DEPTH TO BEDROCK IN THE SEAL COVE RIVER VALLEY, NEWFOUNDLAND: A GEOPHYSICAL CASE STUDY

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Depth to bedrock was determined over part of the Precambrian Holyrood granite in the Seal Cove River valley, Avalon Peninsula, Newfoundland, using both electromagnetic and refraction hammer seismic methods. These geophysical interpretations, based on an assumed two-layer geometry, were compared with direct probe and drilling records of depth to bedrock. Combined data show that the cover sequence (glacial drift and peat bog) ranges from zero to eight meters in thickness, and overlies subhorizontal glaciated granite. The buried granite surface dips gently northwards, down valley, and includes isolated hummocks and hollows, which are interpreted to be buried roche mountonnee and ice-plucked depressions. Granite resistivity and compressional wave velocity minima coincide, and are thought to indicate areas of dense mesoscopic fracturing in the granite. Seismic depths are within 0.2 m of true depth where thicknesses are less than one meter, and are generally accurate to 10% elsewhere. EM depths are subject to uncertainties of upper layer resistivity values, and problems caused by power line interference, but, by cross-calibration with other methods, are within 0.28 m of true depth in the one meter range, even in saturated peat bog, and within 0.86 m where thicknesses are approximately seven meters.

On a déterminé la profondeur du socle sur une partie du granite précambrien d'Holyrood, dans la vallée de la rivière Seal Cove, grâce aux méthodes électromagnétiques et de sismique réfraction par marteau. On a basé ces interprétations géophysiques sur un modèle à deux couches, puis on les a comparées aux sondages directs et aux données de forage sur la profondeur du socle. Ces données combinées démontrent que le mort-terrain (moraine et tourbière) a une épaisseur de zéro à huit mètres et recouvre un granite légèrement incliné ayant subi l'ablation glaciaire. La surface enfouie du granite plonge faiblement vers le nord, en aval, et comprend des mamelons et des creux isolés que l'on interprète comme étant des roches moutonnées et des ombilics enterrés. La résistivité et les minimums de vitesse d'onde de compression coïncident et indiquent, on le croit, des zones de fracturation mésoscopique dense dans le granite. Là où l'épaisseur est moins d'un mètre, les profondeurs sismiques s'approchent à moins de 0.2 m des vraies profondeurs. Ailleurs, leur exactitude est généralement de 10%. Les profondeurs déterminées par l'électromagnétisme sont sujettes aux incertitudes dans la valeur de la résistivité de la couche supérieure ainsi qu'aux problèmes causés par l'interférence des lignes à haute-tension. Par contre, une interprétation combinée a permis de s'approcher à 0.28 m de la profondeur réelle lorsqu'elle est d'environ un mètre, même dans les tourbières saturées, et à 0.86 m là où l'épaisseur du mort-terrain est d'environ sept mètres.

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INTRODUCTION

Hydrogeological studies of groundwater recharge and discharge, and of contaminant plume migration, require knowledge of overburden thicknesses and buried bedrock topography. These can be determined using surface geophysical techniques (e.g., Arnow and Mattick, 1968; Eaton and Watkins, 1970; Kosinski and Kelly, 1981; Merkel, 1972; Stewart, 1980). Overburden thickness and bedrock topography have been mapped at horizontal scales from tens of meters to kilometers, with varying success. Difficulties arise due mainly to the limitations of any single method (e.g., power line interference of electromagnetic measurements; D.C. resistivity survey costs), and due to effects of complex subsurface geometries and varying material properties (Zohdy *et al.*, 1974). Multiple surveys over the same area can alleviate these single-method limitations under some circumstances. We present here results of depth-to-bedrock surveys utilizing two geophysical methods, electromagnetic resistivity (EM) and refraction hammer seismic (HS), calibrated by direct probing and drill record ground truth data. Data collection and reduction is fast and simple, and thus the surveys are cost-effective, and provide efficient coverage. Our study was undertaken in 1986 in the Seal Cove River valley, Avalon Peninsula, Newfoundland (Fig. 1 inset), as part of broader hydrogeological investigations of groundwater recharge and discharge in fractured granite, currently underway at the Department of Earth Sciences, Memorial University. Our objectives were to 1) determine overburden thicknesses and bedrock topography in the eastern half of the valley, and 2) to evaluate the utility of geophysical methods in providing information about the bedrock.

The Seal Cove River valley is underlain by Precambrian granitic rocks of the Holyrood Plutonic Series (King, 1982), which were glaciated by northerly-moving Wisconsinan glacial ice (Henderson, 1972). It is typical of the north-trending, broad, flat valleys produced by this glaciation with the valley floor covered with unstratified, poorly sorted glacial drift, talus along the valley margins and peat bog adjacent to the Seal Cove River (Fig. 1). Glacial drift grain sizes range from silt to boulders. Glacial boulders up to one meter in diameter occur sporadically in the peat. Fig. 1 shows the Seal Cove River valley topography, survey station locations, peat bog distribution and bedrock outcrop boundaries.

Electromagnetic and refraction surveys were carried out over the eastern part of the Valley (an area roughly 700 m x 1500 m), with stations at 50-100 m intervals. In the boggy, northern area (see

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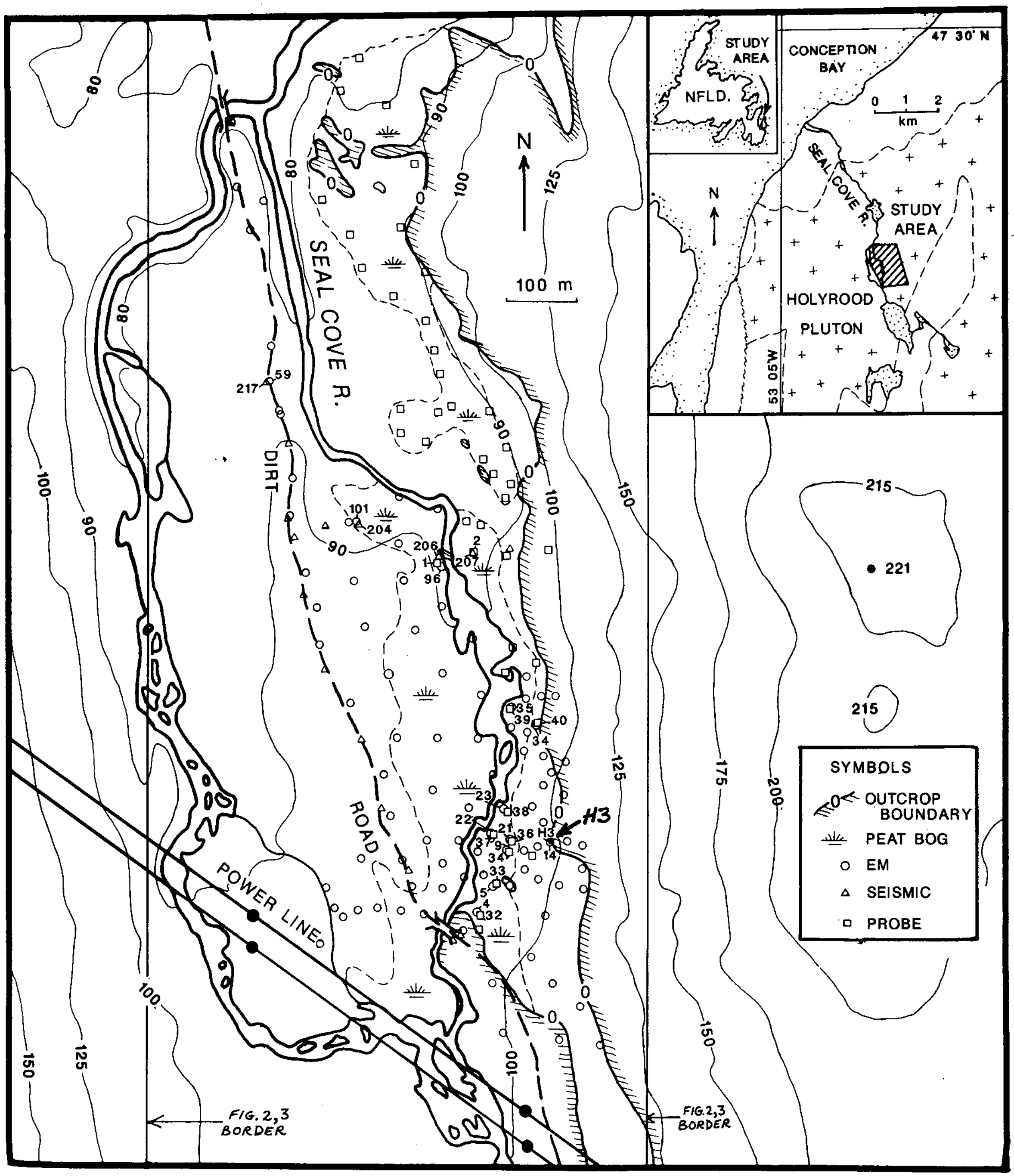


Fig. 1. The Seal Cove River valley showing topography, survey locations, bog areas and outcrop boundaries ("0" contour line); the vertical lines within the map show the borders for Figs. 2 and 3; the insets show location and geological setting of the study area; all contours in meters; north is true north for this and all other Figures.

Fig. 1), and for many of the southern EM stations, direct probe depths were determined and used as ground truth to calibrate EM depth measurements. Two seismic stations (206 and 207, Fig. 1) were also probed directly. Because the interpretation of the electromagnetic measurements requires the most assumptions for determining depth, we adopted a hierarchy of depth reliability when combining data: direct probing as true depth, refraction seismic depths as next most reliable, and EM depths as least reliable.

REFRACTION HAMMER SEISMIC SURVEY

A Huntec FS-3 seismograph was used in the refraction survey, with a 9 kg sledge hammer and 30 cm x 30 cm x 2.5 cm steel striking plate as acoustic source. Refraction lines were measured in one direction, and were aligned parallel to topographic contours to eliminate elevation corrections when reducing data. Reverse profiles were not done as the exposed glaciated granite surfaces on the valley floor were flat at the scale of the refraction lines. Seventeen seismic profiles were measured, at approximately 100 m intervals, along two traverses: one N-S along the dirt road, the other E-W across the middle of the valley (Fig. 1). A low velocity layer, interpreted to overlie a higher velocity layer in the area, was correlated with the overburden. The higher velocity layer was correlated with the underlying granite bedrock. Depths were calculated using crossover distances, x_c (Dobrin, 1976):

$$[1] \quad z = (x_c/2)\ \{(V1-V0)/(V1+V0)\}^{1/2}$$

where: z = lower velocity layer thickness [m]; x_c = crossover distance from the time-distance curve [m]; V0 = lower velocity [m/s]; V1 = higher velocity [m/s].

Data from all seismic profiles, except 211 and 214, are interpreted as showing two seismic layers with two distinct velocities, and a clearly defined crossover distance. Stations 211 and 214 show three velocity segments on time-distance curves, and are interpreted as three-layer cases which are correlated with peat, gravel and granite layers.

Seismic low velocity layer thicknesses are contoured in Fig. 2a. Low velocity values range from 250 to 750 m/s in wet bog, and from 712 to 1150 m/s in gravelly drift-covered areas. These are appropriate values for peat and glacial till (Clark, 1966). It is notable that interpretable time-distance data were produced in completely saturated, "soupy" peat bog less than one meter thick.

Velocities in the lowest layer, interpreted to be granite, range from 1046 to 5454 m/s. Granite commonly has compressional wave velocities ranging from 4780 to 5880 m/s (Clark, 1966), suggesting that in areas with velocities lower than about 4000 m/s, the granite is weathered or highly fractured, or both. Exposed glaciated granite outcrops show no weathering rind, but do show variable fracture densities, from dense crushed zones adjacent to faults to wide-spaced (> 1 m) orthogonal joint sets. This leads us to interpret low velocity bedrock zones as areas of dense fracturing or shear zones.

ELECTROMAGNETIC SURVEY

A Geonics EM16R earth resistivity meter was used to measure apparent resistivity, ρ_a, and phase angle difference, ϕ, between magnetic and electrical fields from the 24 KHz VLF EM transmitter at Cutler, Maine, U.S.A. A total of 101 EM stations were located - in the southern half of the valley, distributed at approximately 50 m intervals, and along the dirt road in the northern half (Fig. 1). Most of the hillslope to the east is granite outcrop, or outcrop with less than 0.5 m of overburden, hence no EM stations were placed there because overburden depths are essentially zero. Electrode spacing with this method is 10 m.

EM readings were strongly perturbed by electromagnetic fields within 150 m of the power lines in the southern part of the study area. Depths from EM stations in that area were not used.

A two-layer EM inversion algorithm for a programmable TI-59 calculator (Frignet, 1981) was used to calculate the thickness of the upper layer, z, and the resistivity, ρ_2, of the underlying material. This algorithm assumes that ρ_1, resistivity of the upper layer, is known. In this study ρ_1 was unknown and was found to vary for different types of overburden. Therefore, for each overburden type, ρ_1 was estimated by iteratively varying its value in the algorithm until a depth was calculated which was consistent with the depth

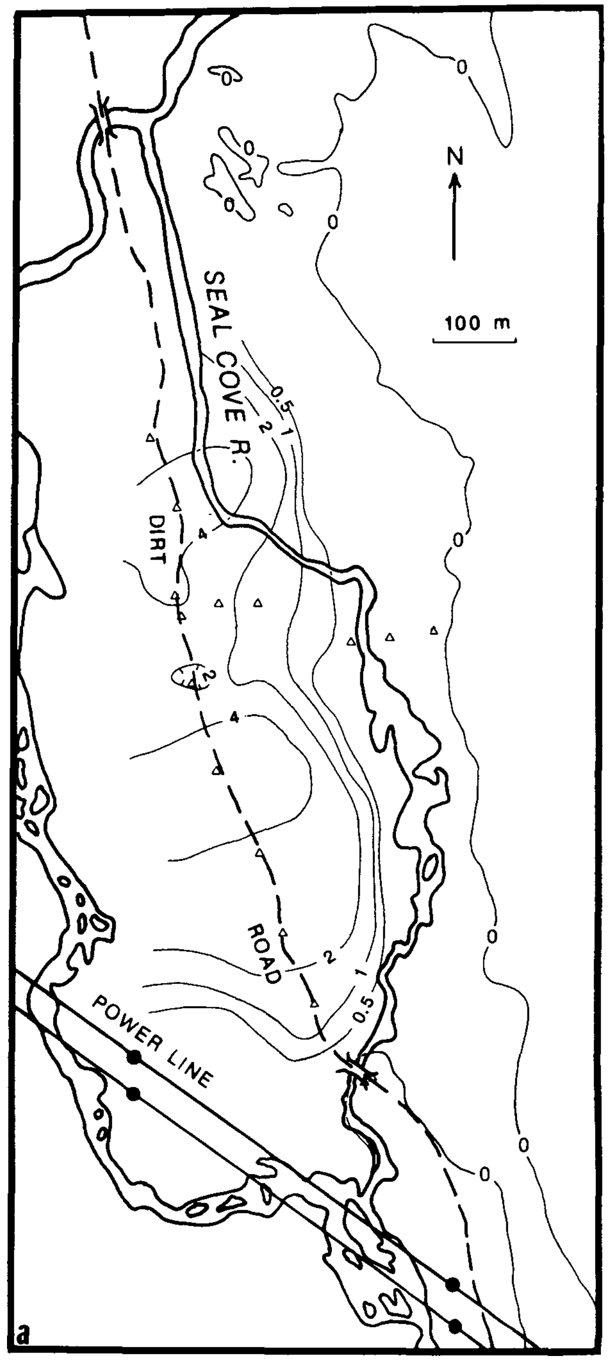


Fig. 2. a) contoured overburden thicknesses interpreted from refraction hammer seismic profiles; b) contoured overburden thicknesses interpreted from EM surveys; c) contoured granite resistivities, ρ_2. Coincident areas of low seismic velocity for the granite layer (V1 4000 m/s) indicated by solid ▲ inside 4000 m contour; d) contoured overburden thicknesses from direct probe survey; NOTE: all contours in meters; contour intervals are variable.

found at the same location by probing or refraction methods. Table 1 shows that ρ_2 is relatively insensitive to variations in ρ_1. Thus ρ_1 was interpreted to represent the overburden resistivity, z the overburden thickness, and ρ_2 variations to represent variations in the granite resistivity. It is recognized that the depth is very sensitive to ρ_1, but our technique of determining ρ_1 by cross calibration against the probe or seismic results minimizes such sensitivity. Values of ρ_1 used for typical overburden types at the EM stations are (in ohm-meters): wet mud - 25; saturated peat - 50; wet bouldery peat - 100; dry gravelly peat 600.

Table 1. Comparison of ρ_1 and ρ_2 variations for EM station 82 for which "true" depth = 0.76 m

ρ_1 (Ω-m)	ρ_2 (Ω-m)	depth (m)
10000	86566	127.4
5000	57346	48.4
1000	48418	7.90
500	47663	3.68
100	47099	0.76

Interpreted EM depths are contoured in Fig. 2b. The "0" contour, defined by ground observation, is the granite outcrop perimeter.

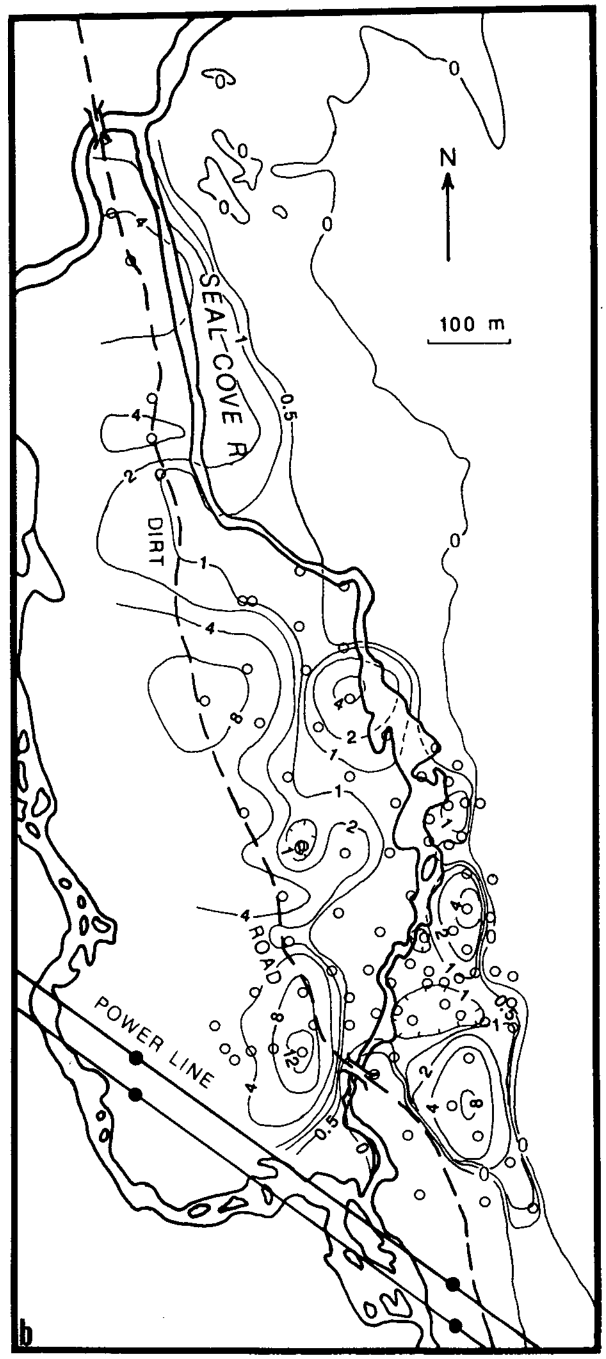
According to the results of the electromagnetic survey interpretation, overburden thicknesses are four meters or less at the foot of the hillslope, thinning to one meter or less in boggy areas, then thickening up to 12 meters in gravelly drift-covered areas in mid-valley. The depth contours in Fig. 2b are relative to the ground surface at the station, so they do not depict buried bedrock topography, but constitute an isopach map. The same applies to depth contours in Fig. 2a.

At drillsite H3 (see Fig. 1), the overburden thickness is 7.01 m and the EM depth is 6.15 m, assuming 600 ohm-meters as the resistivity of the peaty gravel there. These depths are in reasonable agreement considering that the ground surface is uneven and sloping so that the EM probes were at different elevations. In addition the buried granite surface there is probably irregular as inferred from nearby rugged outcrops. Electromagnetic depth interpretations are reasonable providing a two-layer geometry is assumed, and ρ_1 is less than ρ_2. At some boggy stations, direct probing revealed 0.2 - 0.3 m of gravel directly overlying granite bedrock, indicating a probable three-layer case. The calculated thicknesses may still be considered to give depth to bedrock, as suggested by large ρ_2 values. ρ_1 is correlated with the combined resistivity of the peat and gravel cover sequence.

Fig. 2c shows an irregular ρ_2 pattern in the southern area, with values ranging between 10000 and 35000 ohm-meters. These agree with resistivities for Precambrian granite (Clark, 1966). To the northwest, ρ_2 values define an area of low values, less than 4000 ohm-meters, which coincides with low granite seismic velocity.

DIRECT PROBE SURVEY

Direct probing was conducted at 32 stations at approximately 50 m spacing in the boggy northern area of the Seal Cove River valley, and at ten EM and two seismic stations to the south. Probing was carried out with a graduated steel pipe, 1.4 m long which was pushed or hammered into the ground. Maximum measurable depths in the survey were 1.35 m. At each station four depths were measured at approximately one meter spacing, to eliminate the effect of shallow boulders in the peat giving a



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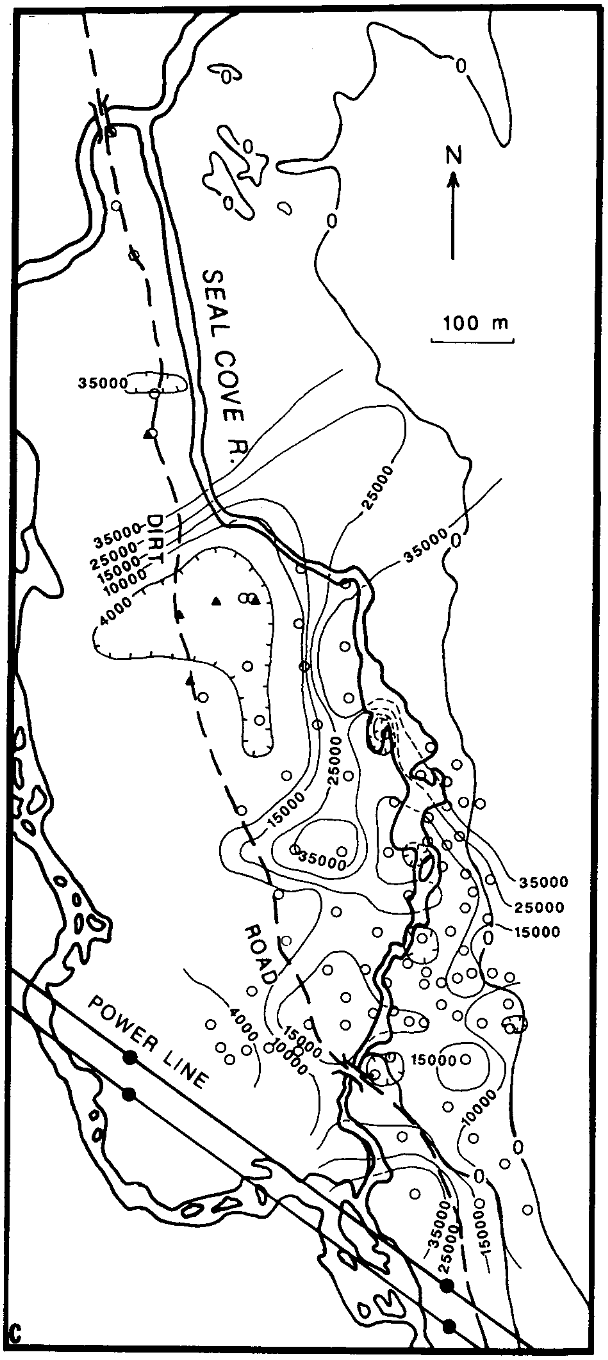

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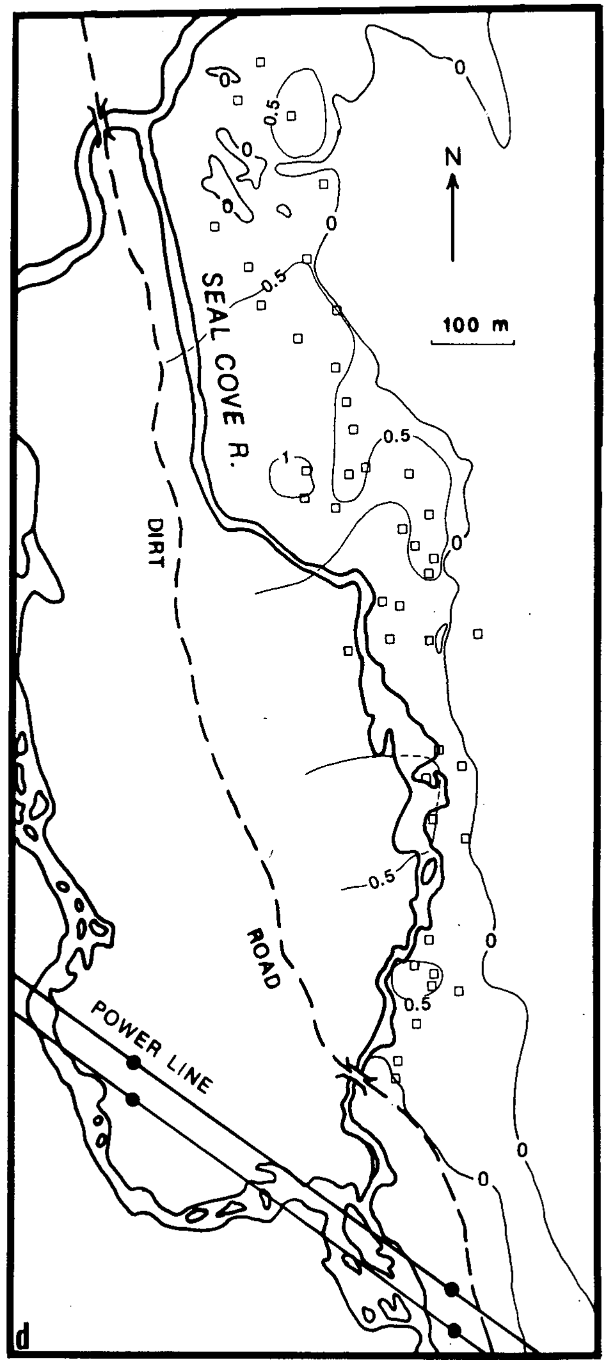

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falsely shallow depth. The average of four similar probe depths at each station was used as the representative depth at that location. The minimum and maximum variation between probings at any station were 0.02 m and 0.46 m, respectively.

Fig. 2d shows contoured probe depths. Boggy areas are all approximately 0.5 thick, and with the exception of a few cases where the probe penetrated 0.2 - 0.3 m of sandy gravel, the peat directly overlies the granite bedrock.

COMPARISON OF RESULTS OF THE REFRACTION SEISMIC, ELECTROMAGNETIC AND PROBE SURVEYS

Contoured overburden thicknesses interpreted from all three methods are combined and shown in Fig. 3a. This indicates that the overburden is less than two meters thick over most of the Seal Cove River valley, and exceeds four meters only in localized areas along the road and against the hillslope. These thickness trends may be interpreted as follows: 1) the overburden at the foot of the hillslope represents a wedge-shaped talus pile; 2) the bog only thinly covers the bedrock and exists due to the presence of subhorizontal glaciated granite beneath the valley floor; and 3) thicker overburden in mid-valley represents a glacial drift pile, either deposited or eroded into a north-trending elongate ridge.

Fig. 3b shows granite topography as contoured bedrock elevations above sea level, obtained by subtracting overburden thicknesses from ground surface elevations at the survey stations. The hierarchy of depth reliability was invoked to obtain a combined dataset for Fig. 3b; i.e., in some cases, probe or refraction depths were used in place of EM depths. Fig. 3b shows that the buried granite surface slopes gently northwards (down valley) and contains isolated depressions and small hummocks. This surface is interpreted to be a continuation of the flat glaciated granite surface seen at outcrops on the valley floor, with buried ice-plucked hollows and roche moutonnee.

Fig. 2b shows areas of low seismic velocity coin-

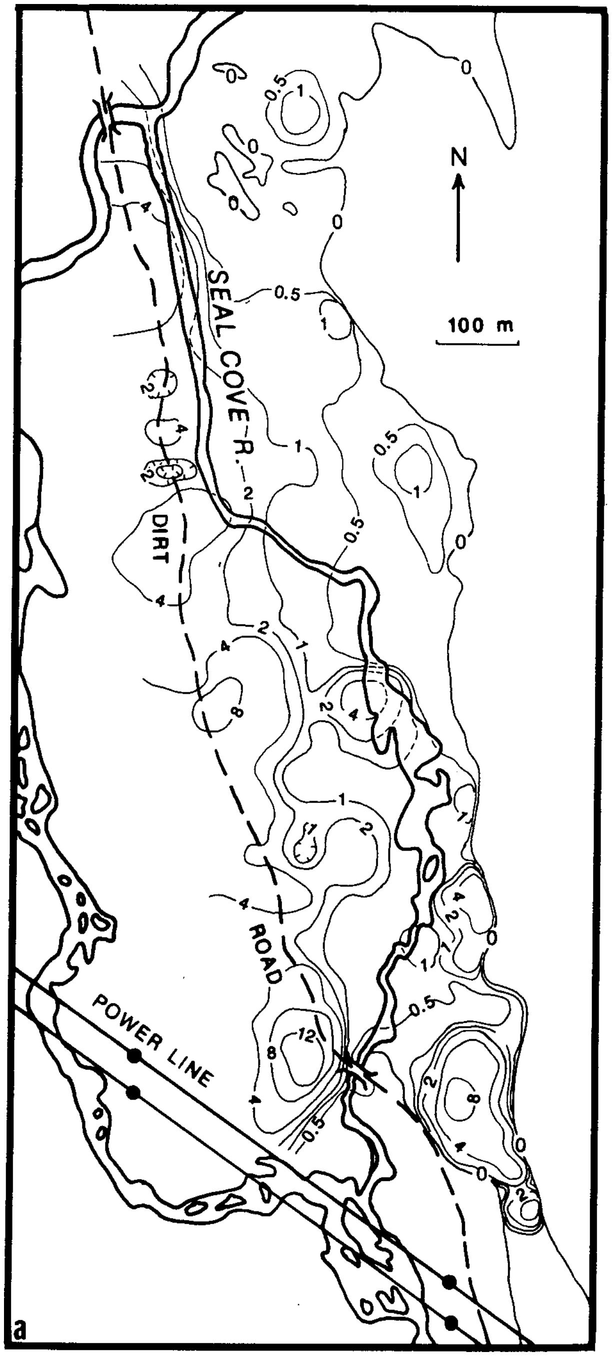

Fig. 3. a) contoured overburden thicknesses from combined data; b) contoured buried granite surface as elevations above sea level in meters. NOTE: all contours in meters; contour intervals are variable.

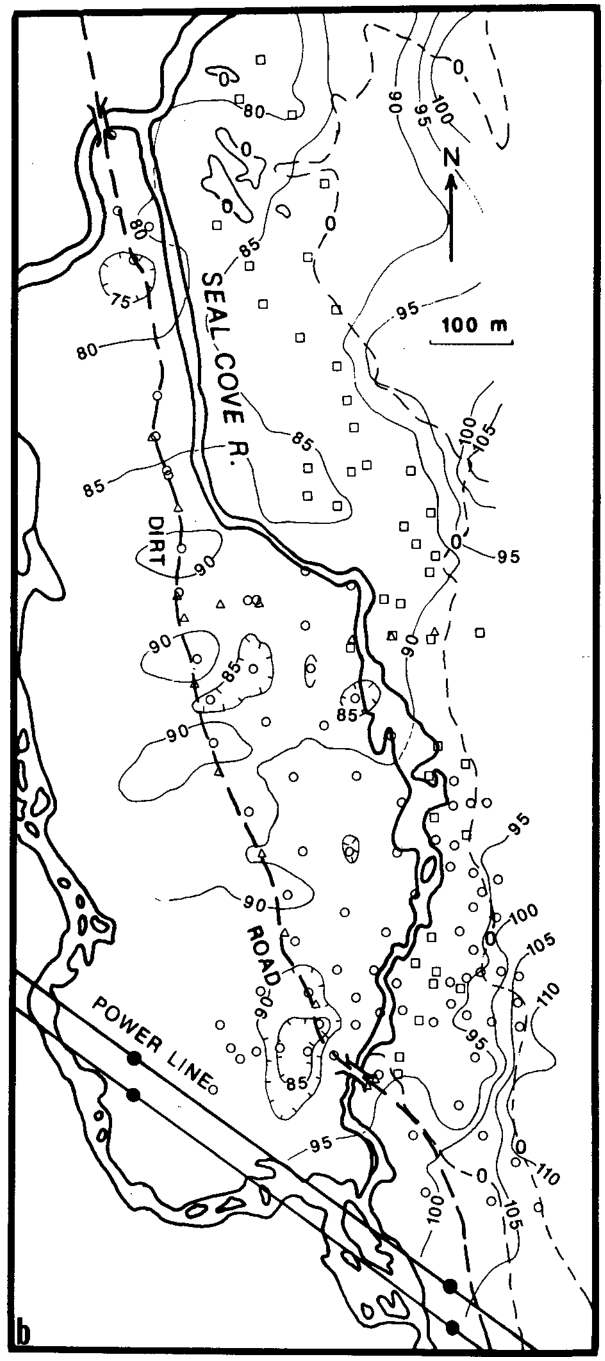

Fig. 3 Continued

cident with areas of low resistivity which are interpreted as either due to fracturing or lithology change. From geological mapping by the principal author, the Seal Cove River valley is known to be entirely underlain by granite and mineralogically similar dike rocks, with no strongly mineralized zones (e.g., conductive sulfides). This suggests that a change in rock type is an unlikely explanation for the geophysical lows. A more probable interpretation is that the combined geophysical minima overlie densely fractured granite bedrock. The more densely fractured areas would result in increased porosity, increased electrical conductivity (assuming saturation with groundwater), and reduced ability to propagate compressional waves. Linear geophysical trends, as may be expected along fault or shear zones (Thomas and Dixon, in press; AECL, 1980), have not been detected in the survey area.

Fig. 4 summarizes comparative results of depth to granite in the Seal Cove River valley. Reference depths for each station are the probe or drill record depths, and are plotted with their numerical values on the horizontal axis. Ranges of values, both for the reference depths and the geophysical depths, are plotted at the stippled bars. For example, the station with DP1, EM96 and HS206 in common, has an average probe depth of 0.29 m, a refraction seismic depth of 0.48 m and an estimated EM depth of 0.38 m. The three stations on the right are plotted with a coarser vertical scale to accommodate larger ranges of values. The error bars around EM and seismic depths are +/-10% and +/-5%, respectively, based on error analyses of the EM inversion algorithm and seismic depth determination procedure.

Four EM depths (stations EM96, 9, 22, and 14) have error bars which overlap the error bars of the reference depth, and therefore are not measurably different from true depth to bedrock. Other EM depths plot either above or below their respective reference depths, but, except for EM59, do not differ by more than 0.28 m from true depth. The EM59 depths (6.52 m) is 4.0 m greater than the HS217 depth (2.52 m) which was measured at the same location. Both EM59 and EM14 are located in bouldery gravel, with an assumed ρ_1 of 600 ohm-meters. However, EM14 error bars overlap the estimated depth range for H3, suggesting that the 600 ohm-meter value is reasonable. A possible explanation for the large deviation at Em59 is the presence of a multi-layered cover sequence.

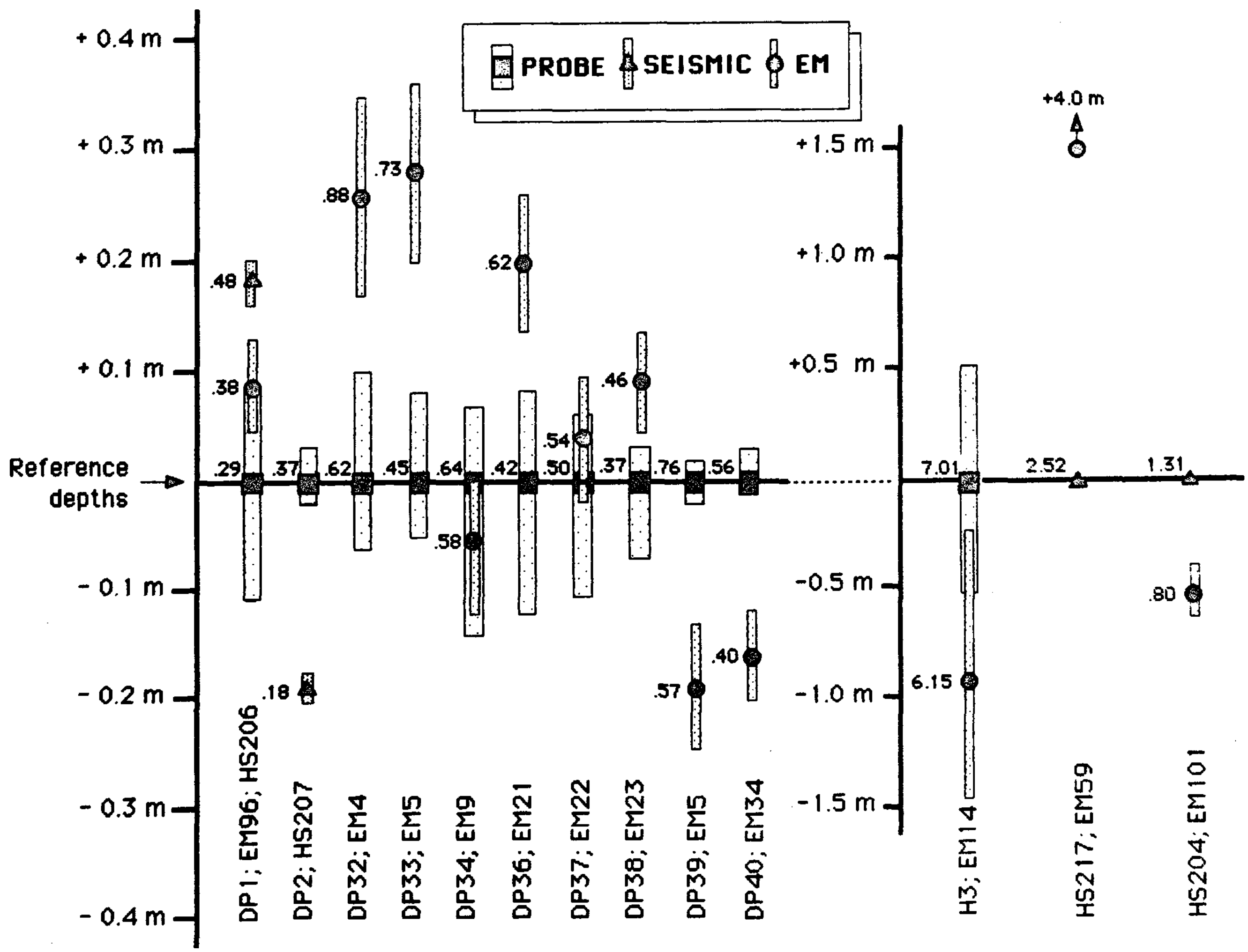

Fig. 4. Comparative results of depth to bedrock for ground truth and geophysical methods (see text for discussion).

Seismic stations which were also probed (HS 206, 207) deviate from the probe reference depths by less than 0.2 m.

SUMMARY

Unique interpretations are not provided by electromagnetic or refraction hammer seismic methods alone. An interpretation of the geophysical results combined with ground truth calibration provides an improved method for determining overburden thicknesses and for inferring bedrock characteristics. Combined geophysical and geological data in the Seal Cove River valley show that the buried granite surface dips gently northwards and that up to eight meters of overburden are present.

Low-velocity and low-resistivity areas in granite bedrock are approximately coincident and are interpreted to represent the effects of dense mesoscopic fracturing in the granite.

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