conditions (200 psi confining stress and 100 psi pore pressure (1 psi = 6.89×10^{-3} MPa)), the range of permeabilities for nonfractured samples was reported as <0.01 to 0.12 μdarcies (1 μdarcy = 9.87×10^{-19} m^2), whereas for the same circumstances CR7 samples have a range of <0.03 to 0.18 μdarcies. When the same sets of samples were measured under confining stresses and pore fluid pressures more representative of in situ conditions (confining stress set at 1 psi for each foot of burial; pore fluid pressure at half that value) permeabilities

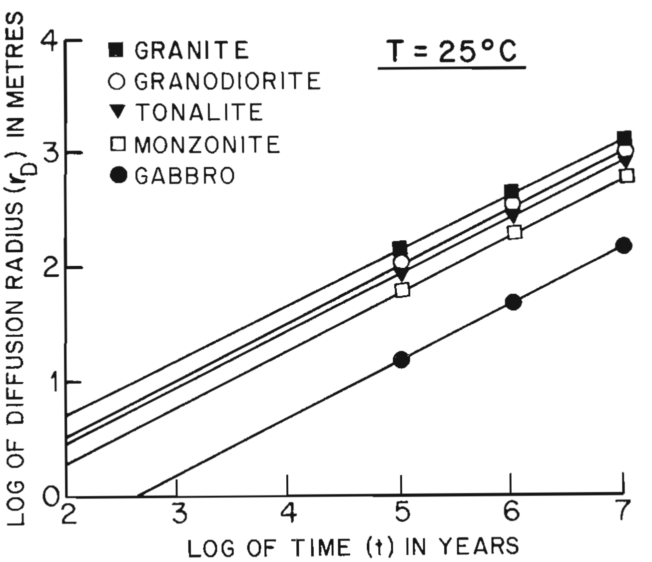

Figure 5. Plots of log of distance travelled (diffusion radius) by sodium iodide ions in various rock types versus log of time (after Katsube, 1979).

ranged from <0.01 to 0.16 μdarcies (CR6, maximum confining pressure 990 psi) and from <0.01 to 0.81 μdarcies (CR7, maximum confining pressure 435 psi), respectively. Cooley and Butters (1979) reported further that (1) increased effective stress decreases permeability (effective stress = confining stress minus pore pressure) and (2) temperatures above 75°C will significantly increase permeability because of thermally-induced microcracking.

Porosity-related studies based on the measurement of mechanical properties of rocks have been undertaken by Stesky (1980) and Simmons et al. (1978); Stesky's results were described in an earlier section. Simmons et al. (1978) used a technique known as differential strain analysis to obtain information on microcracks in Chalk River rocks. They concluded that most cracks are closed when the pressure attains 1000 bars (1 bar = 0.1 MPa), thus indicating that microcracks should be closed at depths greater than 3 km and that many will be closed at depths of about 1.5 km. Other methods of analyzing microcrack structure based on compressional wave velocities in dry, saturated and crack-free samples were also discussed.

Katsube (1979) investigated theoretical aspects of the movement of fluids within the pores and cracks of rocks and the consequences for the transport of radionuclides: rock samples from Chalk River were included in his studies. He concluded that flow mechanisms along fractures were of prime importance, but noted that the diffusion mechanism was also significant. For example, the distance travelled in 100 000 years by diffusion ranges from 50 to 500 m (Fig. 5) depending on the rock type. Katsube (1979) concluded that there were several "fundamental parameters" that controlled the transportation and migration of ions: these are listed in Table 1.

Table 1 Fundamental parameters controlling transportation and migration of ions (after Katsube, 1979)

Fracture aperture
Accumulated aperture
Tortuosity
Connecting pore porosity
Storage pore porosity
Fracture length
Open fraction coefficient
Diffusion sorption coefficient
Flow sorption coefficient

GEOPHYSICAL INVESTIGATIONS OF SUPERFICIAL DEPOSITS

Geophysical investigations of Quaternary deposits, which are widespread in the area, have had three main objectives: (1) estimating depth to bedrock, (2) defining the water table, and (3) detecting internal layering. The first objective has been approached using seismic refraction surveys (Gagné, 1980) and all three have been investigated using impulse radar profiling (Annan and Davis, 1978; Davis and Annan, 1979).

Seismic refraction surveys

The results of seismic refraction surveys carried out in 1977 and 1978 have been reported by Rosnuk and Gagné, respectively (Gagné, 1980). Together the grid of seismic profiles formed by the two surveys provides reasonably detailed sampling of the central part of the research area (Fig. 6). The undulating relief of the region posed problems for field operations and for interpretation. A large range in the velocity of overburden material (150 to 3050 m/s), coupled with the rapidly changing nature of the overburden in places, was a problem in calculating depth to bedrock. In spite of this, and other problems, the calculated depths to bedrock are supported by estimates obtained by radar sounding (Fig. 7). Over most of the central area, the overburden is relatively thin (0 to 8 m), but considerable thicknesses (8 to over 30 m) exist in an irregular belt east of Upper Bass Lake (Fig. 6).

Impulse radar profiling

Radar profiling at Chalk River has been conducted along many of the roadways in the area, on the frozen surface of Perch Lake (Annan and Davis, 1978) and over a sand aquifer in a detailed study supported by control provided by 25 boreholes (Killey and Annan, 1987). Annan and Davis (1978) concluded that the Chalk River area, where the Quaternary deposits are primarily coarse grained and very transparent to radar signals, was well suited to sounding by radar. Depth to bedrock has been estimated along continuous profiles to depths exceeding 20 m (Annan and Davis, 1978), and depths up to 30 m are reported by Killey and Annan (1987). Seismic refraction studies (Gagné,

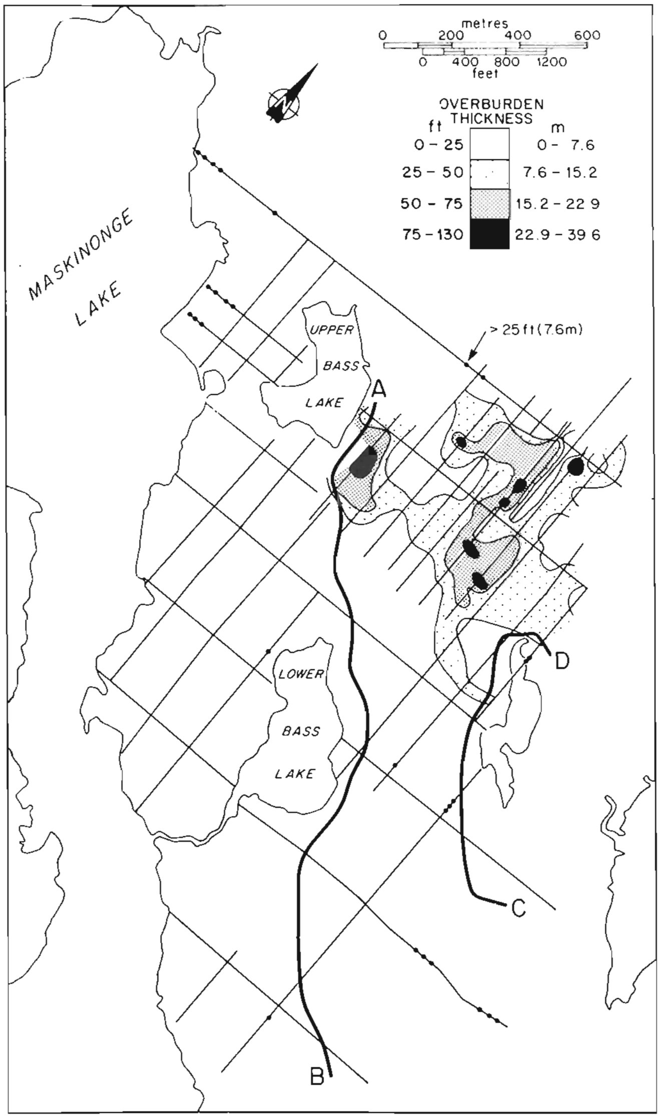

Figure 6. Generalized contours of overburden thickness estimated from seismic refraction profiles; for details see Gagné (1980). Road sections A-B and C-D are the paths of radar traverses shown in Figure 7.

1980) provide independant estimates of depth to bedrock along some of these profiles. There is generally good agreement between depths estimated from radar and depths based on seismic refraction (Fig. 7). There is also good agreement between depth to bedrock as determined by radar and the actual depth to bedrock as measured in boreholes in the sand aquifer study area (Fig. 8) (Killey and Annan, 1987). The method has also been successful in defining the water table and boundaries between various overburden layers. In the sand aquifer, several reflectors identified in the radar record matched with stratigraphic contacts identified in the borehole logs (Fig. 8) (Killey and Annan, 1987). A contact between gyttja and gravel has been mapped under Perch Lake (Annan and Davis, 1978).

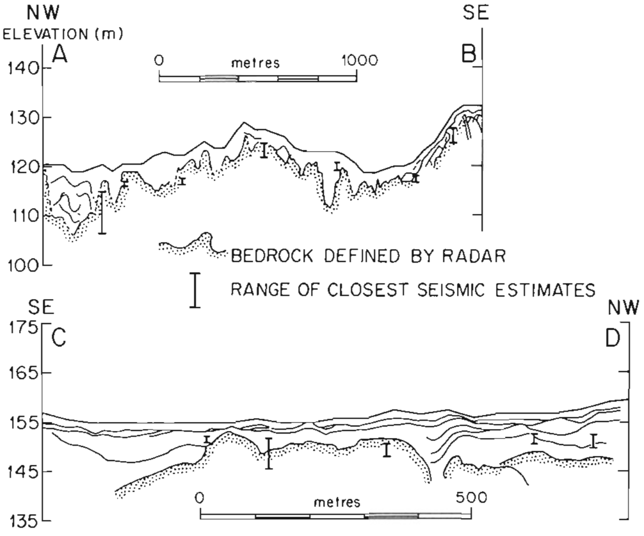

Figure 7. Near-surface geological sections A-B and C-D (see Fig. 6 for locations) illustrating depth to bedrock determined by ground probing radar surveys. Depth to bedrock estimated from seismic refraction profiles that intersect the radar traverses are shown for comparison. A range of seismic depths is shown for each intersection based on the closest (spatially) points along the seismic profile where depth estimates were made (after Gagné, 1980).

AIRBORNE AND GROUND GEOPHYSICAL INVESTIGATIONS OF BEDROCK

Gravity studies

Early measurements of gravity and vertical gravity gradient at Chalk River have been described by Liard (1980). More recently, a Bouguer gravity anomaly map has been compiled by Thomas and Tomsons (1985): a detailed interpretation of the anomalies is presented by Thomas and Tomsons (1987). An integral part of the gravity studies was the measurement of almost 1100 rock densities using samples obtained from outcrops and core from boreholes CR1 through CR9. The most prominent feature of the Bouguer gravity field is a roughly oval-shaped positive anomaly (Fig. 9) that coincides largely with a unit of monzonitic orthogneiss, believed to be in folded contact with adjacent and probably subjacent paragneiss (Brown et al., 1979): the anomaly has an amplitude of about 2 mGal. The density of orthogneiss is estimated to be 0.04 g/cm^3 larger than that of the paragneiss and this, coupled with the fact that a section of the orthogneiss-paragneiss contact coincides with a belt of steep gradients defining the southwestern flank of the anomaly, suggested that the anomaly was related to a body of relatively dense, downfolded orthogneiss. Other flanks of the anomaly, however, occur entirely within the orthogneiss. This observation and difficulties encountered in matching observed gradients in modelling the anomaly in terms of a single orthogneiss source indicated that the anomaly was not a product of orthogneiss alone.

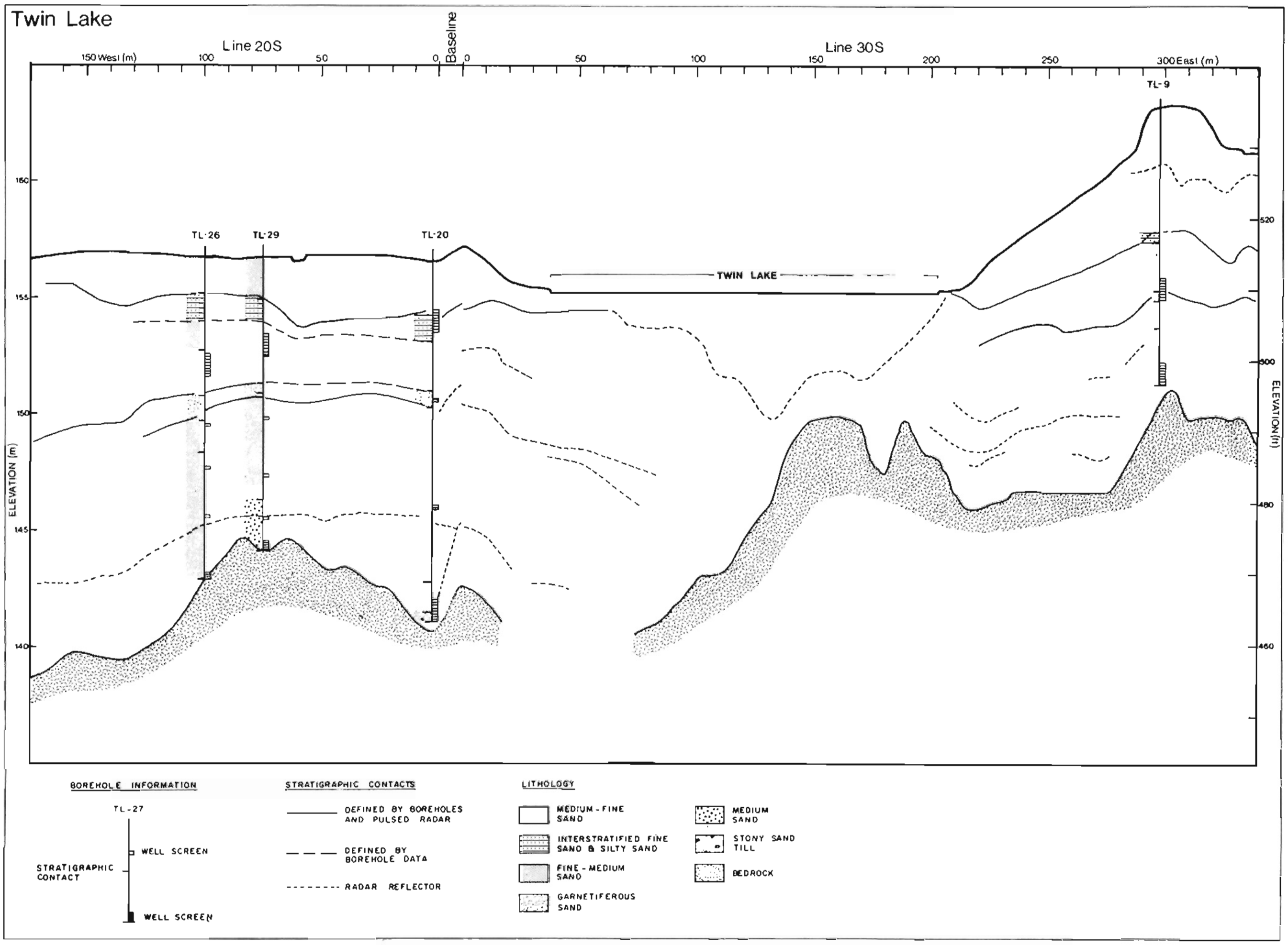

Figure 8. Internal stratigraphy of a sand aquifer defined by radar profiling with borehole control (profile R in Fig. l); bedrock surface is also defined. Radar reflector beneath Twin Lake marks lake-overburden and gyttja-overburden contacts. Diagram is from Killey and Annan (1987) and is reproduced here with permission of the authors.

A preferred explanation is that the anomaly is produced largely by a high density (3.08 g/cm^3) metagabbro sheet occurring along the orthogneiss-paragneiss contact. This is inferred from the coincidence of a prominent culmination (A in Fig. 9) of the anomaly with a small outcrop of metagabbro near the southern extremity of Maskinonge Lake: a smaller culmination (B) also coincides with metagabbroic rock. Modelling of the gravity anomaly indicates that the metagabbroic sheet generally ranges in thickness from about 50 to 150 m and is folded into a syncline (Fig. 10, after Thomas and Tomsons, 1987); the overlying orthogneiss unit attains a maximum thickness of about 500 m in the centre of the syncline. At its northern end the syncline is truncated by a fault that juxtaposes a body of low density gneiss (2.63 g/cm^3) that is significantly lighter than other rocks in the area. Controls used in modelling were foliations observed by Brown et al. (1979), borehole logs (Dugal and Kamineni, 1987), geological contacts and rock density information.

Magnetic studies

Studies of magnetic anomalies have been limited essentially to mapping the anomalies by aeromagnetic surveys: very little interpretation of the collected data has been attempted. The Geological Survey of Canada conducted a regional survey at an altitude of 150 m and a flight-line spacing of 150 m and produced high-resolution total-field and vertical-gradient maps (Geological Survey of Canada, 1980a,b, respectively). A total-field aeromagnetic map has also been produced by Fraser and Dvorak (1979) from a survey flown at an altitude of 55 m and average line-spacing of approximately 100 m. There is, apparently, little correlation between anomalies on these maps and those geological bodies and boundaries shown in Figure 1. In the central part of the research area, however, the total aeromagnetic field is dominated by a prominent east-west belt of positive anomalies that have been related to two diabase dykes by Hayles (1982). In places, the belt has the

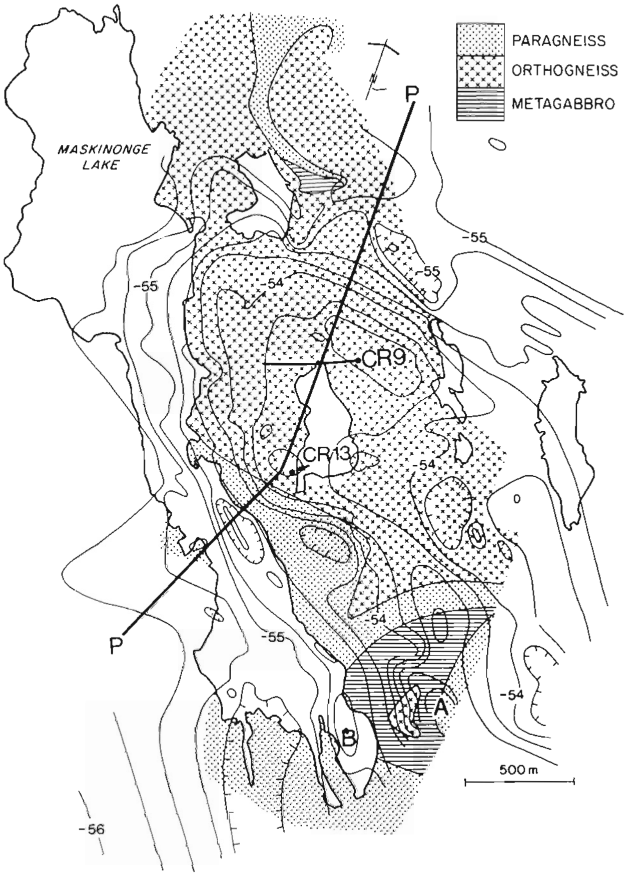

Figure 9. Bouguer gravity anomaly map (contour interval 0.25 mGal) superposed on geological map of central region of Chalk River research area (after Brown et al., 1979): closed contours with tick marks indicate a gravity low. Location of boreholes CR9 and CR13 are shown. P is line of gravity profile modelled in Figure 10.

form of a single magnetic high, but elsewhere appears as two linear culminations separated by an intermediate low; the resolution into two highs is particularly well seen in the map prepared by Fraser and Dvorak (1979). On the vertical-gradient map, the belt manifests itself as two linear belts of positive gradient.

An interpretation by us of the aeromagnetic anomaly associated with the east-west diabase dykes is shown in Figure 11. The location of the profile A-A′ (Fig. 11a) used for the two-dimensional interpretation was selected because of the control provided on the subsurface contacts of diabase dykes by boreholes. Along this particular profile, the anomaly appears as a single positive peak, presumably because the two main dykes interpreted to underlie it (Hayles, 1982) are closer together in this area. A regional field estimated by eye (Fig. 11b) was removed from the observed profile to obtain the residual anomaly (Fig. 11c) used to interpret the two-dimensional model shown in Figure 11d. The model consists of three dykes dipping northward at 70°: from south to north, these have thicknesses of approximately 28, 38 (below a depth of 100 m) and 9 m, respectively. The dykes are modelled as extending to infinite depth. A susceptibility of 3.5×10^{-2} S.I., based on values measured on core from CR6 by Coles et al. (1987), was used to model the dykes. In the absence of any information regarding remanent magnetization, the magnetization was assumed to be induced by the earth's present magnetic field. The position of the central dyke is partly constrained by lithological logs for CR6 and CR8, and the surface position of the thin northernmost dyke is based on the presence of diabase in the shallow FS12 and FS14 percussion boreholes (see Fig. 18 for locations). A ground total-field magnetic survey along a line subparallel to, and crossing, A-A′, carried out in June 1985 by one of the authors (J.G. Hayles), provided strong support for the model in Figure 11d: three prominent positive peaks were mapped coinciding in position with the three dykes.

Fraser and Dvorak (1979) derived an "enhanced magnetic map" by filtering their aeromagnetic data "to enhance the magnetic response of the near-surface geology". They claimed that the enhanced map was similar to a ground magnetic map and that it could be used to define near-surface local geology while de-emphasizing deep seated regional features. They concluded also that, because magnetic anomalies sometimes coincide with EM anomalies, the enhanced map may be of use in differentiating between EM anomalies caused by magnetic conductors and those due to other sources.

Seismic studies

A synthesis of seismic studies conducted at Chalk River has been presented by Wright (1982). Four different kinds of experiments are described: a location map of the experiments showing shot point and geophone locations is shown in Figure 12. For one of the experiments hydrophones were placed in borehole CR1. The following summary of the seismic studies is based on Wright (1982): for more details the reader is referred to the reference list in that publication. The following references are recommended for further reading: Lam and Wright (1980) give information on derivation of P and S wave velocities; Mair and Lam (1979) describe a shallow reflection survey; Wright et al. (1980) describe a method of calculating seismic velocities from data obtained in a reflection survey; Wright and Johnson (1981) describe an experiment to produce shear waves using a hammer source; Huang and Hunter (1980) and Wright and Huang (1984) describe borehole seismic experiments.

The first experiment was designed to detect seismic velocity variations that might be related to earth tides deforming cracks and joints. It involved continuous monitoring of P and S wave velocities over a 3 day period; the experiment was not successful. Significant changes in P wave travel times were measured along profile 1 (Fig. 12a) but they were too large to be related to earth tides. Glacial overburden is much thicker along profile 1 than along the other profiles, and Wright (1982) attributed the changes in travel times to varying saturation of the overburden resulting from variations in the water table.

A shallow seismic reflection survey using a hammer source was conducted along profiles A and B (Fig. 12b).

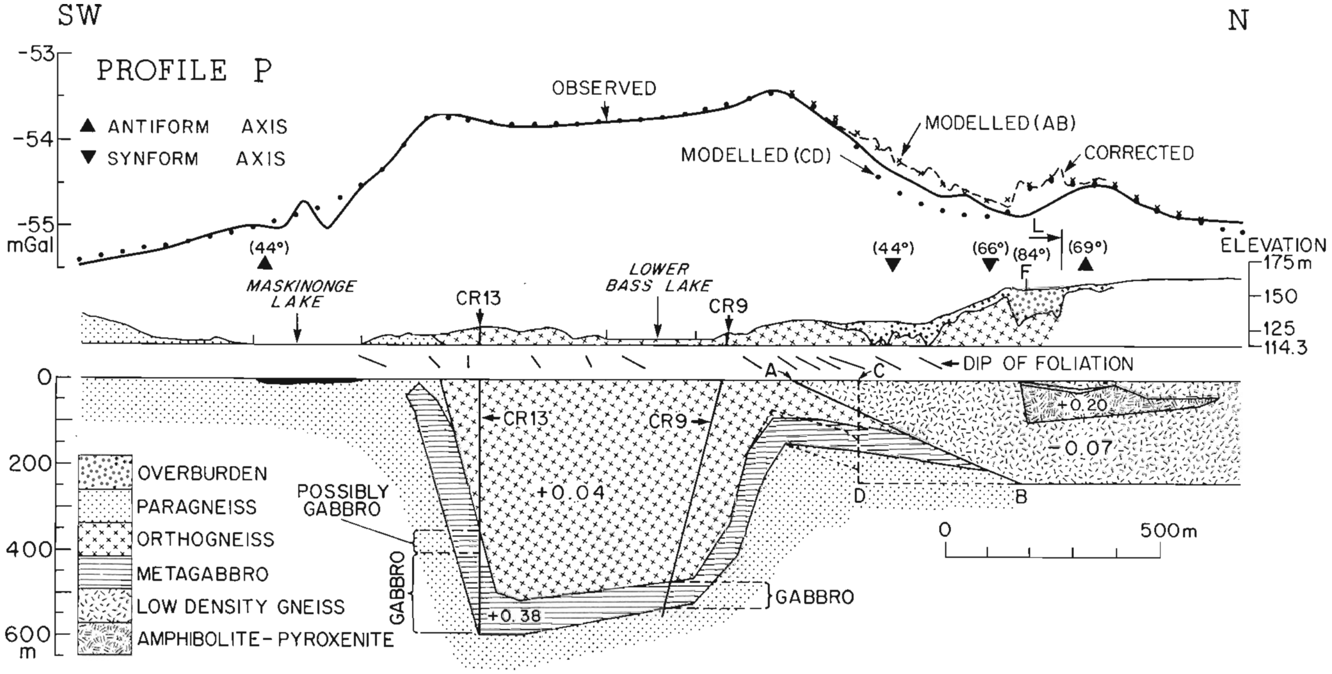

Figure 10. Two-and-a-half-dimensional crustal model interpreted along north-south gravity profile (see Fig. 9 for location) suggesting synclinal folding of a gabbroic sheet (after Thomas and Tomsons, 1987). Folded sheet is truncated by a fault in the northern part of the model: two possible fault positions are indicated, AB (dipping 25° north) and CD (vertical). The dipping fault is the preferred model as it provides a better match with the observed profile. Note that the observed curve has been corrected for overburden effects to the north of Lower Bass Lake. The core log from CR9 and rock chips from CR13 provide some control on the positioning of the gabbro sheet. Numbers in the model are density contrasts in g/cm^3 relative to the background paragneiss density. Position marked by arrow labelled L is northeastern limit of geological mapping by Brown et al. (1979). F is a mapped fault. Angles accompanying symbols for synform and antiform axes and F are those at which these features intersect the line of the profile.

Profile A coincides with profiles 2 and 3 (Fig. 12a) used to monitor velocity variations. The data from this reflection survey were analyzed as a series of overlapping reversed refraction profiles to provide details of P wave velocity variations in the uppermost parts of the rock body. Along profile A, individual determinations of P wave velocity exhibit considerable variation, although along the greater part of the profile a smoothed curve maintains a fairly consistent value of about 5.5 km/s (Fig. 12c). At 210 m from the north end of profile A, the smoothed velocities undergo a noticeable decrease to a minimum value of about 4.9 km/s: Wright (1982) interpreted a fault at this location. At the southeast end, a similar velocity low (4.5 km/s), coinciding with a zone of high electrical conductivity, was attributed to a zone of extensive fracturing.

The average P wave velocities for profiles 2 and 3, obtained from the monitoring experiment, are about 6.1 and 5.4 km/s, respectively. Whereas the latter value is close to the typical 5.5 km/s value for profile A, the former value is considerably higher. A higher value is not altogether unexpected because the seismic energy from the shots used in the monitoring experiment penetrated deeper than the hammer-generated energy and thus possibly travelled through less weathered and less fractured rock at depth. Because the 6.1 km/s velocity of profile 2 is so much higher, Wright (1982) suggested that the waves had travelled through gabbro.

For profile B (Fig. 12d), the scattering of velocity data is somewhat greater than for profile A, with extremely high values (>6.2 km/s) at the northeast end: the latter were attributed to propagation through gabbro. As for profile A, the average value of a smoothed profile is around 5.5 km/s. Gabbro was also predicted to underlie profile 1, where a high P wave velocity of 6.56 km/s and S wave velocity of 4.1 km/s were measured in the monitoring experiment.

P and S wave velocity determinations were also made using a shear wave hammer source. High values at the southeast end of profile 2 near borehole CR1 and at the northeast end of profile 3 were explained by propagation through gabbro.

P wave velocities were measured in CR1 between depths of 20 and 247 m using an array of 12 hydrophones spaced 1.13 m apart. Surface shots were used as an energy source and the array was lifted generally by 1 m for successive shots. Wright (1982) observed that there was no clear correlation between variations in borehole velocities

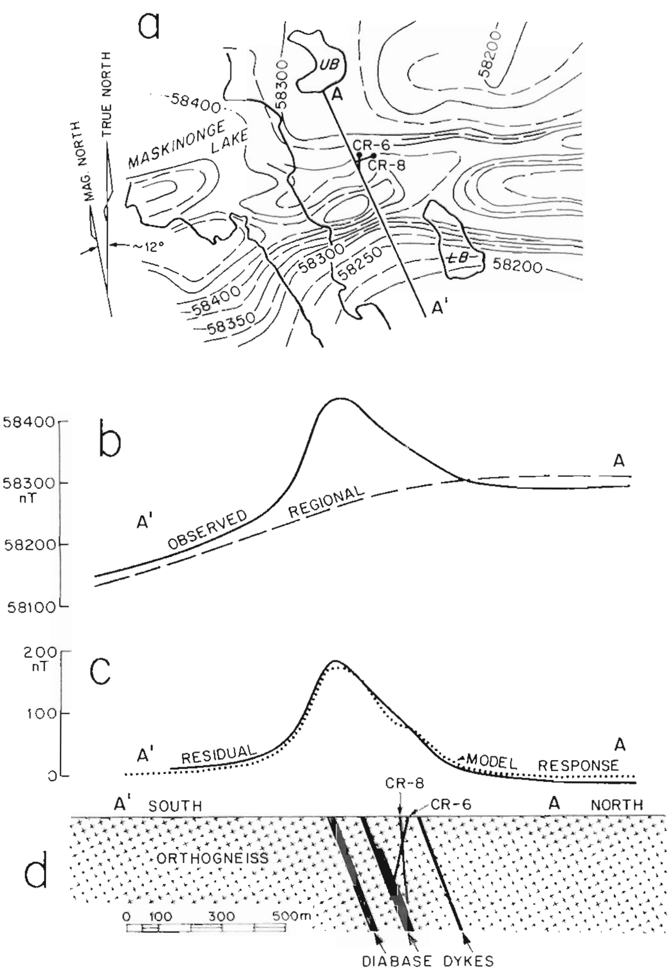

Figure 11. a) Total field aeromagnetic anomalies in the area between Upper Bass (UB) and Lower Bass (LB) lakes (after Fraser and Dvorak, 1979): contours are labelled in nanotesla (nT). A-A' is line of interpreted profile. b) Observed magnetic profile and regional profile estimated by eye. c) Residual profile derived by subtracting the regional profile from the observed profile, and profile generated by model shown in (d). d) Diabase dyke model providing a close fit to residual magnetic profile in (c), interpreted using a two-dimensional technique.

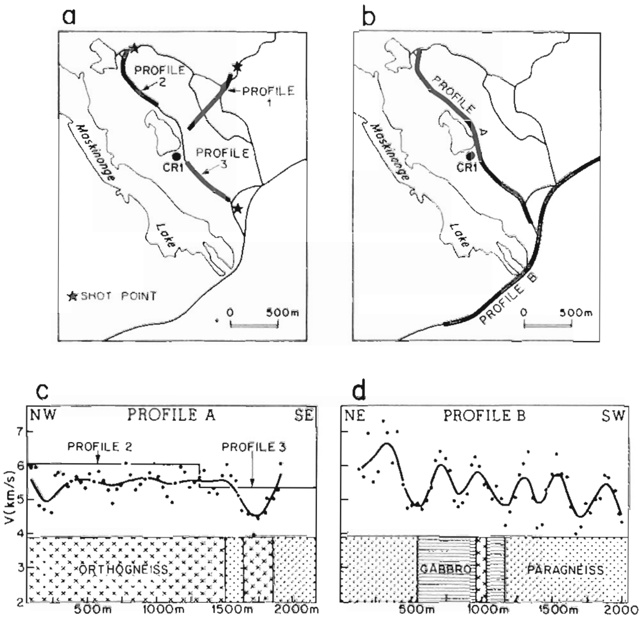

Figure 12. Modified from Wright (1982): a) Location of geophone spreads (heavy lines) for seismic experiment involving continuous monitoring of P and S wave velocities during a period of 3 days. Position of borehole CR1 is also indicated. b) Positions of shallow seismic reflection profiles A and B surveyed using a hammer source: data from these surveys were analyzed as a series of overlapping reversed refraction profiles to obtain detailed P wave velocity information for the uppermost levels of the underlying bedrock. c) Plot of P wave velocities (dots) obtained from the seismic reflection surveys (b above) along profile A: a smoothed velocity profile (heavy line) is also shown. Mean P wave velocities along profile 2 and profile 3 obtained from the monitoring experiment (a above) are indicated by horizontal lines. d) Plot of P wave velocities (dots) obtained from the seismic reflection surveys (b above) along profile B; a smoothed velocity profile (heavy line) is also shown.

and petrological changes and concluded that fractures controlled most of the variations. Increases in fracture concentrations correlated closely with pronounced minima in the velocity profile. The correlation between the borehole velocities and P wave velocities measured on samples of saturated core at 100 kPa by Simmons et al. (1978) was noted to be statistically significant. This suggested to Wright (1982) that high concentrations of microfractures in the cores may be associated with larger fractures or networks of fractures that perturbed the seismic velocities measured at the lower frequencies of the in situ method. The borehole velocities were much lower than crack-free P wave velocities obtained by laboratory determinations on dry borehole cores at pressures of 250 MPa by Simmons et al. (1978).

Using laboratory measurements of seismic wave velocities by Simmons et al. (1978) and Stesky (unpublished data, 1981) and various results from the in situ velocity measurements, Wright (1982) made estimates of the crack density parameter ε and saturation parameter ξ along profile 3 (the only profile where such estimates were feasible). Here the ε values exceeded 0.25, indicative of rock with low integrity. The data, however, apply only to the top 10 to 20 m of the rock body.

Electromagnetic and electrical studies

The bedrock at Chalk River has been investigated using a variety of electromagnetic and electrical techniques. Aerial, ground and borehole methods have been used.

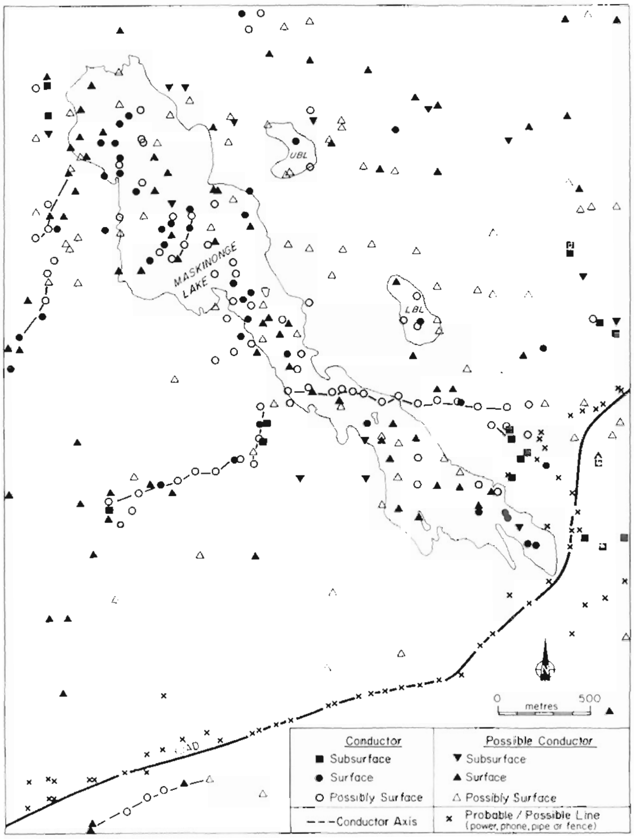

Figure 13. DIGHEM^{II} airborne EM anomalies (after Fraser and Dvorak, 1979).

(1) Airborne electromagnetic studies

Two kinds of airborne electromagnetic surveys were carried out simultaneously at Chalk River: a DIGHEM^{II} electromagnetic survey with the EM sensor at an altitude of 35 m and a VLF-EM survey using a Herz Totem 1A VLF electromagnetometer operating at an altitude of 60 m (Fraser and Dvorak, 1979). The surveys were flown along two sets of mutually perpendicular flight lines, one oriented north-south and using the U.S. Navy transmitting station NAA located at Cutler, Maine, and the other oriented east-west and using NSS at Annapolis, Maryland: a total of 425 line-kilometres was flown.

The data obtained from the DIGHEM^{II} electromagnetic survey (multicoil system using a transmitted frequency of 918 Hz) were treated in different ways depending on the nature of the electromagnetic response. Responses considered discrete (sharp, well defined anomalies) were interpreted according to a vertical sheet (half-plane) model, whereas those classified as broad were interpreted using a conductive earth (half-space) model that provides information on resistivity. A map of electromagnetic anomalies interpreted according to the vertical sheet model is shown in Figure 13. These anomalies are graded according to the conductance (mhos) (1 mho = 1 S; S = siemens) assuming a vertical sheet model (Fraser and Dvorak, 1979): conductance is defined as the product of conductivity and thickness and is the reciprocal of resistance (ohms). Most natural conductors identified at Chalk River, i.e. those unrelated to power lines or other man-made features, have a conductance of 1, typical of swamps, conductive overburden or weak bedrock conductors. The anomaly shapes from the multiple coils often provide a means of recognizing surface conductors and these are indicated in Figure 13. Fraser and Dvorak (1979) attempted to produce depth estimates for the various conductors, but cautioned that for a variety of reasons these might be erroneous: the conductance measurement is considered more reliable. Flight-line to flight-line correlations that outline conductor axes have been made.

Apparent resistivity maps were prepared using two different half-space models that yield a homogeneous half-space resistivity and a pseudo-layer half-space resistivity; details are described by Fraser and Dvorak (1979). In addition to apparent resistivity, use of the pseudo-layer half-space model yields the apparent thickness of an assumed highly resistive upper surface layer. The two half-space models yield identical apparent resistivities when the apparent thickness obtained for the pseudo-layer half-space model is zero.

Maximum apparent resistivities in the region, based on either of the described half-space models, attain just over 3000 ohm-m. Maskinonge Lake is associated with a prominent resistivity low (resistivities range from 200 to 500 ohm-m on the homogeneous half-space map, and 200 to 1800 ohm-m on the pseudo-layer map). According to Fraser and Dvorak (1979), the low is the product of numerous EM anomalies within the lake that may indicate the presence of a major fault zone. They also concluded that the resistivity patterns suggested the presence of a low resistivity layer along the lake, probably reflecting conductive lake bottom sediments, a conclusion supported by negative apparent thickness values.

The airborne VLF-EM survey located many linear conductors that were preferentially oriented north-south and east-west, thus reflecting the bias of the signal from the VLF-EM transmitter in detecting conductors oriented more or less at right angles to its path. Scott (1987) observed that most of the DIGHEM^{II} electromagnetic anomalies correlate with the VLF-EM anomalies. Airborne and ground VLF-EM anomalies are compared in the following section.

(2) Ground electromagnetic studies

Several types of ground electromagnetic survey have been applied at the Chalk River site: VLF-EM, horizontal loop EM (HLEM), Maxi-Probe, EM-37, EM-34 and scalar audio-frequency magnetotelluric (AMT).

VLF-EM surveys have been described by Dence and Scott (1979) and Scott (1987). Scott noted that VLF anomalies can be generated in two ways. The VLF field may interact inductively with a conductor to produce a local EM field that manifests itself as a perturbation on the primary field, or an EM anomaly may arise as a result of current chanelling in which current flow in the earth, produced by a transmitter, may be concentrated in low-resistivity zones. In surface VLF-EM surveys, current channelling of the EM field in a fracture zone or a linear depression containing conductive overburden produces a secondary magnetic field that is distinct from the primary field. Measurements of total magnetic field inclination taken along a profile perpendicular to the fracture (and to the transmitted direction of the EM signal) reveal a sinusoidal signature centred above the fracture: the centre of the sinusoid is normally referred to as the crossover. It is the recognition of such signatures that allows the identification of fracture locations. The surface method is well suited to detecting fractures that are vertical or steeply inclined where overburden effects are not severe.

In VLF-EM surveys, the anomalies attain a maximum amplitude when the conductors are oriented parallel to the propagation direction of the transmitted signal. Any conductor whose strike is perpendicular to the direction of the transmitted signal will not produce an anomaly. Scott (1987) recommended that in order to detect all conductors in an area, it is necessary to use at least two transmitters whose signals travel in directions that are roughly mutually perpendicular. Fortunately, at Chalk River this requirement is fulfilled by VLF signals from the U.S. Navy transmitters NAA (Cutler, Maine) and NSS (Annapolis, Maryland) that propagate along 280 ± 10° and 355 ± 10°, respectively. An orthogonal grid of north-south and east-west lines spaced 100 m apart was established so that traverses could be made in directions perpendicular to these transmitted signals.

In 1978 and 1979 Scott surveyed approximately 100 km of line along the grid using a Geonics EM 16 instrument and taking measurements every 20 to 25 m. The Geonics EM 16 instrument measures the dip angle and quadrature components of the VLF field. Scott (1987) interpreted conductor axes primarily on the basis of the amplitude and crossover position of the dip angle data. The locations of these axes are shown in Figure 14; these are based on the surveys along both north-south and east-west lines.

The question of the dependence of the strength of the VLF anomaly on the geometrical relationship between the azimuth of the conductor and of the transmitted signal was examined by Hayles and Sinha (1982). In their experience, conductors oriented within ±45° of the direction of propagation of a VLF signal will usually be detected, whereas weakly conductive zones oriented at angles greater than 45° to the signal may not be detected. Hayles and Sinha (1982) developed and tested a portable VLF transmitter at Chalk River, using it to simulate the U.S. Navy transmitters NAA (Cutler, Maine) and NSS (Annapolis, Maryland). It was established that conductor axes mapped using the portable transmitter were almost identical to those mapped by the Navy transmitters. A further study was made in which the direction of propagation of the signal from the portable VLF transmitter was oriented at 45° to the directions associated with NAA and NSS. The same conductor axes were delineated with a few minor shifts in position, suggesting that conductors whose axes lie within 45° of the direction of a transmitted signal will be detected. The study demonstrated that two VLF signals propagating at right angles to each other are capable of mapping all VLF conductors in a region.

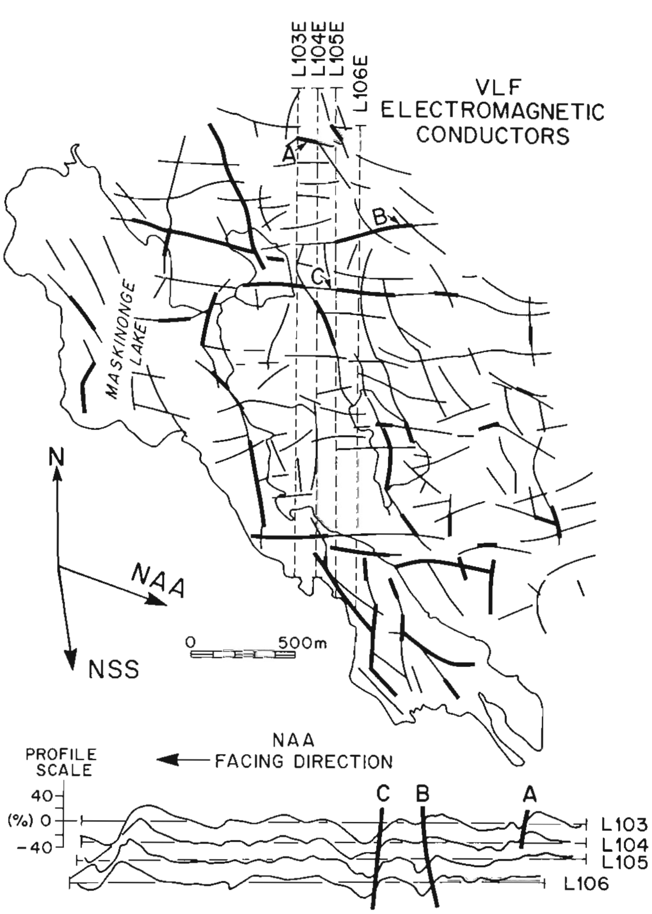

Figure 14. Ground VLF-EM conductors (after Scott, 1987) based on transmitted signals from U.S. Navy transmitters at Cutler, Maine (NAA) and Annapolis, Maryland (NSS). Strongest conductors are indicated by heavy lines. Lower section of figure illustrates four north-south profiles (Lines 103 to 106) of dip angle data with crossover positions corresponding to conductors A, B and C indicated.

Scott (1987) compared the results obtained from his ground VLF survey with those obtained by an airborne VLF survey that also used U.S. Navy transmitters NAA and NSS (Fraser and Dvorak, 1979). He noted that in some cases a single conductor interpreted from airborne data was resolved by the ground survey into a complex series of individual conductors, and that positions of airborne and ground conductors did not always coincide precisely and might be displaced from one another by a few tens of metres. Most anomalies delineated by the airborne VLF survey were identified by the ground survey. The ground survey also located many weaker conductors that were not evident in the airborne data: that these weaker responses probably represent bedrock conductors was suggested by the fact that several shear zones encountered in the inclined borehole CR9 were located below conductor axes. The interpretation of VLF conductors as shear zones must, however, be approached with care, because sometimes the conductor may correspond to overburden or to a particular lithology. For example, drilling to investigate the source of conductor B (Fig. 14) revealed the presence of both a fracture zone and a large section of low resistivity mafic rock, either of which could act as a conductor. A comparison of the results of the airborne and ground VLF-EM studies demonstrated that airborne surveys are quite useful for outlining major conductive fractures and for planning detailed follow-up ground surveys.

The overburden at Chalk River was considered to be quite resistive (no values specified) by Scott (1987), who suggested that most of the conductors identified in the DIGHEM^{II} EM survey and by the airborne and ground VLF surveys were probably bedrock conductors. In Scott's opinion the presence of resistive overburden makes the Chalk River area well-suited to investigation by the VLF technique. A comparison, by Scott, of the pattern of conductor axes determined by the VLF survey and a pattern of airphoto lineaments, which probably represent fractures (Brown et al., 1979), revealed some good correlations between conductors and lineaments, supporting Scott's argument that the VLF conductors are largely related to bedrock fractures. Scott (1987) cautioned, however, that not all conductors are necessarily in the bedrock. Some may occur within the overburden, where bedrock depressions are filled with conductive soils or where the prevailing coarse grained overburden is replaced by silts or clays. A resistivity survey by Hallof (1980) indicated that some overburden was indeed more conductive than the bedrock. Phillips and Richards (1975) have noted that the presence of conductive overburden may cause problems in discriminating between those anomalies associated with conductivity changes in bedrock and those related to changes occurring either within the overburden or at the overburden-bedrock interface.

If a pseudo-section of apparent resistivities determined with a 12.5 m dipole-dipole resistivity survey (Hallof, 1980) is compared to a nearby overburden section near Upper Bass Lake determined by seismic refraction (Gagné, 1980), it is apparent that the ratio of bedrock to overburden resistivity may be 10 or greater. A model study of Vozoff (1971) implies that ratios of this magnitude can generate moderate VLF-EM responses if the overburden occurs in long linear troughs and is in sharp contact with bedrock. Superficial deposits are widespread in the area of the VLF grid, so that there is a strong likelihood that some conductors arise within overburden.

The results of horizontal loop EM (HLEM), Maxi-Probe, EM-37, and EM-34 surveys are described by Sinha and Hayles (1987). Three of the methods, HLEM, Maxi-Probe, and EM-37, are most commonly used in metallic mineral exploration where the zone of interest may be 10 to 1000 times as electrically conductive as the host and as deep as 350 to 400 m below the surface. The fourth method, EM-34, is an inductive resistivity system that works best in areas of horizontally-layered surficial materials and has a maximum penetration of about 25-30 m.

The three exploration methods were employed experimentally to determine how successful they would be at detecting poorly conductive fractures. In comparison to the VLF-EM technique, all three have the advantages of greater depth of penetration, a large range of operating frequencies and the option of having variable separation between receiver and transmitter permitting investigation over a range of depths.

The HLEM technique was apparently the most successful in detecting the same conductors as those found by the VLF-EM survey, the quadrature data for the largest coil separation (200 m) giving the best correlation. The in-phase responses were quite low on all profiles, except for the 200 m data, so no quantitative interpretation was attempted. This method has the same difficulties as the VLF-EM method in discriminating between overburden and bedrock conductors.

The deep-sounding EM methods (Maxi-Probe and EM-37) were used on a more experimental basis than the HLEM and, hence, covered a more limited area. The Maxi-Probe system located unconfirmed subhorizontal conductive zones at depths up to 250 m just east of Upper Bass Lake. The EM-37 appears to have located conductive features at depth that correlate in horizontal position in some cases with VLF-EM conductors.

The EM-34 technique worked well on overburden-covered areas, giving apparent resistivities very similar to those measured in the dipole-dipole resistivity survey (Hallof, 1980). The method, however, did not perform well on outcrop or near contacts between bedrock and overburden.

In audio-frequency magnetotelluric surveys electromagnetic impedance (ratio of horizontal electrical field (E) in the ground to the orthogonal horizontal magnetic field (H)) is measured at a number of frequencies to yield earth resistivities as a function of frequency; the process is a form of depth sounding. AMT studies at Chalk River have been reported by Redman and Strangway (1978) and Strangway et al. (1980). Redman and Strangway (1978), in a preliminary feasibility study of the method, used both natural source fields and U.S. Navy transmitters. They concluded that the overall resistivity values at Chalk River were considerably lower than those found in many parts of the Canadian Shield, and that considerable amounts of fluid were present in the bedrock; resistivities are typically a few thousand ohm-m compared to values up to 100 000 ohm-m in many Shield areas. At one locality, "granite" was estimated to have a resistivity of approximately 3000 to 5000 ohm-m. At another locality "the conductive surface layer of overburden and fractured rock and/or conductive fault structure probably have resistivities of approximately 100-400 ohm-m" (Redman and Strangway, 1978, p. 5). They also concluded that fault structures may be readily detected by the AMT method if they have low resistivity as a result of water-filled fractures.

Strangway et al. (1980), in their experiments, were forced to use two infinite line sources (power lines) because the latter were contaminating the preferred natural signals in the range 10 Hz to 10 KHz. Apparent resistivities were measured at 60 Hz and three of its stronger harmonics (180 Hz, 300 Hz and 660 Hz). Measurements were made near Upper Bass Lake at 50 m intervals along seven north-south lines that had also been surveyed by the VLF method. The apparent resistivities measured by the AMT survey are similar to those obtained by a VLF-EM

Table 2 Contracted logs — AECL, CHALK RIVER SITE — Length of holes logged (Metres)

Hole	Survey Dates	Total Hole Length	E Log 16" & 32" Normal	Resist Log Single Point	Self Potential[1]	Focused Beam	Neutron Neutron	Natural Gamma	Temperature	Density	Caliper	Fluid Resistivity	Sonic Transit Time	Total Distance Logged	Remarks
CR-1	Feb 12-13/79	270	245	263	NR	253	270	270	NR[4]	269	269	NR[10]	NR[10]	1839	
CR-2	Feb 11/79	213	146	146	146	NR[2]	155	155	NR[4]	154	NR[3]	NR	NR	902	perforated plastic pipe lining hole
CR-3		160										NR	NR		Broken rock and difficult drilling- No geophysical logging done.
CR-4	Feb 10/79	113	104	104	104	NR[2]	112	112	NR[4]	111	NR[3]	NR	NR	647	perforated plastic pipe lining hole
CR-5	Feb 9-10/79	230	216	216	218	NR[2]	229	229	NR[4]	228	NR[3]	NR	NR	1336	perforated plastic pipe lining hole
CR-6	Feb 14-16/79	305	283	294	294	268	285	285	NR[4]	285	285	NR	NR	2279	Density tool stuck briefly at 260 m.
CR-7	Feb 15-16/79	153	130	140	140	139	152	152	NR[4]	152	151	NR	NR	1156	
CR-8	Feb 13-14/79	306	283	292	292	291	304	303	NR[4]	304	304	NR	NR	2373	
CR-9	Nov 13-15/80	704	NR[5]	702	702	699	702	703	703	703	702	NR	NR	5616	
CR-10	Nov 15/80	122	NR[5]	121	121	120	121	122	122	121	121	NR	NR	969	
CR-11	Nov 16/80	122	NR[5]	120	120	127	121	121	122	121	121	NR	NR	973	
CR-12	Nov 16/80	131	NR[5]	117	117	128	129	131	131	130	130	NR	NR	1013	
CR-13[6]		610												0	percussion drilled (no core) No standard logging done.
FS-7[7,8]	July 4/82	75	55	74	74	74	74	72	72[9]	73	73	73	73	787	percussion drill hole
FS-10[7,8]	July 3/82	44	20	38	20	38	45	46	47[9]	47	47	47	47	442	percussion drill hole
FS-11[7,8]	July 2/82	43	20	38	16	42	37	41	42[9]	43	42	43	37	401	percussion drill hole
FS-12[7]	July 1/82	43	22	40	23	40	40	41	41[9]	37	42	34	34	394	percussion drill hole
FS-13	June 30 - July 1, 82	42	23	43	33	43	43	40	40[9]	43	43	43	43	437	percussion drill hole
FS-14	June 28 & 29, 82	42	31	42	31	41	41	40	40[9]	35	41	41	35	418	percussion drill hole
TOTALS (metres)		3728	1578	2790	2451	2303	2860	2863	1360	2856	2371	281	269	21 982 metres	

[1] All self (spontaneous) potential logs are suspected to be of poor quality

[2] Perforated plastic pipe used in these holes. The focused beam log reads every hole (6" separation) in the pipe and every coupling in the pipe (10' separator). An analog record of the Focused beam exists for a section of CR-5 but has not been digitized.

[3] Caliper was not run inside the plastic pipe.

[4] Temperature logging was not part of the February 1979 contract.

[5] Long and short normal E logs were not part of this contract.

[6] Hydrogeochemisry hole CR-13 is a percussion drilled hole that has not been logged yet.

[7] Hydrogeology holes FS-1 to 6, 8, 9, 15, 16 & 17 totalling about 470 m of 6" diameter percussion drilled holes have not been logged.

[8] Hydrogeology holes FS-7 and 10 to 14 are 6" diameter percussion drilled holes.

[9] This data is of low quality due to a probe malfunction.

[10] Fluid Resistivity and Sonic Transit time are now considered part of the Standard Contracted log suite. These instruments became available in 1982.

resistivity survey along line 106E. This is interesting, considering that the AMT frequencies are very much lower than VLF frequencies and that the AMT survey used a 30 m electric field dipole compared to a 10 m dipole for the VLF resistivity survey. The interpretation of the AMT data at the Chalk River site is difficult because of the heterogeneous nature of the overburden and bedrock gneisses and variations in overburden thickness. The study was limited, therefore, to correlating the resistivity lows between adjacent lines in an attempt to outline linear east-west structures that might be conductive faults (Fig. 15). Strangway et al. (1980), on the basis of apparent resistivity data provided by W.J. Scott, stated that a reasonable resistivity for modelling the Chalk River area as a half-space was probably 1000 to 5000 ohm-m.

Niblett (in Strangway et al., 1980) commented that the AMT survey identified resistivity lows along the profiles, which were associated with conductive faults or fractures near the surface. The survey thus supplemented results obtained by the ground VLF-EM survey and other electromagnetic techniques but provided no new information on resistivity variations at depth. The reason for the lack of depth information in this case is that the usual interpretative techniques, employed for natural fields, providing information to appreciable depths in the crust, could not be used. This problem was caused by the proximity of the power lines, used as sources for the survey, which prevented the usual approach of plane wave analysis.

(3) Ground resistivity studies

Results of dipole-dipole resistivity measurements along sections of three north-south lines of the grid near Upper and Lower Bass lakes have been reported by Hallof (1980). Dipole separations ranging from 300 to 12.5 m were used. Pseudo-sections of apparent resistivity prepared by Hallof indicate that the exposed bedrock of the region has a resistivity in the range of 5000 to 15000 ohm-m, somewhat higher than the 5000 ohm-m maximum value estimated by Redman and Strangway (1978), whereas overburden often exhibits resistivities well below 200 ohm-m. The survey delineated several low-resistivity zones, some of which correlated line to line (Fig. 15). Both broad zones (300 to 400 m wide) of low resistivity and narrow conductive zones detected only with dipole separations of 25 and 12.5 m were interpreted. The identification of low resistivity zones in this area is at variance with the picture of a generally resistive overburden at Chalk River presented by Scott (1987).

Hallof (1980) concluded that, even with measurements using the shortest electrode intervals, there was virtually no indication of a horizontal contour pattern that would suggest the presence of a substantial thickness of conductive glacial overburden; therefore, within the surveyed area the glacial overburden must be less than 5 to 10 m thick. This is in general accord with the seismic refraction results of Gagné (1980). However, in an area traversed by the resistivity survey immediately east of Upper Bass Lake, the seismic results indicate that the glacial deposits locally attain 20 to 30 m (Fig. 6).

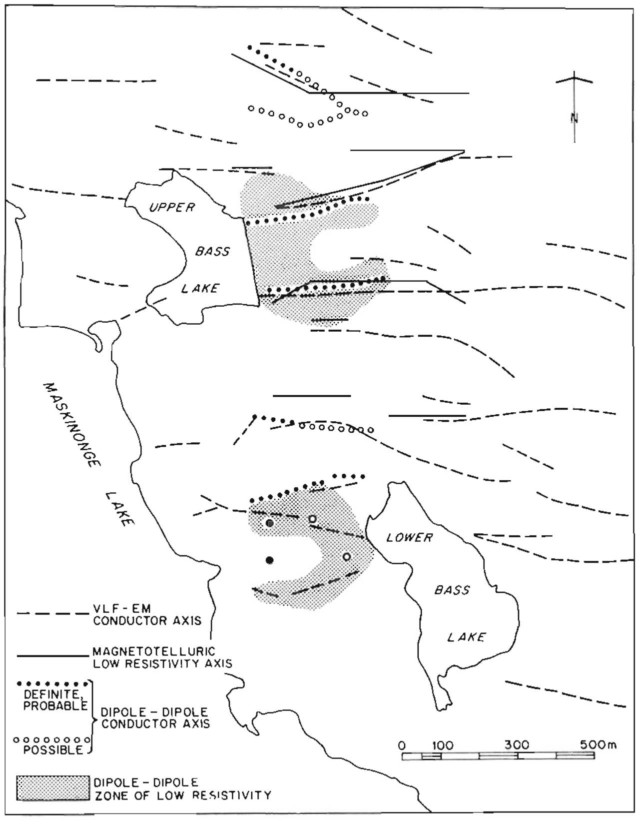

Figure 15. VLF-EM conductor axes (after Scott, 1987) based on transmitted signal from U.S. Navy transmitter at Cutler, Maine (NAA), audio-frequency magnetotelluric low resistivity axes (after Strangway et al., 1980) and dipole-dipole conductor axes and low resistivity zones (after Hallof, 1980) in the region of Upper and Lower Bass lakes.

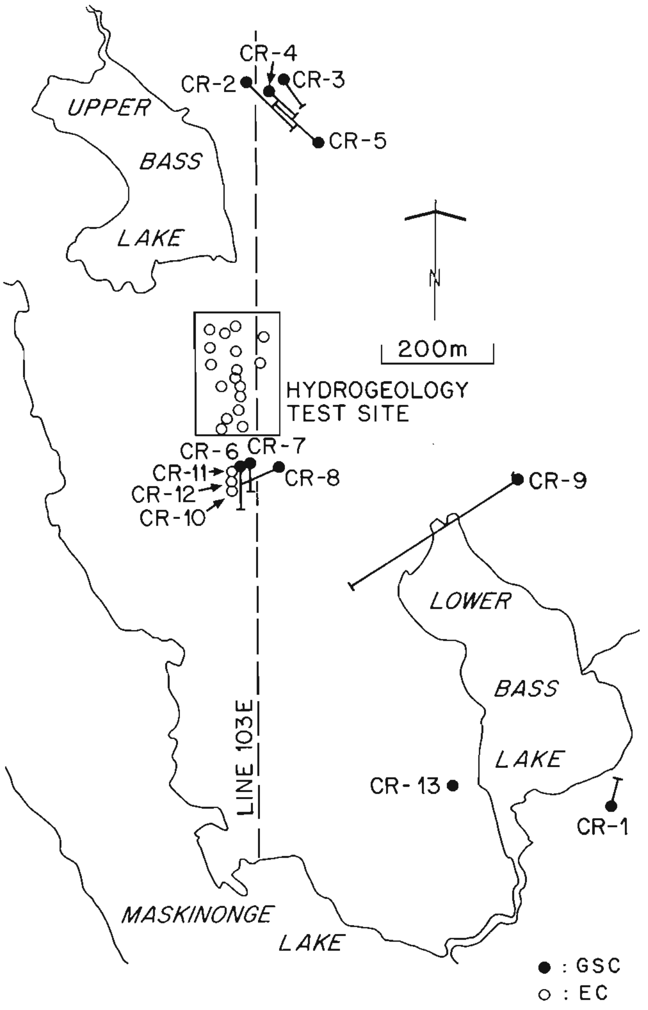

Figure 16. Locations of CR series and FS series boreholes drilled by the Geological Survey of Canada (GSC) and Environment Canada (EC); FS boreholes are located within rectangle outlining the hydrogeology test site.

The dominant resistivity feature outlined by the survey is located east of Upper Bass Lake (Fig. 15) and is interpreted as a zone of low resistivities (100 to 500 ohm-m) in the bedrock having a width of at least 350 to 400 m (Hallof, 1980): the low resistivity rocks were believed to extend fairly close to the surface, perhaps within 10 m, and to a depth of at least 100 to 150 m.

BOREHOLE GEOPHYSICAL INVESTIGATIONS OF BEDROCK

Standard geophysical logs

About 4200 m of borehole drilling has been carried out in the bedrock at the Chalk River site, using both continuous coring and percussion methods. The former method has yielded approximately 3000 m of core, whereas the remaining 1200 m drilled by the percussion method has yielded rock chips only. A location map of the principal holes is provided in Figure 16. The deepest holes (CR1 through CR13) range in length from 113 to 704 m and total 3439 m (Table 2). The FS series of holes, occurring within the enclosure labelled as hydrogeology test site (holes are numbered in Fig. 18), was drilled mainly for hydrological studies; these holes are relatively shallow, the maximum depth being 75 m. In most of these boreholes, standard geophysical logging has been carried out under contract by Roke Oil Enterprises, Calgary, Alberta; several holes have also been logged by the United States Geological Survey (Davison et al., 1984). Particulars of the logging activities in the various holes are given in Table 2 and Figure 17.

The suite of standard logging techniques includes neutron-neutron, gamma-gamma, natural gamma and the following electrical methods: focused beam, resistivity (16 and 32 inch), single point resistance and spontaneous potential. These methods have been used extensively in the petroleum industry and, to a lesser extent, in hydrological studies; a description of these and other methods may be found in Keys and MacCary (1981) and Schlumberger Ltd. (1972). The use of standard logging techniques in regions of sedimentary rocks is traditional and well documented, and interpretation techniques are relatively sophisticated (Cant, 1983; Pirson, 1977). Their use in crystalline rocks, however, has been more limited, although several studies have demonstrated their utility (e.g. Keys, 1979; McCann et al., 1981).

AECL CHALK RIVER BOREHOLE LOGS

HOLE	CORE LOG	MAGNETIC SUSCEPTIBILITY	TV LOG	ACCOUSTIC TV LOG	RESISTIVITY FOCUSED BEAM	RESISTIVITY 16"& 32" NORMAL	RESISTIVITY SINGLE POINT	SELF POTENTIAL	NATURAL GAMMA	DENSITY	POROSITY	CALIPER	FLUID RESISTIVITY	SONIC TRANSIT TIME	TEMPERATURE	VLF	SEISMIC TUBE WAVE	INDUCED POLARIZATION	RESIS-TIVITY 16"& 32" NORMAL	RESIS-TIVITY 75 & 15m NORMAL	SELF POTENTIAL AND TIE IN	AQUIFER TIDES	RADAR	SONIC LOG	TELEVIEWER	NATURAL GAMMA	DENSITY	POROSITY	HIGH RES. CALIPER
CR-1	░	▨	░		▤	▤	▤		▤	▤	▤	▤			▨	░ ▦	░	▦	▦	▦	▦	▨							
CR-2	░	▨	░			▤	▤	▤	▤	▤	▤				▨	░						▨							
CR-3	░	▨														░						▨							
CR-4	░	▨				▤	▤	▤	▤	▤	▤					░													
CR-5	░	▨	░			▤	▤	▤	▤	▤	▤				▨	░													
CR-6	░	▨	░		▤	▤	▤	▤	▤	▤	▤	▤			▨	░ ▦	░	▦	▦	▦	▦	▨	░	○	○	○	○	○	○
CR-7	░	▨	░		▤	▤	▤	▤	▤	▤	▤	▤			▨	░							░						
CR-8	░	▨	░		▤	▤	▤	▤	▤	▤	▤	▤			▨	░							░						
CR-9	░	▨	░		▤		▤	▤	▤	▤	▤	▤			▨ ▤	░ ▦	░	▦	▦	▦	▦	▨							
CR-10			░	░	▤		▤	▤	▤	▤	▤	▤			▤									○	○	○	○	○	○
CR-11			░	░	▤		▤	▤	▤	▤	▤	▤			▤									○	○	○	○	○	○
CR-12			░	░	▤		▤	▤	▤	▤	▤	▤			▤									○	○	○	○	○	○
CR-13	N/A		░																										
FS-1	N/A		░	░																									
FS-2	N/A		░	░																									
FS-3	N/A		░	░																									
FS-4	N/A		░	░																									
FS-5	N/A		░	░																									
FS-6	N/A		░	░																									
FS-7	N/A		░	░	▤	▤	▤	▤	▤	▤	▤	▤	▤	▤	▤	░													
FS-8	N/A		░	░																									
FS-9	N/A		░	░																									
FS-10	N/A		░	░	▤	▤	▤	▤	▤	▤	▤	▤	▤	▤	▤	░													
FS-11	N/A		░	░	▤	▤	▤	▤	▤	▤	▤	▤	▤	▤	▤	░													
FS-12	N/A		░	░	▤	▤	▤	▤	▤	▤	▤	▤	▤	▤	▤	░													
FS-13	N/A		░	░	▤	▤	▤	▤	▤	▤	▤	▤	▤	▤	▤	░													
FS-14	N/A		░	░	▤	▤	▤	▤	▤	▤	▤	▤	▤	▤	▤	░													
FS-15			░													░													
FS-16			░													░													
FS-17			░	░												░													

░ EMR / GSC
▨ EMR / EPB
▤ EMR / GSC CONTRACT
▦ EMR / GSC CONTRACT
○ E.C. / U.S.G.S

Figure 17. Summary of geophysical logging carried out in CR and FS series boreholes. EMR — Energy, Mines and Resources; GSC — Geological Survey of Canada; EPB — Earth Physics Branch; E.C. — Environment Canada; U.S.G.S. — United States Geological Survey.

Davison et al. (1984) have reported results of a detailed study of logs from Chalk River and Whiteshell Nuclear Research Establishment, Manitoba, and arrived at a number of conclusions regarding the utility of such logs in igneous-metamorphic terranes. Electric logs were considered to be very useful, under the right conditions, for detecting major fractures and major lithological changes. Neutron-neutron logs, which reflect primarily changes in the hydrogen content of rocks, were also considered very useful in these respects. For example, major fracture zones at Chalk River (presumably water-filled) are reflected in reduced count rates in the log; Davison et al. (1984) cautioned, however, that reduced rates may also relate to major concentrations of primary hydrous mica minerals or to secondary alteration products such as clay or chlorite. These authors noted also that basic rocks, such as the diabase in CR6 (Dugal and Kamineni, 1987), often had a higher hydrogen content than unaltered acidic igneous rocks, thereby indicating the usefulness of the neutron-neutron technique for distinguishing certain lithologies.

Natural gamma logs, noted to be widely used for correlating sedimentary lithologies, were described as more difficult to apply in the Canadian Shield. Difficulties in correlating rock types between holes located only 10 to 20 m apart (clustered near CR6) on the basis of the gamma logs alone were cited to illustrate this point; irregular gneissic structure in the area was suggested as a possible reason. The natural gamma activity in unfractured igneous rock is controlled primarily by potassium in orthoclase feldspar and biotite and this influence was noted by Davison et al. (1984) in CR6. Bottomley et al. (1987) used natural gamma logs to try to define more precisely a contact between monzonitic gneiss and gabbro in CR13, which was drilled by the percussion method and logged lithologically on the basis of rock chips. Cross plotting of neutron-neutron and gamma logs was found to be particularly useful for distinguishing between different lithologies: such a cross plot for CR6 clearly distinguished between the granitic rocks and the gabbro (now identified as diabase) and also pointed to fractured and altered zones in each rock type.

Davison et al. (1984) regarded gamma-spectral data to be useful for identifying hydrothermally altered zones. Killeen and Mwenifumbo (1987) have reported results of spectral logging at Chalk River (CR1) noting that some quartz-potassium feldspar veins correlated with potassium and thorium peaks. However, there is apparently no significant correlation between fracture zones and the spectral logs. Gamma-gamma logs, which provide density estimates of the rocks, were considered to be less useful than many of the other logs by Davison et al. (1984) who noted that, for igneous rocks, the gamma-gamma response was often mainly a reflection of changes in the diameter of the hole.

In their study of geophysical logs from several AECL research areas, including Chalk River, Hillary and Hayles (1985) arrived at conclusions similar to those of Davison et al. (1984). The main causes of anomalies were considered to be fractures, which showed up particularly well on electrical logs, but lithological changes also featured prominently on many logs.

In addition to providing information on fractures and lithologies, geophysical logs provide an excellent means of correlating features from borehole to borehole, because they provide a continuous display of the variations in the measured parameters. This utility is exemplified by correlations between the cluster of boreholes CR6,7,8,10,11 and 12 and CR9 (Fig. 18), which were not recognized during any of the other geoscience investigations. The pattern of variability of the log trace provides a signature that can be recognized in adjacent boreholes, even though the correlation may not be apparent from lithological descriptions or even from visual inspection of core. The single-point resistance, neutron-neutron, natural gamma and gamma-gamma logs all contain signatures that correlate well between these boreholes. Four of the more prominent ones are produced by thin mafic layers (Fig. 18). Most of the boreholes are very close together, roughly 15 to 50 m apart, and correlations are to expected. Some were noted by Hayles (1982) and Davison et al. (1984), although the latter authors also noted that correlation of rock types between some of the holes using only natural gamma logs was quite difficult. The ambiguities of interpretations based on individual logs draws attention to the importance of multiple-log borehole surveys to obtain the maximum benefit from borehole geophysics. The correlations between CR8 and CR9, separated by over 300 m, demonstrate the power of geophysical logs for aiding interpretations of geological structure. In this case, the structure is a sequence of gneisses dipping approximately 20° to the northeast. It is interesting to note (Fig. 18) that some of the mafic units have distinct natural gamma signatures.

Borehole VLF-EM surveys

The borehole VLF-EM method was tested at Chalk River during the period 1979 to 1983, commencing with prototype instruments and rudimentary surveying procedures. Dyck and Hayles (1981) reported the results, with particular emphasis on the application of the VLF-EM technique to identifying fractures in boreholes. They considered the borehole method a useful extension of the surface technique.

In the borehole surveys at Chalk River, the amplitude and phase of the components of the electric or magnetic field parallel to the borehole were measured with respect to the magnetic field recorded at a stationary sensor on the surface to obtain in-phase and quadrature responses. For the electric field surveys, the difference in the electric field over an interval of 10 m was monitored continuously along the length of the borehole. Dyck and Hayles (1981) noted that the electric field is sensitive to large water-filled fractures, a single, isolated fracture oriented more or less perpendicular to the borehole producing a typical sinusoidal signature. Where fractures occur close together, however, the individual responses may interfere, producing more complex signatures; even in these cases, fracture locations can usually be determined based on the crossovers. Examples of distinct crossovers that correlate with faults observed on the TV and core logs occur below a depth of 200 m in CR1 for the NSS signal.

In boreholes the VLF-EM electric field method is best at detecting horizontal or subhorizontal planar fractures. The orientation of such a fracture, if it is tabular, with respect to the exciting signal is an important control on the signature. When the long axis of the fracture is parallel to the signal's direction of propagation, the response is most pronounced; conversely, when it is orthogonal to the propagation direction, the response is suppressed. Examples that probably illustrate this phenomenon are the faults at approximate depths of 205, 230 and 250 m in CR1 (Fig. 19). The in-phase response to these faults for the northerly-directed signal from NSS is greatly enhanced relative to the response for the westerly-directed signal from NAA.

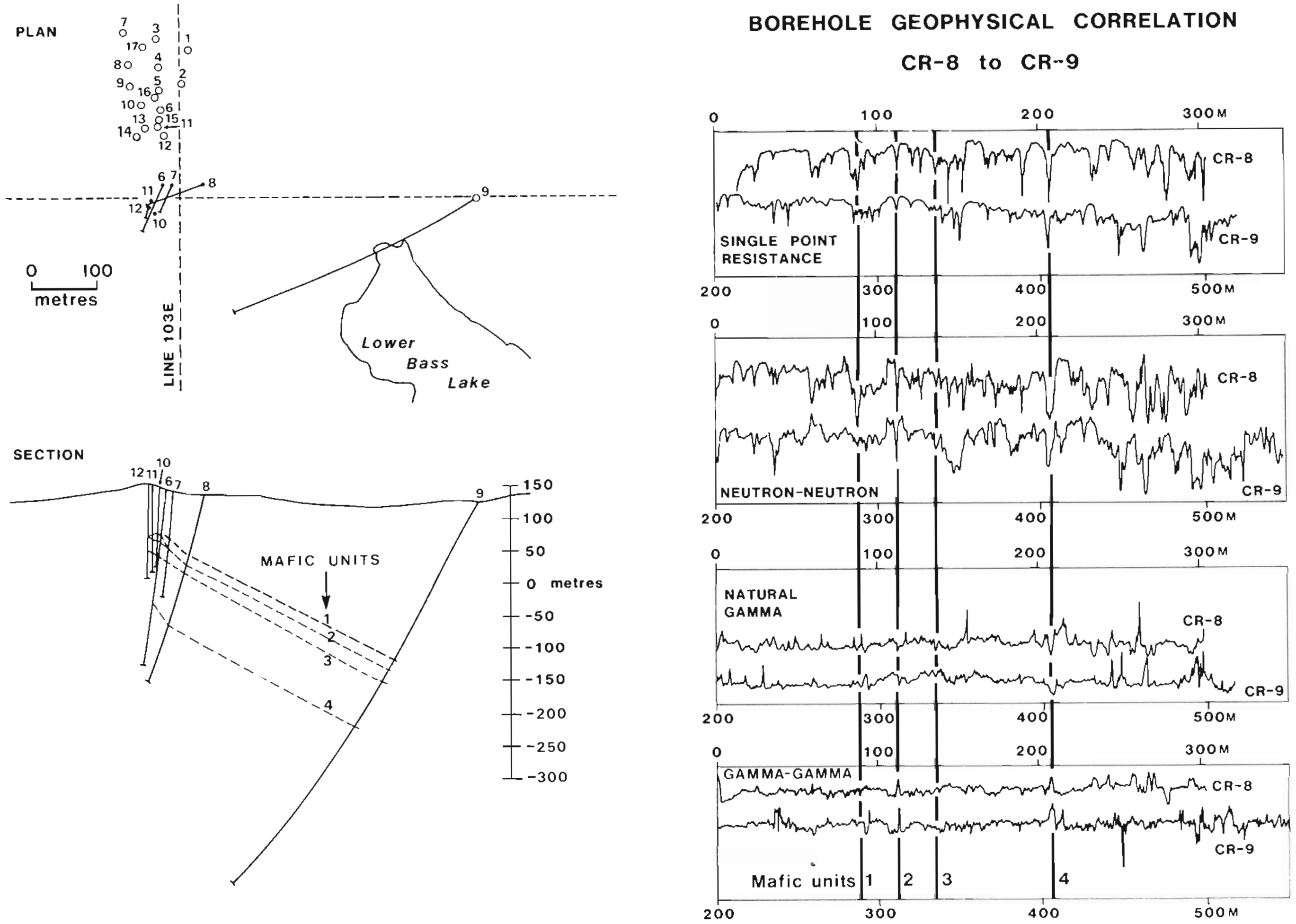

Figure 18. Hole to hole correlations of mafic-rich zones (approximately 1 m wide) based on standard geophysical logs. Logs from holes CR8 and CR9 illustrate the types of signatures that are correlated.

This suggests that, if these faults are near-horizontal, they are tabular with the long axis oriented north-south. Responses at depths of about 50 and 70 m are roughly the same for both NAA and NSS signals, indicating that the long axis of the fracture is oriented northwest-southeast or northeast-southwest, or that the geometry of the fracture plane is essentially equant. For vertical or subvertical fractures, Dyck and Hayles (1981) believed that the VLF-EM method should be able to determine the strike.

The wavelengths of the VLF signals in the resistive Chalk River rocks range from about 500 to 1200 m; consequently, the borehole technique provides a picture of the electrical structure of the rock for some distance away from the borehole. Dyck and Hayles (1981) suggested, therefore, that the width of the signatures can provide some indication of the lateral extent of the causative conductors. For experiments conducted in CR1 and CR8, they suggested that the conductors extend for at least 10 to 20 m from the hole. The success of the method in identifying the locations of fractures has been supported by CR1 and CR8 core logs. Comparison of the core logs with the VLF data shows that the depths of rubble zones and areas of low rock quality correspond to the depths of the VLF-EM signatures. Anomalies in the VLF electric field also coincide with regions of low resistivity and fractures observed or suggested by various geophysical logging techniques (Fig. 19). Because of the large wavelengths it uses, the VLF-EM method has the potential to detect fractures that do not intersect the borehole.

Borehole TV and acoustic televiewer studies

Standard geophysical logs can provide an idea of the location and distribution of fractures within a borehole and possibly a qualitative hint of the size of the fractures. However, there are two borehole logging techniques that provide additional quantitative information regarding the orientation and size of fractures; one is borehole television logging (Lau, 1980), the other borehole acoustic televiewer logging (Lau et al., 1981; 1982).

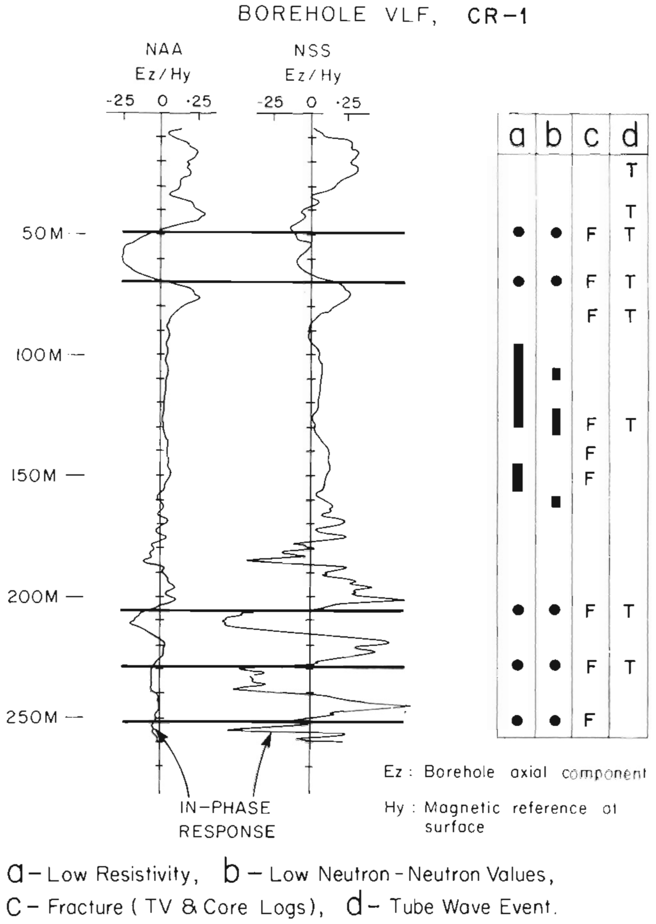

Figure 19. Borehole VLF-EM electric field profiles (differences in the field over a distance of 10 m) for signals transmitted from U.S. Navy transmitters NAA and NSS obtained in CR1. Horizontal bars at crossover positions at depths of 49, 70, 206, 229 and 251 m are interpreted positions of fractures. Interpretation is supported by coincidental locations of (1) low apparent resistivity values logged on both short (16 inch) and long (32 inch) resistivity records, (2) high apparent porosities indicated by neutron-neutron logging, (3) fractures (F) identified by examination of core and TV logs and (4) fractures (T) interpreted from tube-wave investigations.

In the TV logging system a camera probe photographs the entire 360° of the wall of the borehole and records all fractures and veins having an aperture or thickness greater than 0.1 mm. Azimuth measurements are made with respect to a magnetic compass mounted inside the probe. The system has been tested to depths of 500 m and the picture quality has been found to be good, provided there are good optical contrasts and the borehole fluid is transparent. The system is designed to perform to depths of about 600 m. From the images obtained, it is possible to estimate the dip and strike of each fracture/vein. The technique is particularly useful in cases where core orientation methods fail to orient fractures in shear zones and in air-drilled boreholes, where core is not available for investigation (Lau, 1980).

The acoustic televiewer logging system emits pulses of acoustic energy having a frequency of 1.3 MHz at a pulse rate of 1700 Hz and measures the acoustic reflectivity of the borehole wall. Whenever a fracture is encountered, the intensity of the reflection is diminished. As in the case of TV logging, the entire 360° of borehole wall is surveyed. The image is recorded by a Polaroid camera. The resolution of the acoustic logger is not as fine as the TV logger, the minimum width of fracture that can be detected being 1 mm (Lau et al., 1982), compared to 0.1 mm for the TV system. The acoustic televiewer, however, has some advantages over the borehole television in that it can operate in less favourable environments and at greater depths (Geological Survey of Canada TV system and acoustic televiewer system have cables that are approximately 600 m and 1500 m long, respectively (Lau, pers. comm., 1983)). On the other hand, the TV camera takes better and much more detailed pictures especially in shear and highly fractured zones and appears to obtain more accurate measurements of fracture widths and aperture openings (Lau et al., 1981). Results of TV and acoustic televiewer logging at Chalk River demonstrate that subsurface fracture and vein patterns are similar to those mapped at the surface (Lau et al., 1987).

Seismic tube-wave studies

The seismic tube-wave method of investigating fracture distribution in a borehole utilizes a small dynamite charge detonated in a shallow borehole located at distances ranging from 10 to 60 m from the collar of the borehole. The energy generated is recorded on a hydrophone array located within the borehole. This is moved for successive shots to a position that overlaps the previous position until the entire length of the hole has been surveyed (Huang and Hunter, 1983). A tube-wave is generated in the fluid of a borehole when compressional wave energy produced by a surface explosion encounters a fracture zone intersecting the borehole, squeezing it and forcing a pulse of the contained fluid into the borehole. The tube-wave travels up and down the hole (Fig. 20) and its arrival time at the various hydrophones is recorded. Huang and Hunter (1983) estimated that a volume of rock with a radius of 8 to 15 m centred on the borehole was sampled during the conversion of P-wave energy into a tube-wave. The method may thus provide information on fracture permeabilities several metres into the borehole wall. Apparently, the method can detect single isolated open fractures with a width of 0.1 mm or greater: this is the same resolution as the TV logging method. If two or more open fractures are less than 1.5 m apart, their individual tube-waves combine into a broad waveform, which itself is generally a good indication of fracture zones with multiple open cracks.

The method thus provides useful information on fractures that are open to fluid flow at the borehole wall. Correlation between fractures identified on the basis of tube-waves and those based on geological and hydrological studies indicate that some fractures logged by the TV method as closed do in fact have a measure of permeability. It is further noted in some boreholes that the relative amplitudes of tube-waves appear to be correlatable with

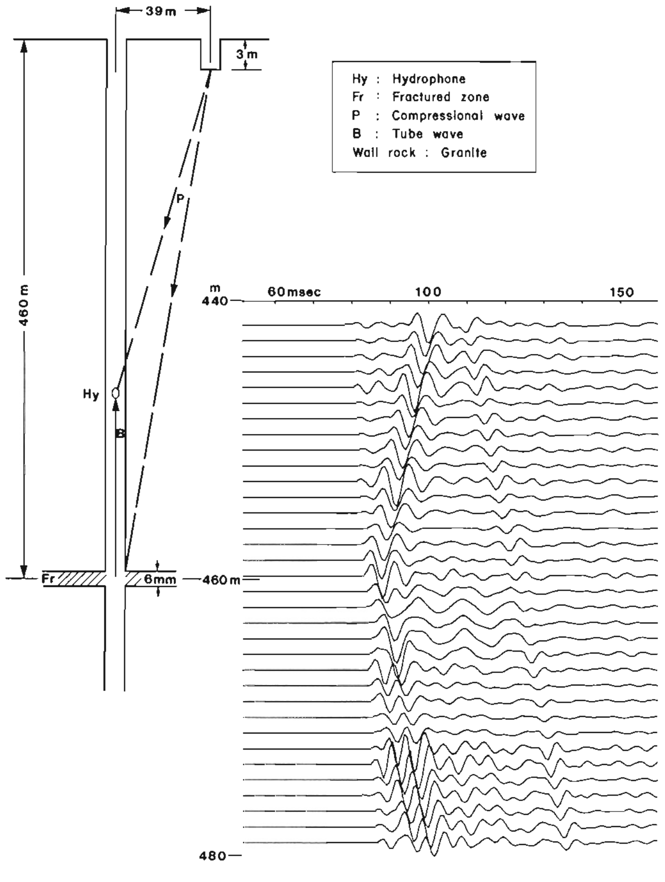

Figure 20. Schematic diagram illustrating generation of tube-wave by impingement of P wave on a fracture intersecting a borehole, and a seismogram with P wave and tube-wave arrivals indicated (after Huang and Hunter, 1983).

measured hydraulic conductivities (expressed as the aperture size of an equivalent single open fracture). Tube-waves have been recorded at depths of up to 1100 m without any noticeable change in the quality of the seismic record; conceivably it should be possible to use the method at even greater depths. Tube-wave investigations in CR1 and CR9 have been reported by Huang and Hunter (1981). It should be noted that tube-waves can be generated in boreholes by conditions other than the presence of fractures (Balch and Lee, 1984), hence a tube-wave response is not necessarily definitive evidence of fracturing.

Well tides

Measurements of the rise and fall of water levels in an open borehole form the basis of studies of well tides, which have been used to determine the strike and dip of fractures intersecting the borehole (Bower, 1983). The method is based on the mechanical response of a single plane fracture to stresses generated by the regular tidal deformation of the solid earth. The theory assumes that changes in tidal stress acting on a plane fracture are supported by the fluid in the fracture rather than by the asperities. As the earth tides squeeze the fracture, the pore pressure of the contained fluid is increased and fluid is squeezed out of the fracture into the borehole. Because tidal stress near the earth's surface is almost entirely horizontal, fractures that are steeply dipping are influenced to a greater extent than those that are gently dipping. Tidal stress consists of two main components having different frequencies and azimuths: the main semidiurnal tide (M_2) produces stresses that are larger in a north-south direction than in an east-west direction, whereas the main diurnal tide (O_1) produces its largest stress in an east-west direction.

From the information on variations in the water level within the borehole, which are related to pore pressure changes, and by calculating the tidal stress from theoretical models, it is possible to determine the orientation (dip and strike) of a single fracture that could produce the observed tidal variations. Bower (1983) found that the amplitude and phase of the well tide in several boreholes could indeed be explained on the basis of a single plane fracture intersecting the borehole. He indicated, however, that independent evidence to support the reality of a single-fracture interpretation is not available, because other geophysical logs indicate that the boreholes intersect many fractures. Even though the aperture and orientation of many of the fractures have been estimated by other techniques, their combined effect cannot be calculated reliably. For this reason the method would be most effective if fluid pressure measurements were made within a sealed off interval of a borehole containing a single fracture. Nevertheless, the method has had some encouraging results; in boreholes CR2 and CR3, which may be dominated by the same fracture zone, the tidal interpretation indicated a fracture strike similar to that indicated by intersection data at the surface and in other boreholes.

When fractures have apertures that are less than 0.2 mm, the method offers the further advantage of obtaining information on the lateral extent of a fracture, but this requires a knowledge of the compressibility of the asperities. If this were accomplished, the possibility exists of estimating fracture permeability out to a distance of a few hundred metres (D.R. Bower, pers. comm., 1984).

Temperature logging

Temperature measurements in boreholes are made at vertical intervals of a few metres to define the geothermal gradient and to delineate thermal anomalies. Water flow is a very effective means of transferring heat and, accordingly, many thermal anomalies detected in boreholes are associated with water flow into, or out of, the borehole or within the borehole between permeable zones after drilling.

The various effects of a fluid-filled fracture on a borehole temperature profile have been described by Drury and Jessop (1982). They categorized fractures according to the manner in which they controlled the movement of fluid before and after drilling. Four main types have been identified and their effect on a borehole temperature profile is illustrated in Figure 21; these are described briefly.

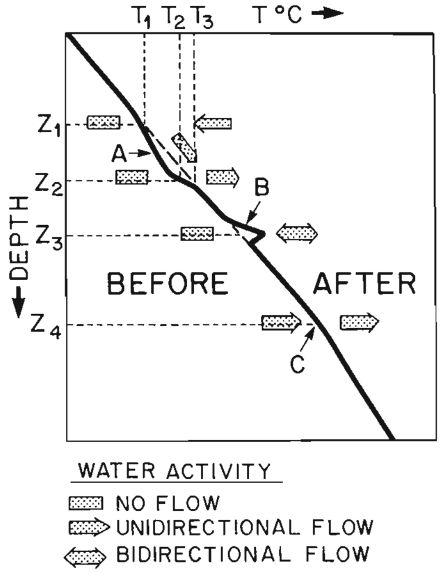

Figure 21. Schematic geothermal log containing three types of thermal anomaly related to water activity associated with fractures at positions Z_1, Z_2, Z_3 and Z_4 below ground level. Water activity before and after drilling is indicated schematically to left and right sides of geothermal log respectively. Anomaly A is generated by water entering the borehole at fracture Z_1 at temperature T_1, flowing down the hole to fracture Z_2, where it exits at temperature T_2, which is lower than the normal temperature T_3 encountered immediately below fracture Z_2. Because water from the Z_1 level is cooler, it has the effect of reducing the temperature between Z_1 and Z_2 (dashed line indicates normal temperature). Anomaly B is related to a fracture Z_3 that was not associated with water flow before or after drilling, but that accepted water during drilling. The entry of drilling fluid at a temperature different to that of the adjacent rock mass produces a transient anomaly. Anomaly C is caused by a fracture Z_4 that transmits water before and after drilling. Such a flow provides a source (or sink) of heat that increases (or reduces) the normal conductive heat flux above the fracture leading to a difference in the geothermal gradient above and below the fracture. In the example shown (Z_4), relatively warm water flowing in the fracture enhances the normal conductive heat flux above the fracture (after Drury and Jessop, 1982).

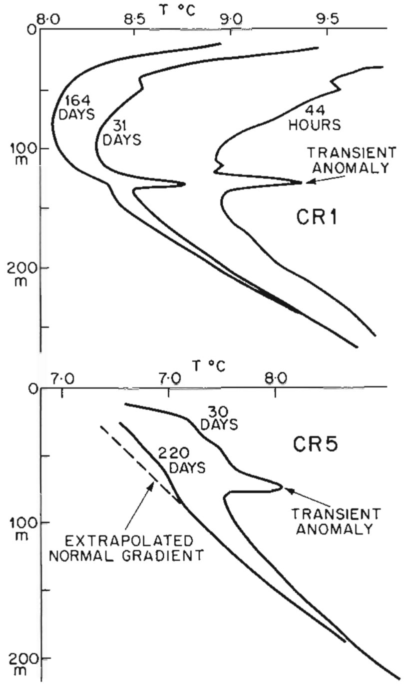

Figure 22. Geothermal logs for boreholes CR1 and CR5 (after Judge, 1979) based on temperature measurements made at intervals of 3 m in CR1 and 8 m in CR5. Transient anomaly in CR1 is attributed to a passive permeable fracture that accepted circulation fluid during drilling. A similar anomaly in CR5 in the log taken 30 days after completion of drilling may have a different origin because the second log contains a significant gradient anomaly with temperatures offset to higher than expected values above the anomaly indicating flow into the borehole of warmer fluid, probably coming from depth.

(1) Fractures that provide water flow to, or accept water flow from, a borehole after drilling, but were not associated with flow before drilling. A change in thermal gradient occurs when such fractures intersect the borehole and in cases where two fractures combine to permit flow along the borehole from one to the other, temperatures between the fractures are offset from those temperatures expected if no flow had developed. (2) Fractures that are not associated with flow before or after drilling, but accept circulation water during drilling. The entry of drilling fluid with a temperature different from that of the adjacent rock formation produces a transient thermal anomaly. (3) Fractures that allow water flow before and after drilling. The flow provides a source (or sink) of heat that enhances (or reduces) the normal conductive heat flux above the fracture and produces a difference in the thermal gradient above and below the fracture (a change in thermal conductivity within the rock can produce a similar effect). (4) Fractures that do not provide a flow path at any time; no thermal anomaly will be associated with these.

Temperature logs can therefore provide insights not only in regard to the positions of fractures within boreholes, but also in regard to the direction of fluid flow that might take place within the fractures and/or within the borehole between fractures. The resolution of the method is dependant on the sampling interval within the borehole. Judge (1979) has discussed the results of geothermal measurements conducted in seven boreholes at Chalk River to maximum depths ranging from 110 to 305 m. Just a few of his results are discussed to illustrate the utility of the method. In CR1 (Fig. 22), Judge (1979) has identified thermal anomalies at depths of 49, 128, 168, 198, 229 and 241 m based on four sets of logs made 44 hours, 31 days, 164 days and 355 days after completion. The anomalous zone at 128 m depth is particularly prominent and its progressive decrease with time suggests that it relates to a Type-2 fracture, i.e., a passive permeable fracture that is not associated with fluid flow either before or after drilling, but which accepts circulation fluid during drilling. In CR5, a pronounced anomaly at a depth of 73 m is

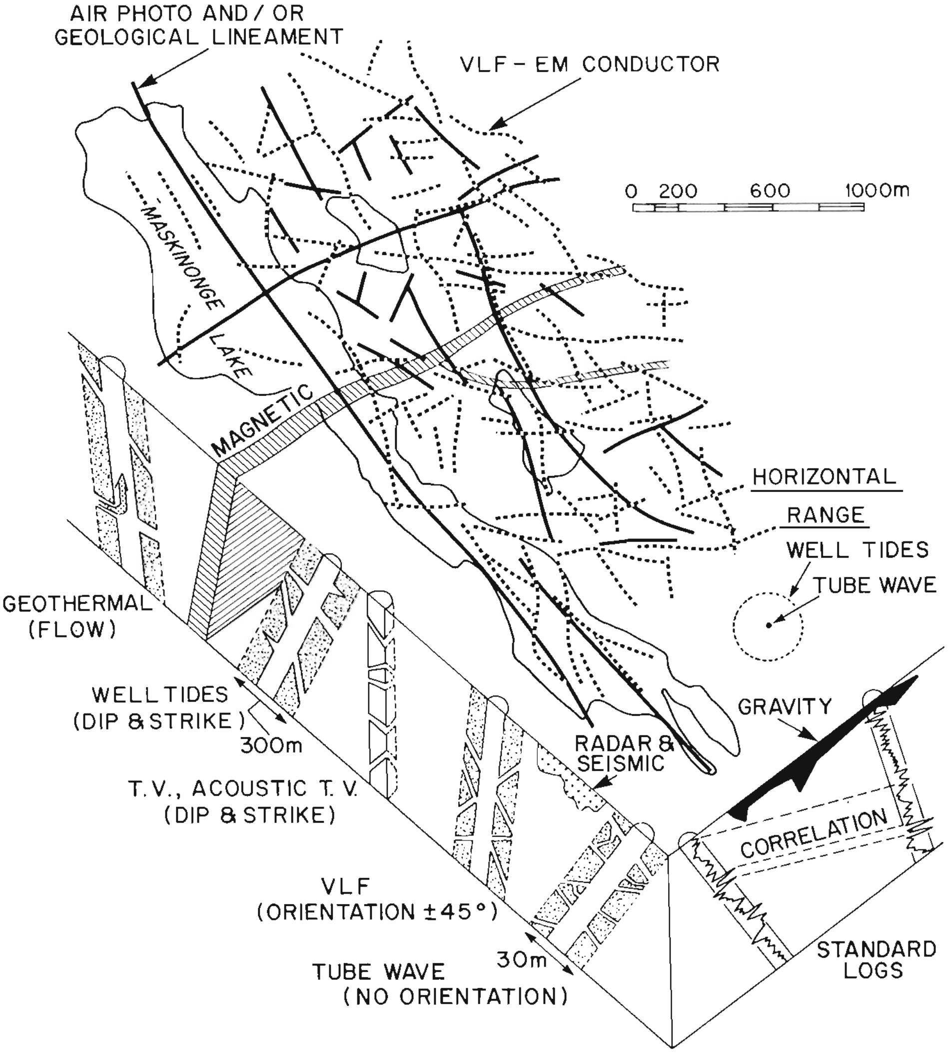

Figure 23. Schematic block diagram of Chalk River research area summarizing the contribution of various geophysical techniques to an understanding of overburden thickness (radar and seismic), crustal structure (gravity, magnetics and standard logs), fractures (tube-waves, standard logs, geothermal logs) and fracture patterns (T.V., acoustic T.V., well tides, surface and borehole VLF-EM). Surface geology has been omitted in the interest of clarity. In order to obtain the illustrated perspective, the lakes, lineaments and VLF-EM conductors have been somewhat distorted, so this diagram should not be regarded as an accurate representation of those features. The circle and dot on the lower right-hand side indicate, at a reasonably representative scale, the horizontal range of the well tides and tube-wave methods, respectively.

probably not an indicator of fracture permeability alone, because the second log (taken 220 days after drilling) indicates a persistent gradient anomaly and temperature offset to higher values above the zone, indicating a probable upward flow. This type of fracture is a Type-1 fracture, where the fracture did not provide a flow path before drilling, but now is a conduit for water into the borehole. In CR6 and CR7, which are just 15 m apart, the holes generally have different temperatures along most of their lengths, but at a depth of 40 m the temperatures are very similar. Judge (1979) believed that because the gradients at depth were very uniform and inversions at 70 to 80 m were well developed, no water flow was present throughout most of the holes: he suggested that the zone at 40 m probably represented an interconnecting fracture between the holes.

Borehole radar

Annan and Davis (1987) have conducted experiments on borehole radar in several holes at Chalk River and their results are encouraging. Because radar is sensitive to variations in water content, its response to water-filled fractures is significant. Radar profiling of boreholes is therefore an effective means of detecting water-filled fractures along the length of a borehole. Annan and Davis also investigated hole to hole transmission in which variations in arrival time of a transmitted radar pulse allows estimation of the propagation velocity between the holes. Variations in this velocity signify changes in lithology and electrical characteristics. At Chalk River it was apparent that structure out to a distance of at least 20 to 30 m from the borehole could be investigated by the radar technique.

CONCLUDING REMARKS

Geophysical studies can make a major contribution to the evaluation and characterization of potential sites for nuclear fuel waste disposal. The results of such studies at the Chalk River site has demonstrated the effectiveness of the discipline in providing valuable information on crustal architecture, overburden and, perhaps most importantly, major controls on water flow through a rock mass. A pictorial summary of the contribution of some of the geophysical methods to the characterization of the Chalk River site is presented as Figure 23.

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