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2001-D3

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Use of high-resolution shear-wave-reflection methods for determining earthquake fundamental site period response near Alfred, Ontario

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Benjumea, B., Hunter, J.A., Burns, R.A., Good, R.L., and Pullan, S.E., 2001: Use of high-resolution shear-wave reflection methods for determining earthquake fundamental site period response near Alfred, Ontario; Geological Survey of Canada, Current Research 2001-D3, 10 p.

Abstract

Fundamental site resonance periods due to earthquake shaking have been calculated in a sediment-filled bedrock basin located near Alfred, Ontario, using a high-resolution shear-wave-reflection method. This area is characterized by postglacial marine (Champlain Sea) sediments exhibiting surface disturbance that has been postulated to be the result of paleo-earthquake activity ca. 7060 BP. Hence, the study of parameters that govern the basin response to shaking will aid in understanding deformation within this zone. Shear waves can provide straightforward estimates of the fundamental site period from nearly vertical reflection travel times. Data have been collected at 21 locations that show wide variations in values of fundamental site periods. The quality of the reflection data strongly depends on near-surface conditions. A refraction study in one area provided the shear-wave velocities within bedrock and overburden necessary to evaluate the resonance amplification effect.

Résumé

Les périodes fondamentales de résonance du site provoquées par des secousses sismiques ont été calculées dans un bassin du substratum rocheux rempli de sédiments situé près d'Alfred (Ontario), à l'aide de la méthode de réflexion des ondes de cisaillement haute résolution. Cette région est caractérisée par des sédiments marins postglaciaires (Mer de Champlain) qui montrent des perturbations de surface attribuées à l'activité sismique ancienne ayant eu lieu vers 7060 BP. Par conséquent, l'étude des paramètres qui régissent la réaction du bassin aux secousses nous aidera à mieux comprendre la déformation survenue dans cette zone. Les ondes de cisaillement peuvent donner des estimations directes de la période fondamentale de résonance à partir du temps de propagation des ondes à réflexion quasi verticale. À l'heure actuelle, des données ont été recueillies sur 21 sites montrant de grands écarts dans les valeurs des périodes fondamentales de résonance. La qualité des données de réflexion dépend largement des conditions présentes près de la surface. Une étude de réfraction réalisée dans une zone a permis d'obtenir les vitesses des ondes de cisaillement dans le substratum rocheux et dans la couverture qui sont indispensables pour évaluer l'effet d'amplification de la résonance.

INTRODUCTION

It has been long established that sites where soil overlies bedrock are subject to increased earthquake ground-motion amplification effects compared with bedrock outcrop sites (Aki, 1988). To obtain first-order estimations of these effects, the assumption is made that the soil–rock system acts in an elastic manner to earthquake strains, and no significant nonlinear visco-elastic phenomena occur. This approximation appears to be valid for low strains (small to moderate earthquakes), but may require modification for large strains (large earthquakes). The nonlinear response also appears depend on soil type (Bard, 1997).

The soil amplification phenomenon results from significant contrasts in shear-wave velocity and density (acoustic impedance) between near-surface unconsolidated overburden and bedrock at depth. For a one-dimensional model consisting of soil with an average density of ρ_S overlying rock characterized by a density ρ_R, in the absence of anelastic attenuation, this amplification effect is given by the following equation:

$$A(\omega)=\left(\frac{\rho_R V_R}{\rho_S V_S(\omega)}\right)^{1/2} \qquad (1)$$

where V_R is the shear-wave velocity in bedrock and V_S is the average shear-wave velocity in the soil taken from surface down to a depth of one quarter wavelength for a particular frequency component ω. For normally consolidated young (e.g. Holocene) sediments overlying competent rock, the amplification effect can range from 3 to 6 (Bard, 1997).

In addition to the amplification given by equation (1), resonance effects can occur within the surface layer wherever an abrupt acoustic impedance contrast is associated with the overburden–bedrock boundary. The resonant periods for a layer of unconsolidated overburden with thickness H and average shear wave velocity V_{ave} are given by the following (Bard and Bouchon, 1980):

$$T_n=(2n+1)\frac{4H}{V_{ave}} \quad n=0,1,2,3,\ldots \qquad (2)$$

A value of n=0 gives the fundamental period, n=1 the first harmonic, etc. An approximation for the resonance amplification value (A_{res}) can be obtained assuming absence of anelastic attenuation (Shearer and Orcutt, 1987), as follows:

$$A_{res} = \frac{\rho_R V_R}{\rho_S V_{ave}} \tag{3}$$

where ρ_R and ρ_S are the densities for bedrock and soil and V_R and V_{ave} represent the shear-wave velocities for bedrock and the average for soil.

A knowledge of such resonance peaks in soil response is of considerable interest for the design of buildings and other structures constructed on or within the soil. For loose soils having low near-surface shear-wave velocities overlying high-velocity bedrock, the resonance amplification effect can be a significant addition to the overall soil–rock amplification effect (Cassidy et al., 1997).

Near-surface geophysical techniques provide a way of obtaining information about physical parameters of the overburden with great significance in earthquake engineering. For example, in previous surface seismic-refraction and downhole studies of the Fraser River delta near Vancouver (British Columbia), we have established a shear-wave velocity–depth function valid for the young Holocene deltaic sediments within that survey area (Hunter et al., 1998). From this relationship a curve of depth versus fundamental site period was derived and was checked against several boreholes encountering the large acoustic impedance contrast associated with the top of the Pleistocene sediments (Hunter et al., 1998).

The survey area for the present study is near Alfred, Ontario, where geological information supports the occurrence of a paleo-earthquake (ca. 7060 BP) with large, soft-soil amplification effects (Aylsworth et al., 2000). The survey area consists of thick Holocene sediments overlying overconsolidated glacial till and/or bedrock. These surficial sediments include zones of surface disturbance and near-surface deformation (**Fig. 1**). Ample data on the variation of overburden thickness using high-resolution P-wave reflection techniques have been compiled by Hunter et al. (2000). The results of that study are summarized in **Figure 2**. Disturbed areas coincide with ares of thicker overburden.

The objective of this paper is to demonstrate the application of a shear-wave reflection technique to directly estimate the fundamental site period without the requirement for estimating overburden thickness or average velocity. Additional measurements of the average shear-wave velocity in overburden and bedrock were made at one location in the study area to provide an approximate estimate of resonance amplification. These amplification estimates are considered as an upper limit since we do not consider effects of anelastic attenuation.

TECHNIQUE AND DATA ACQUISITION

The shear-wave reflection method provides a direct way of obtaining the fundamental site period (T) since this parameter is related to the two-way travel time of a nearly vertical S-wave reflection (T_o), as follows:

$$T = \frac{4H}{V_{ave}} = 2T_0 \qquad (4)$$

where H and V_{ave} are the overburden thickness and average shear-wave velocity, respectively. The challenge, then, is to develop a reflection technique that can yield a nearly normal bedrock reflection travel time with a minimum of estimation error. In this regard, the array geometry, geophones, and source must be chosen to optimally record high-frequency reflection events at shallow depth (minimal two-way reflection time) with minimal interference from other source-generated noise.

The preferred reflection method is SH mode wherein the horizontal geophones are aligned perpendicular to the line of the array. We have used an array of 24 eight-Hertz geophones at 3 m spacing. The polarized shear-wave source is a triangular block of wood with a 20 cm by 60 cm base and a 20 cm height, aligned along the axis of the geophone array and struck on alternate sides (to generate polarized energy) using a carpenter's hammer fitted with an electronic trigger. To obtain nearly normal incidence, a 'centre-spread' shot was located between traces 12 and 13. Additional off-end shots were positioned on either end of the array to provide velocity and dip information for the observed reflections.

Data were recorded on a stacking engineering seismograph with no filters applied. Both single-direction and two-direction source configurations were recorded (using the polarity reversal feature of the seismograph). The bidirectional stacking reduces non-SH-mode signal-generated noise. Usually four stacks per direction at each source point were sufficient to obtain data with a good signal-to-noise ratio.

RESULTS

Figure 3 shows two shot gathers corresponding to the centre-spread of P-wave (right) and SH-wave (left) surveys, located at site 35 (Fig. 1). From this figure we can compare the relative vertical resolution of P-wave and SH-wave reflection techniques. The dominant frequency of the S-wave reflection is approximately 40 to 50 Hz and is typical of that observed throughout the study area. Using an average overburden shear-wave velocity of 200 m/s, these frequencies correspond to a wavelength of 4 to 5 m. This implies that the application of shear-wave reflection techniques in profiling mode may give results with similar or better vertical resolution than that obtained in P-wave reflection surveys (central frequency of 300 Hz and average velocity of 1500 m/s resulting in a wavelength of 5 m).

The seismic data acquired at this site (**Fig. 3**) show two significant reflections above the interpreted bedrock surface (intra-overburden reflections) in both shot gathers. The correlation between P and SH events is evident with the use of the appropriate time-scale ratio between the two records, to compensate for the different velocities.

Figure 4 is a compilation of centre-spread SH reflection records at several sites along the transects shown in **Figure 1**, along with the fundamental site periods estimated from the two-way travel times (equation 4). As shown in Figure 3, reflectors within overburden are observed at several sites.

Considerable variation in estimated fundamental site periods is observed throughout the area with values from 1.9 s (site 15) to 0.85 s (site 1). This suggests that significant lateral differences in the response to earthquake shaking would occur within the survey area. Although reflected energy from the overburden–bedrock contact can be seen in all the shot gathers shown in Figure 4, differences in data quality are observed. Lower quality data were obtained at sites 14, 37, and 15, all within the disturbed area (Fig. 1). These differences are not as significant in P-wave surveys, which suggests to us that near-surface conditions within the zone of the disturbed sediments may more strongly influence the attenuation of SH energy.

Figure 5a is a plot of shear-wave refraction first arrivals from site 26 (Fig. 1). At this location, we used extended source offsets from the geophone array to obtain refraction events from the bedrock. Assuming that the subsurface is a combination of homogenous layers, we obtain the model shown in **Figure 5b**, using standard seismic-refraction techniques. This model consists of a 15 to 20 m thick, near-surface layer characterized by a shear-wave average velocity of 140 m/s overlying a high-velocity (530 m/s) overburden layer. We observe a dipping refractor corresponding to the overburden–bedrock contact at 35 to 40 m. The shear-wave velocity obtained for bedrock is 2300 m/s (Precambrian granite, outcrops 200–300 m north of this site).

Using the seismic-refraction velocity model, we calculate a thickness-weighted average velocity of the overburden of 240 m/s. Assuming an overburden–bedrock density contrast of 0.75, the resonance amplification estimated from equation 3 would be approximately 12.8. This value has to be considered as an upper limit as we did not consider the effects of anelastic attenuation.

DISCUSSION

The estimation of fundamental site periods using shear-wave reflection techniques is relatively straightforward at the sites included in this particular test. From other similar shear-wave reflection tests conducted by us on Champlain Sea sediments in the Ottawa–Montréal area (not discussed here), good quality, high-frequency reflection energy has been obtained from the overburden–bedrock interface. Hence it is suggested that this method may be used at most Ottawa–St. Lawrence River valley lowland areas with thick, unconsolidated overburden. Further, this type of reflection test may be much more reliable than calculations made from combining depth to bedrock from borehole (water wells, geotechnical borings) data with estimates of shear-wave velocity–depth structure, since in most areas of thick overburden, shear-wave velocities are not well known.

Shear-wave reflection data is still being gathered in this study area. The goal is to produce a map showing variations of fundamental site periods. In the near future, the estimations obtained in this study will be compared with the results of seismic-monitoring surveys currently underway (J. Adams, M. Lamontagne, pers. comm., 2000).

ACKNOWLEDGMENTS

Funding for this work was provided by a fellowship awarded to B.B. by the University of Granada (Spain) and Project AMB 99-0795-C02-01-CICYT (Spanish Interministerial Commission for Science and Technology). We thank Jan Aylsworth for encouraging this work and reviewing this manuscript.

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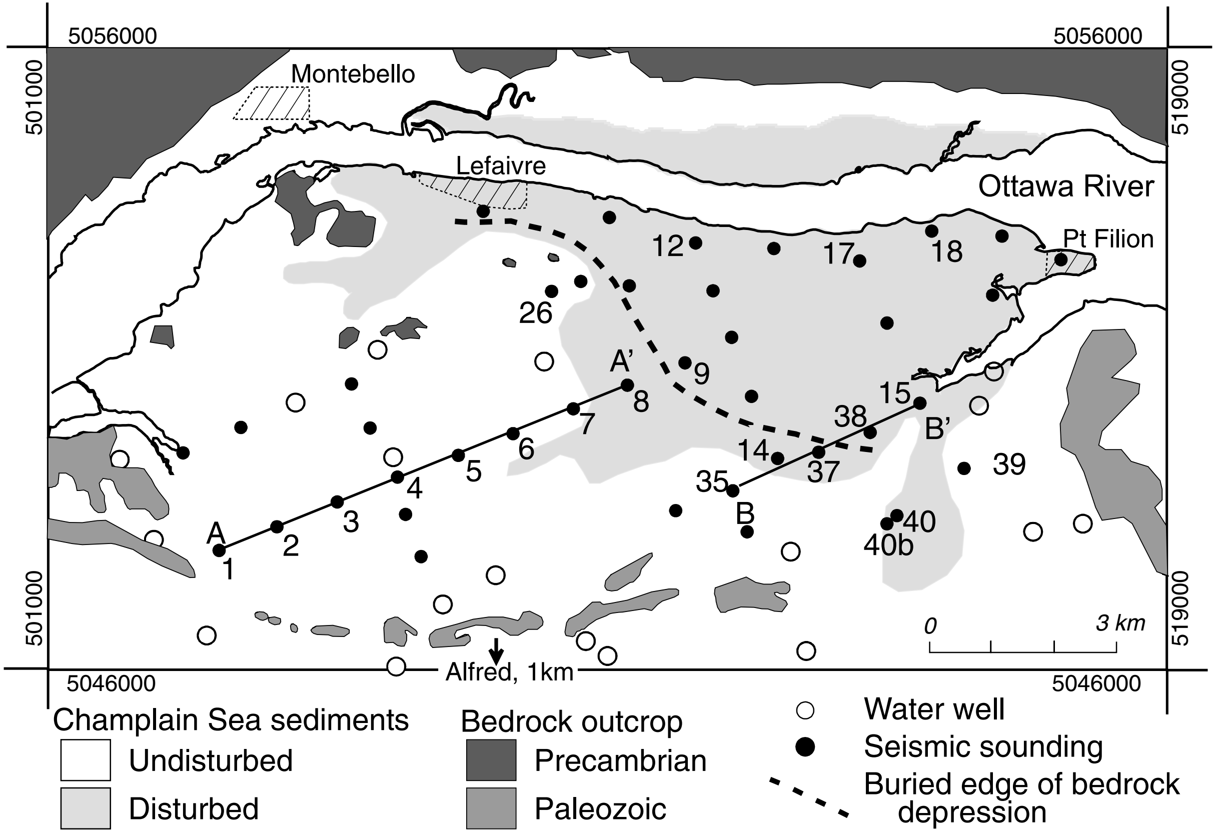

Figure 1. Survey area near Alfred, Ontario, showing locations of the seismic test sites, boreholes, the mapped 'disturbed' ground, and bedrock outcrops. Dots indicate locations of the P-wave test sites (described *in* Hunter et al., 2000); numbered sites are the 21 locations where SH-wave reflection surveys have also been carried out. The numbering system used in the P-wave surveys has been maintained. The grid labels are UTM northings and eastings (Zone 18) using the NAD27 datum. Profiles A-A' and B-B' are used in Figure 4.

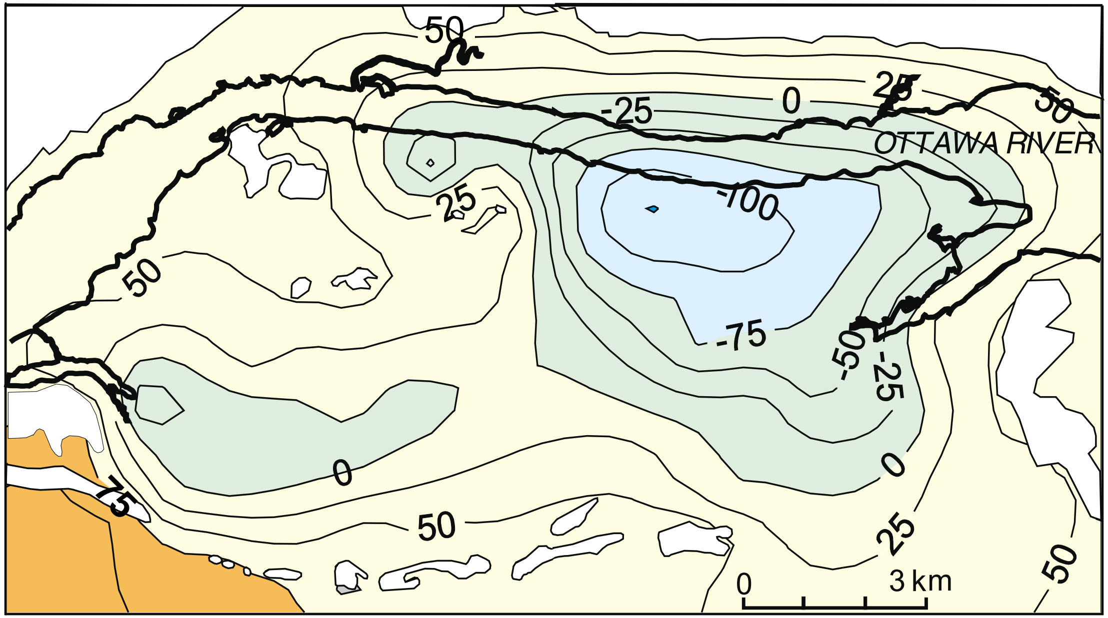

Figure 2. Bedrock elevation map for the survey area based on P-wave seismic test sites and available water-well information as well as elevations of bedrock outcrop on both sides of the river. Contours are given in metres above mean sea level (m a.s.l.); surface elevation is approximately 53 m a.s.l. The white regions are areas of bedrock outcrop (*after* Hunter et al., 2000).

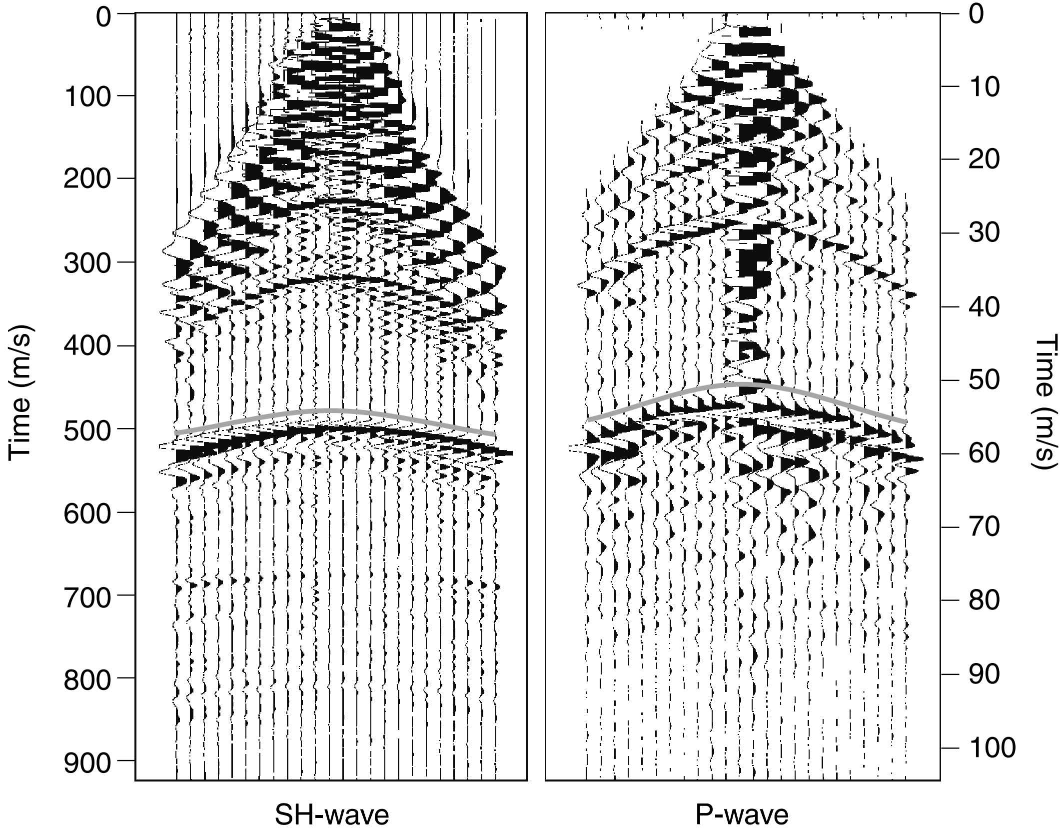

Figure 3. Comparison between the central spread of site 35 (Fig. 1) from SH-wave (left) and P-wave (right) reflection surveys. The grey line indicates reflection from bedrock. The SH-wave shot gather is displayed without any previous filtering. The P-wave record has been filtered using a Butterworth filter with frequency corners 200-300-800-1000 Hz to remove the Rayleigh wave interference. The vertical scales differ between the P-wave and SH-wave shot gathers allowing direct correlation of events in both records.

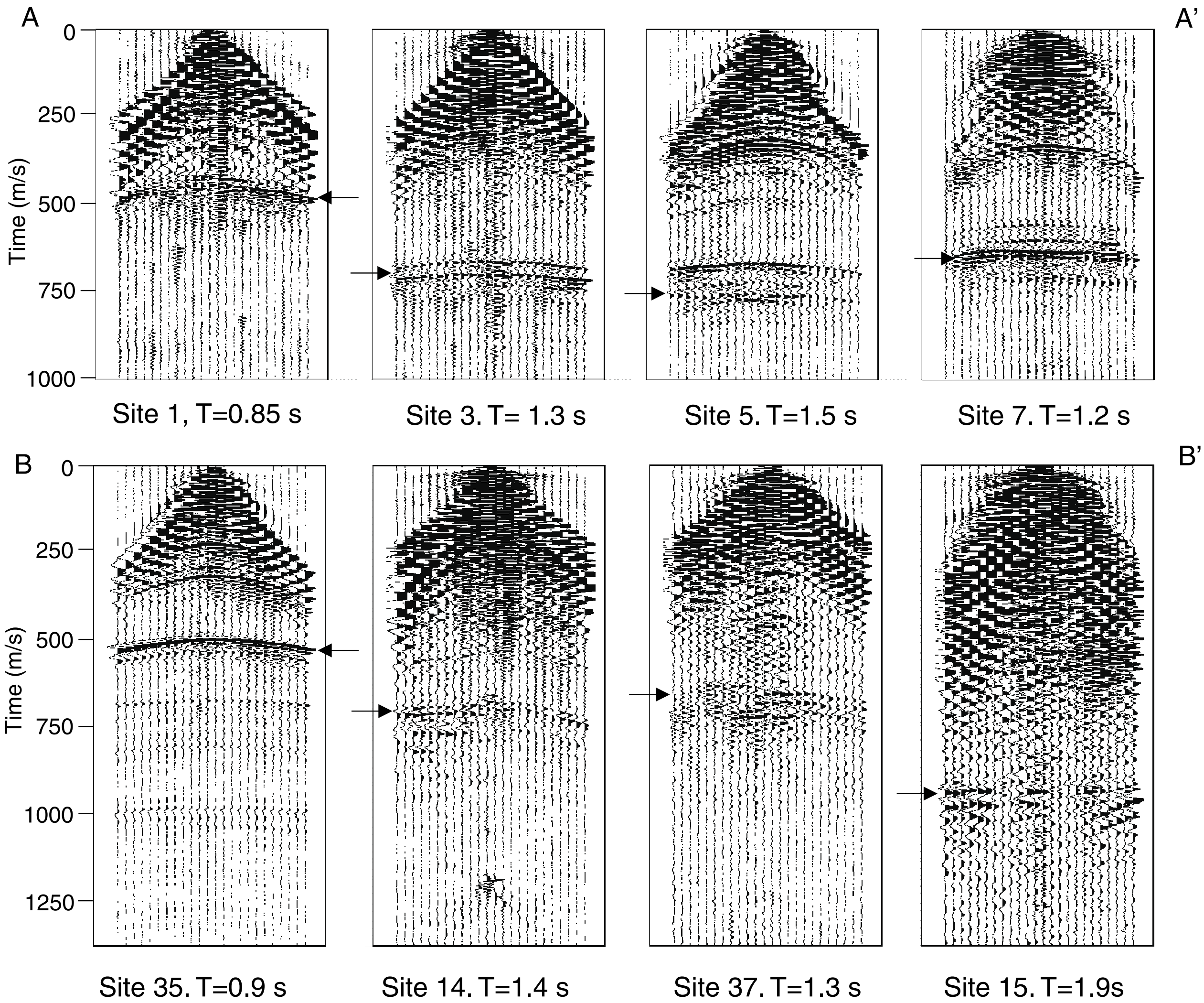

Figure 4. Compilation of centre spreads and fundamental site periods (T) at sites along two profiles (AA’ and BB’ in Figure 1). Arrows show bedrock reflection.

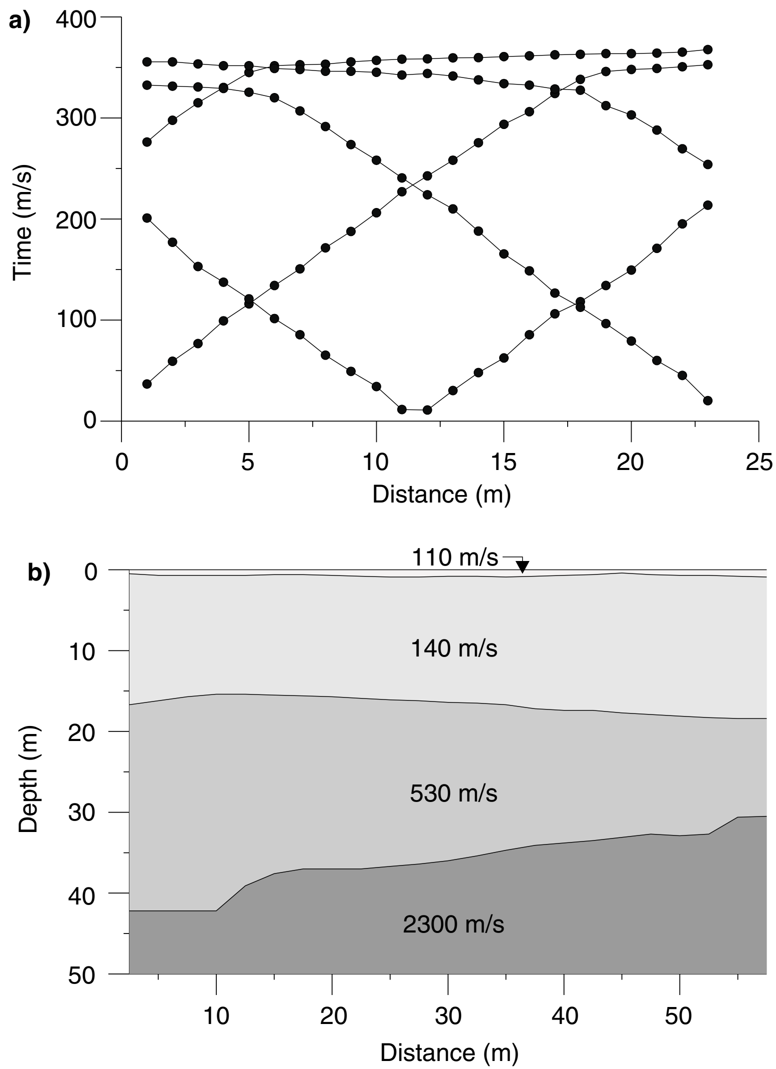

Figure 5. a) Travel-time versus distance diagram for first-arrival refractions compiled from five records acquired at site 26 (Fig. 1). **b**) Shear-wave velocity model resulting from application of the seismic refraction method.