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Abstract: A preliminary near-surface seismic-reflection study was carried out in a 10 km by 18 km area near Alfred, Ontario, to determine depth to bedrock and the potential for this technique to delineate stratigraphy within unconsolidated overburden. The work was part of a study examining unstable Champlain Sea sediments in the St. Lawrence valley. The surficial sediments of the area include zones of surface disturbance that have been postulated to be the result of earthquake shaking, and are possibly linked to the shape of the buried bedrock surface. Forty seismic-reflection test sites outlined a deep, bowl-shaped, bedrock basin beneath the zone of disturbed surface sediments. The circular basin is approximate 8 km in diameter with a maximum sediment thickness of 175 m. Seismic-reflection quality was excellent with dominant reflection frequencies in the 300 Hz range; intraoverburden reflectors were identified at most test sites which indicate potential resolution of near-surface structure.

Résumé : Pour déterminer la profondeur jusqu'au substratum rocheux, on a réalisé une étude provisoire de sismique-réflexion proche de la surface dans une zone de 10 km sur 18 km près d'Alfred (Ontario). Ce faisant, on voulait évaluer le potentiel de cette technique pour la délimitation de la stratigraphie de la couverture de dépôts meubles. Ces travaux faisaient partie d'une étude visant à analyser les sédiments instables de la Mer de Champlain dans la vallée du Saint-Laurent. Les sédiments superficiels de cette région incluent des zones où les sédiments superficiels ont été perturbés par un hypothétique séisme; la forme de la surface du substratum rocheux enfoui a pu jouer un rôle. Grâce à 40 sites de sismique-réflexion, on a tracé le contour d'un bassin profond en forme de cuvette sous la zone de sédiments superficiels perturbés. Le bassin circulaire a un diamètre de 8 km environ et l'épaisseur maximale des sédiments est de 175 m. La sismique-réflexion a donné des résultats d'excellente qualité, les fréquences dominantes se situant autour de 300 Hz; des réflecteurs étaient présents à l'intérieur de la couverture de dépôts meubles à la plupart des sites d'essai, ce qui laisse entrevoir la possibilité d'établir la structure des sédiments près de la surface.

INTRODUCTION

North of Alfred, Ontario, a unique area (46.3 km^2) of very disturbed terrain lies within the generally flat erosional plain adjacent to the Ottawa River (*see* Fig. 1). The ground surface in this disturbed area is gently hummocky with small shallow ponds or wet areas lying in the low areas. Local relief is of the order of 3–8 m. The disturbed area was initially identified as a landslide based on disturbed sediment found in a borehole (Crawford, 1961) and was mapped as landslide by Richard (1984). Although the irregular surface is similar in appearance to the surface of massive earthflows, the general slope across the area is almost flat and there is no landslide headscarp. Elevation of the tops of the hummocks are relatively uniform and coincide with the surrounding level plains, and the boundaries between the disturbed and undisturbed areas are gradational.

Recently, Aylsworth and co-workers (J.M. Aylsworth, D.E. Lawrence, J. Guertin, unpub. manuscript, 2000) have postulated that this disruption is the result of liquefaction, differential settling, and lateral spreading in response to earthquake shaking of sensitive marine sediments. It is known that anomalous ground-surface motions can be created by earthquakes in soft soils. Variations in unconsolidated overburden thicknesses and the shape of the buried bedrock surface can result in amplification, site period resonances, and focusing effects of ground motion (Shearer and Orcutt, 1987; Abbiss, 1989; Rial, 1989; Lomnitz, 1990; Rial et al., 1992; Frankel and Vidale, 1992; Fischer et al., 1995; Zhang and Papageorgiou, 1996; Jongmans et al., 1998). These near-surface large seismic strains in soft soils can trigger liquefaction, deformation, and failure phenomena (Degg, 1987; Lomnitz, 1994; Beresnev et al., 1995; Obermeier, 1996; Lomnitz et al., 1999; Yang et al., 2000).

Surface sediment in the area bounded by the communities of Lefaivre, Point Filion, and Alfred consists of marine clayey silts with scattered sand patches. Because of a paucity of water-well information, the thickness of unconsolidated sediments was unknown; however, the record of an isolated water well, which ended before bedrock was reached, suggested that a bedrock depression may exist under the disturbed area (Gwyn and Thibault, 1973). Outcrops of Precambrian bedrock lie to the north and west and Paleozoic limestone and sandstone outcrops to the south and east of the area (Fig. 1; Williams et al., 1985). Much of the disturbed area itself is underlain by Precambrian bedrock.

In order to study the area in more detail, a reconnaissance shallow seismic-reflection survey was initiated in 1999 to determine depth to bedrock at a number of locations throughout the area of interest and to determine the potential of the technique for delineation of stratigraphy within the overburden.

SHALLOW SEISMIC-REFLECTION DATA ACQUISITION AND PROCESSING

Shallow seismic-reflection methods are used to obtain information on subsurface structure. Signals generated by a small acoustic source are transmitted into the ground, reflected at subsurface boundaries where there is a change in acoustic

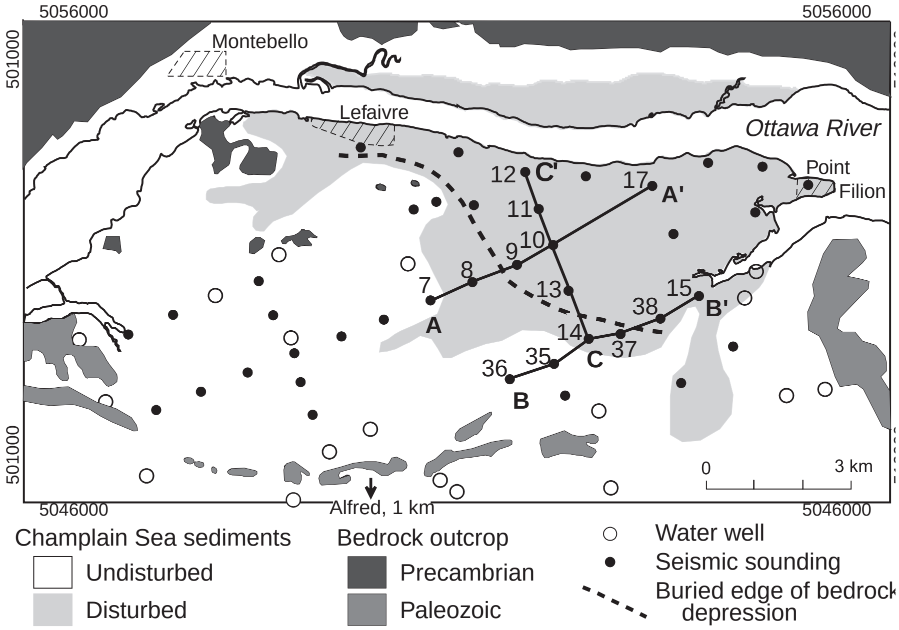

***Figure 1**. Survey area near Alfred, Ontario, showing the locations of 40 seismic sites, borehole data, the mapped "disturbed" ground and bedrock outcrops. Annotated sites and lines are related to Figure 4.*

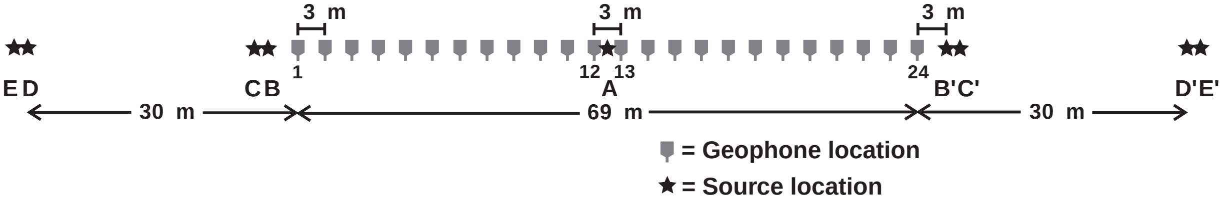

Figure 2. *Diagram of geophone array deployment and shot locations used for the acquisition of test site data. The geophone spread consists of 24 receivers spaced 3 m apart. Data were recorded for shots located in the centre of the geophone spread (A), and at 3 m, 4.5 m, 30 m, and 30.5 m off each end of the array (B-E and B′-E′).*

impedance (the product of material density and seismic velocity), and recorded as a function of time by a series of receivers (geophones) on the ground surface. Contrasts in acoustic impedance are generally associated with lithological boundaries, such as the overburden-bedrock interface, so shallow seismic-reflection techniques provide an effective means of mapping bedrock topography.

Seismic-reflection data were acquired using an array of 24 geophones (Mark Products 50 Hz in marsh cases) at 3 m spacings. Wherever possible, the array was deployed in the bottom of ditches, alongside roads in order to improve the high-frequency response resulting from coupling to water-saturated sediments. The source was an in-hole “Buffalo gun” (Pullan and MacAulay, 1987), that fires a 12-gauge blank charge into the ground from 1 m below surface in a narrow-diameter, drilled hole (water tamping preferred). Using an engineering seismograph, records were obtained for shots fired at the midpoint of the array, and at 3 m, 4.5 m, 30 m, and 31.5 m off each end of the array (Fig. 2). At some sites, additional offset shots were positioned at 60 m and 61.5 m where warranted by extreme depths to bedrock. Forty sites (Fig. 1) were surveyed in this manner. Their locations were selected to provide areal coverage where water-well information was lacking.

A suite of records obtained with this source-receiver geometry can be utilized to produce a low-fold, common-midpoint (CMP) seismic section over a limited subsurface area (Fig. 3). Shallow intraoverburden reflectors and the overburden-bedrock interface can be imaged to depths of 200 m or more, and provide a reconnaissance assessment of the subsurface. The sections in two-way traveltime can be converted to approximate depths (Fig. 3c, d) using the stacking velocities determined from an analysis of the multichannel seismic records. Should the bedrock surface be at shallow depths (0–20 m), these data can be interpreted using standard refraction techniques to provide an estimate of bedrock depth.

RESULTS

At most test sites, the energy of the observed reflections is broad-band, with centre frequencies in the range of 300+ Hz (e.g. Fig. 3), as is typical of the excellent reflection seismic surveying conditions that exist in the Ottawa–St. Lawrence river valleys where surface sediments consist of Champlain Sea sediments. Exceptions occur whenever the seismic array was laid over thick organic beds, since the presence of a small quantity of methane gas in the sediment pore space can result in severe attenuation of high-frequency signals. With such high-frequency content at most sites, processed seismic sections have vertical layer resolutions at shallow depths in the 1–2 m thickness range.

In areas where Quaternary sediments overlie Precambrian or Paleozoic rock, the bedrock surface is generally the deepest reflector in the sequence (e.g. BR in Fig. 3c) since, at the high frequencies used and with the large acoustic impedance contrast at the overburden-bedrock interface, very little energy is transmitted deeper than this boundary. In our experience, significant transmission of high-frequency energy into the bedrock sequence usually occurs only when the acoustic impedance contrasts are lower, such as in the case of consolidated diamicton resting on young semilithified bedrock.

Figure 4 shows west-east and south-north composite sections of the processed test site data; the locations of sections A-C are shown in Figure 1. All sections indicate that there is a large change in depth to bedrock from approximately 20 m to more than 160 m below ground surface (the average surface elevation is +53 m a.s.l.). On all three sections there are abrupt changes in bedrock elevation over short lateral intervals (e.g. between sites 8 and 9, 37 and 38, and 13 and 14) defining the western edge of the bedrock depression as shown in Figure 1.

The seismic data acquired at most sites show at least some reflections above the interpreted bedrock surface (intraoverburden reflections). In many cases these reflections are flat lying and much smaller in amplitude than the bedrock reflection (e.g. Fig. 4; sites 8, 14, 15, 35, and 37). Previous high-resolution, reflection seismic experience in other areas of the Ottawa valley suggests that these reflection events are associated with minor changes in grain size (silt-sand interfaces) within the Champlain Sea sediments (Roberts et al., 1992; Douma and Nixon, 1993). The data acquired in the Alfred area indicates that these sediments may reach thicknesses of more than 100 m at some sites (e.g. Fig. 4, sites 15 and 38).

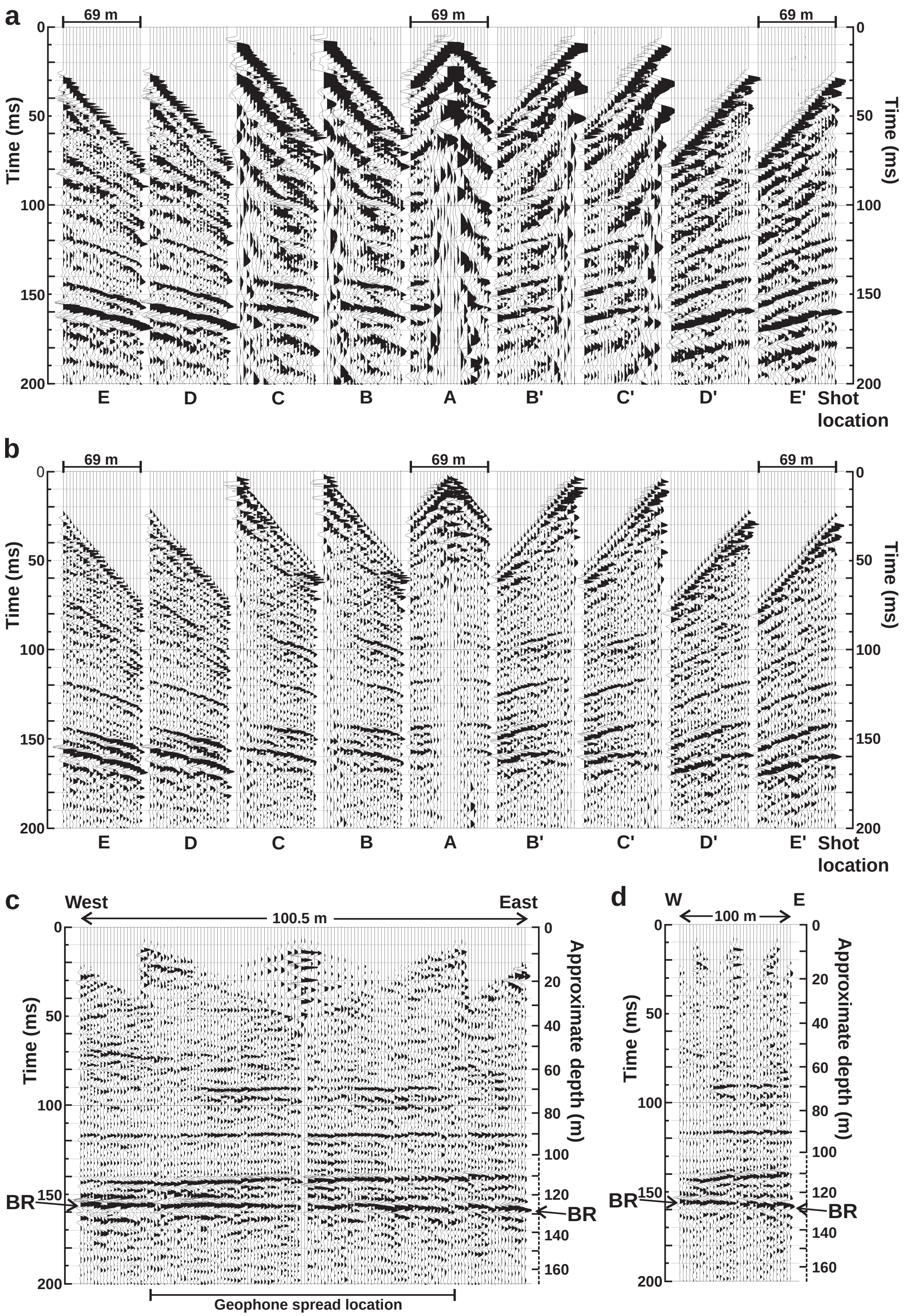

Figure 3. *Processing of data acquired at site 38:* ***a)*** *suite of seven raw records acquired using source-receiver layout shown in Figure 2 (plotted with full trace normalization);* ***b)*** *after digital filtering (100–600 Hz bandpass);* ***c)*** *the 'stacked' common-midpoint section (1–2 fold) produced from records in b) after normal moveout corrections were applied; and* ***d)*** *after summing of every four adjacent traces (to produce the condensed sections used in Fig. 4). The approximate depth scale shown at the right hand side of sections c) and d) has been calculated from the stacking velocities. 'BR' indicates the reflection interpreted as the overburden-bedrock interface.*

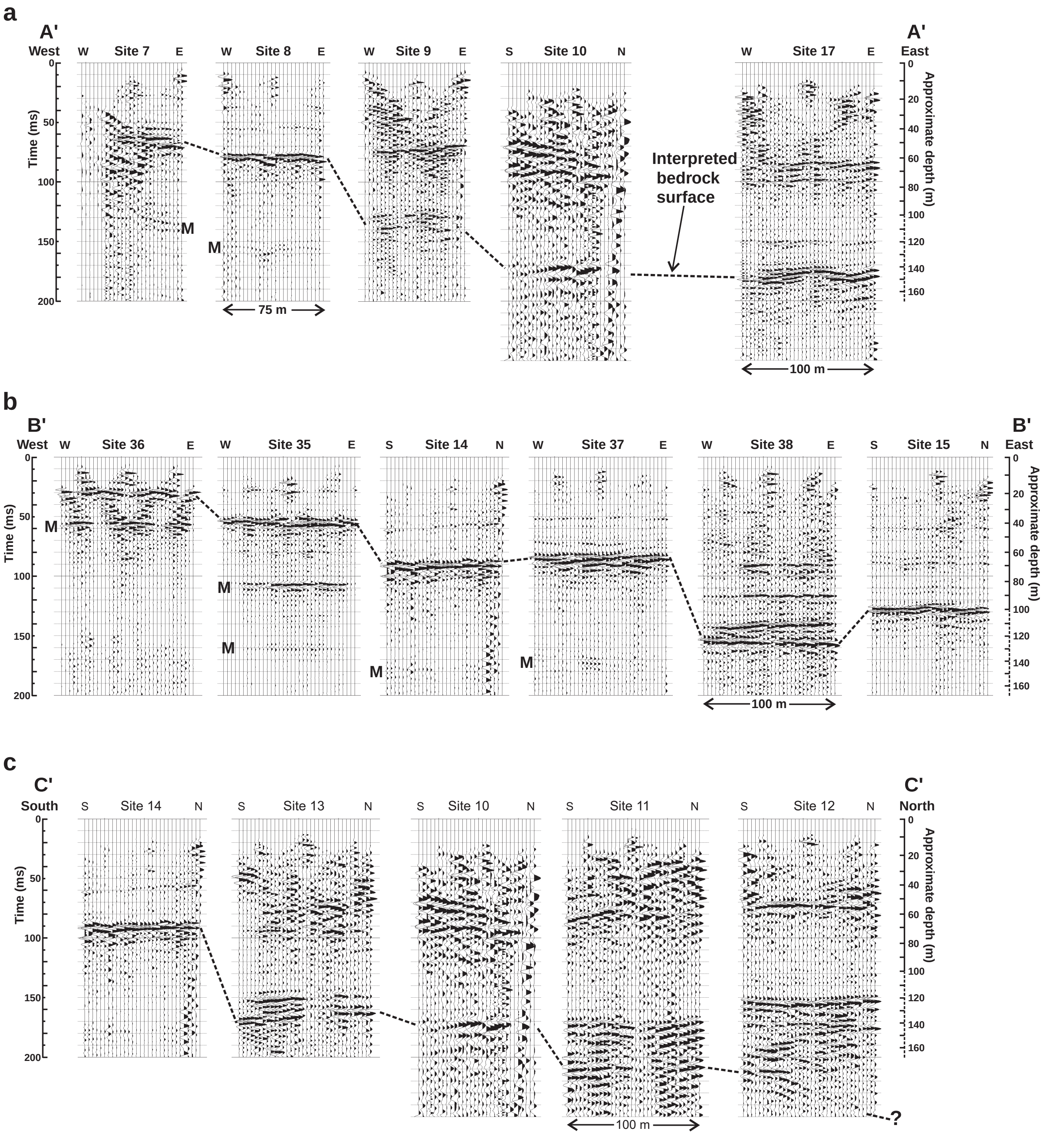

Figure 4. *Representative west-east and south-north sections across the bedrock basin:* ***a)*** *A-A′,* ***b)*** *B-B′, and* ***c)*** *C-C′* (see *Fig. 1 for locations). The dashed line indicates the interpreted bedrock surface. M indicates a multiple reflection (energy that has 'bounced' between ground surface and bedrock more than once).*

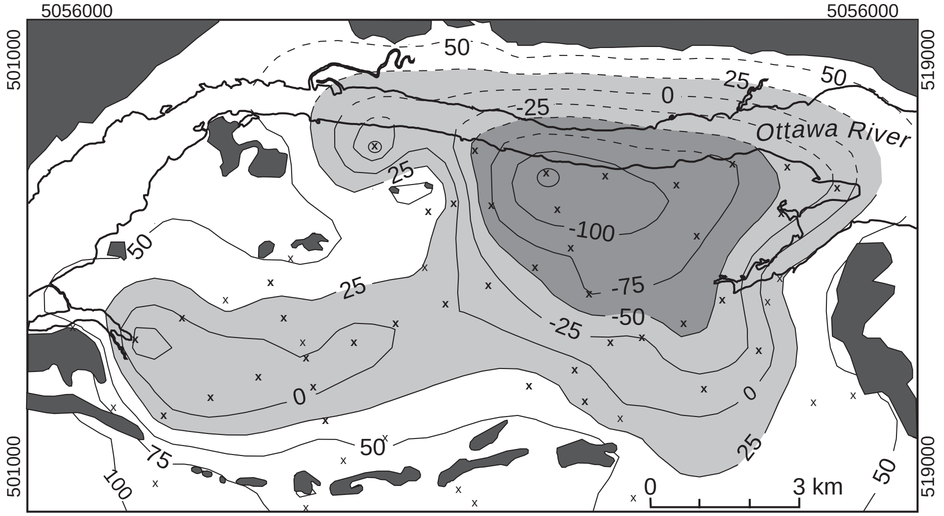

Figure 5. Bedrock elevation map for the survey area based on seismic test sites and available water-well information (indicated by xs) as well as elevations of bedrock outcrop on both sides of the river. Contours are given in metres above mean sea level (m a.s.l.); surface elevation is approximately 53 m a.s.l. The black regions are areas of bedrock outcrop.

Below the upper transparent (low-amplitude) seismic facies that is interpreted as Champlain Sea sediments, some of the deep bedrock sites show relatively thinner, higher amplitude reflection facies above the bedrock surface (e.g. Fig. 4; sites 11, 12, 13, and 37). This facies likely represent glacially derived sediments that underlie the Champlain Sea sediments such as observed in the Ottawa area (Douma and Nixon, 1993). In the deepest parts of the bedrock depression, it is also possible that pre-Quaternary sediments overlie Precambrian ‘basement’ (Fig. 4, site 12).

Figure 5 is a bedrock elevation map derived from the seismic sites with additional control obtained from available water-well information and bedrock outcrop on both sides of the Ottawa River. Given this density of information, the contour map indicates the presence of a deep bowl-shaped bedrock depression with a maximum thickness of stratified sediments of approximately 175 m. From the brief glimpses of structure given by the short section at each site, it appears that the bedrock surface within the depression is not flat lying. Rather, this surface displays irregular topography similar to the ground-surface Precambrian outcrop zones within the survey area.

On the west side of the survey area, there appears to be an east-striking bedrock topographic low between outcrops of Paleozoic to the south, and Precambrian to the north. Overburden thicknesses in this low are 50–75 m. Although not shown here, stratified sediments, probably of Champlain Sea age, directly overlie bedrock in many location in this topographic low. At some sites there is a possibility of a thin veneer of glacial sediments also occurring just above the bedrock surface, as indicated from the diffractoid nature of the reflectors.

DISCUSSION AND CONCLUSIONS

The results of this reconnaissance seismic-reflection survey have indicated the presence of a deep, bowl-shaped, bedrock depression within the survey area with a maximum thickness of sediments of approximately 175 m. This anomaly underlies much of the zone mapped as “disturbed” Champlain Sea sediments. From the data density obtained, the edges of this depression are relatively abrupt on the west side of the feature. Intraoverburden reflectors can be identified from both within and outside the bedrock depression. This suggests that these events may be mapped laterally to provide stratigraphic and structural information about the sediments. At this time, no stratigraphic borehole is available to correlate reflectors to geological stratigraphy; however, from previous experience, it is suggested that flat-lying reflectors in the upper portions of the seismic sections are probably associated with grain-size changes within Champlain Sea sediments. A basal, higher amplitude reflection package may indicate the presence of underlying glacially derived sediments. The detailed structure immediately above the bedrock surface cannot be determined without continuous seismic-reflection profiling having high common midpoint signal stacking.

Within the zone of the bedrock depression, the hummocky nature of the interpreted bedrock interface suggests that it is the Precambrian surface since similar hummocky topography is observed in surface exposures within the survey area. For most of the sites away from the depression, the buried bedrock surface is relatively flat lying, which suggests that these areas may be underlain by Paleozoic sedimentary rock.

If the buried bedrock surface is deemed a possible mechanism for various types of ground motion amplification leading to surface sediment disturbance, then it is suggested that high-resolution reflection seismic surveying be conducted over some key areas. Detailed definition of the steeper western edge of the depression and delineation of deformation of sediment structure at depth are possible using this seismic method. Additional site testing for shear wave velocity structure in the sediments, using different seismic equipment and arrays, could also be carried out to provide the necessary input parameters for future ground-motion amplification studies.

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