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Seismic Wave Velocities in a Rock Body at Chalk River, Ontario: Part 2.

by

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Abstract

Two shallow seismic reflection profiles of about two kilometres in length running from northwest to southeast (profile A) and from northeast to southwest (profile B) were recorded over a crystalline rock body at Chalk River, Ontario. These data were interpreted as a series of overlapping reversed refraction profiles. A smoothed velocity-distance curve between the ends of profile A yielded velocities between 4.5 and 5.6 km/s for the uppermost regions of the rock body, with the velocities below 5.0 km/s confined to narrow zones at the northwest and southeast ends. The velocities between the northwest end and borehole CR1 at a distance of 1300 m are significantly lower than the average velocities over a similar path calculated from an experiment using hydrophones in the borehole. Between CR1 and the southeast end of the profile the velocities from the two experiments show smaller differences. The P velocities for profile B show more scatter, and clearly exceed 6.2 km/s over a distance of about 250 m at the northeast end of the profile; these high velocities are attributed to propagation through gabbro. Further south, the velocities are close to 5.5 km/s with a trend towards slightly lower velocities at the southern end of the profile. No clear correlation with the surface geology is evident from the velocities of either profile, though lower velocities appear to be correlated with lithological changes that may in turn be associated with extensive fracturing.

Introduction

Lam and Wright (1979) have presented P and S wave velocities in a rock body at Chalk River, Ontario, derived as part of an experiment to test a mechanical hammer as a source of P waves and a shear wave gun as a source of S waves. The other major purpose of this experiment was to search for temporal changes in seismic velocities that might be related to the solid earth tide (Wright, 1979). Consequently, it is emphasized that the experiment was not planned primarily to determine seismic velocities, so that any useful information on the structure of the underlying crystalline rock body is largely incidental to the aims of the project.

A shallow reflection survey was also conducted in the Chalk River area using the mechanical hammer as a source, and the results have been described by Mair and Lam (1979). The data from this reflection experiment can also be analyzed as a series of overlapping reversed refraction profiles. One reflection line covers essentially the same terrain as profiles 2 and 3 of Lam and Wright (1979), whilst the second reflection line is almost parallel to profile 1 of Lam and Wright, but offset to the east by a distance of roughly one kilometre.

In this report the results of both experiments are combined and compared with the surface geology so that a consistent interpretation of the underlying structure can be suggested. The main objective of this additional analysis is to determine if the locations of the lateral variations in P and S velocities can be more precisely specified, and if these variations show a clear correlation with the several rock types known to be present in the Chalk River area.

Methodology

The numerical methods used to interpret the series of reversed refraction profiles are described below, and are a straightforward extension of the standard technique that is described in most textbooks on exploration geophysics (e.g. Telford, Geldart, Sheriff and Keys, pp. 281-284). The principle is illustrated in Figure 1. The spacing of adjacent geophone clusters, shown as dots, was about 30 m. As a compromise between smoothing out too much information and retaining too much scatter due to irregularities in the boundary between the glacial overburden and the underlying rock body, just six recording stations were utilized for each shot point; the two closest stations were not used to ensure that the seismic energy had penetrated below the sediments.

Two methods of reversing the profiles were chosen, as shown in Figures 1 (a) and (b). In (a), common recorders were used for the forward and reversed shot points. Thus, if locations 1 and 12 are the two shot points, seismic records for stations 4-9 are involved in the analysis. In (b), locations 1 and 9 are the forward and reverse shot points, so that the geophone locations required are 4-9 and 1-6 respectively. The data for the configurations (a) and (b) were analyzed for all possible sets of reversed profiles. The velocity V_2 in the rock body was assigned a position corresponding to the mid-point between the projections of the shot points on to a line joining the end stations of the profile. This is illustrated in Figure 1 (c). Thus a series of velocities at points corresponding to the star was obtained, which is plotted in Figures 2 and 3.

The refractor velocities V_2 were obtained in the following manner. If V_1 is the velocity in the sediments and V_d and V_u are the apparent velocities in the up-dip and down-dip directions, the critical refraction angle is given by (Telford et al., 1976, p. 283),

$$\theta = \frac{1}{2}\left\{\sin^{-1}\left(\frac{V_1}{V_d}\right) + \sin^{-1}\left(\frac{V_1}{V_u}\right)\right\} \qquad (1).$$

Then $$V_2 = V_1 \operatorname{cosec} \theta \qquad (2).$$

V_1 must therefore be known in order to estimate V_2. V_2 was calculated using an upper bound of 3.0 km/s and a lower bound of 1.5 km/s for V_1. However, if the dip angle ϕ is small so that $\cos\phi \doteqdot 1$ and $\sin\phi \doteqdot \phi$,

$$\frac{1}{V_2} \simeq \frac{1}{2}\left[\frac{1}{V_d} + \frac{1}{V_u}\right] \qquad (3),$$

and the dependence of V_2 upon V_1 has been eliminated. The differences between the velocities calculated from equations (1) and (3) were found to be insignificant ($<$0.1 km/s) in most instances.

The primary arrival times for each shot - recorder configuration were picked by eye from paper records of the seismograms using the microscope attached to a seismogram digitizer.

Results

The individual velocity determinations derived by processing the data in the manner illustrated in Figures 1(a) and 1(b) are plotted in Figures 2 (a, b) for profile A and Figure 3 (a, b) for profile B. The location of these two profiles together with the three profiles of Lam and Wright (1979) are shown in Figure 4.

The 54 individual velocities of profile A show considerable scatter, regardless of whether they were determined by method (a) or (b) of Figure 1.

Smooth curves have been fitted through both sets of data using the cubic spline algorithm of Reinsch (1967), with the smoothing parameter S and the standard deviation on a single velocity measurement set at 100 and 0.25 km/s respectively (Figure 2). The smooth curves show little variation between 300 and 1500 m from the northwest end of profile A, the velocities remaining close to 5.5 km/s. Between 100 m and 300 m, however, the smoothed velocities show a distinct dip, reaching a minimum of about 4.9 km/s at a distance of 210 m from the northwest end. A similar dip is present at the southeast end of the profile, the velocities attaining a minimum of 4.5 km/s at 1730 m and then increasing to 5.6 km/s at 1900 m.

The 55 velocity determinations of profile B (Figure 3) show even more scatter than those of profile A, and the smooth curves through the data points display much more fine structure than those of profile A. Moreover, the two curves corresponding to the different ways of forming the reversed profiles differ considerably in their features, even though the amount of smoothing is greater than for profile A (S = 125). Both curves show high velocities of between 6 and 7 km/s over a distance of more than 300 m south of the northeast end of the profile. Method (b) of Figure 1 yields a quasi-periodic variation in velocity of wavelength about 300 m and with a smoothed amplitude of about ± 0.5 km/s.

Interpretation

Figure 2 shows the smoothed P velocity curves for profile A together with the average velocities for profiles 2 and 3 of Lam and Wright (1979). The average P velocity for profile 2 is about 0.5 km/s higher than the flat regions of the smooth curves calculated here. The average P velocity for profile 3 is close to the smooth curves in the vicinity of the bore hole CR1, but becomes significantly higher closer to the shot point. The velocities of the smooth curves therefore tend to be slightly lower than the average velocity of profile 3. The average velocities for both profiles 2 and 3 are consequently higher than those derived from the reflection data; this is expected, since the seismic waves interpreted by Lam and Wright (1979) had traversed the deeper and presumably less fractured and weathered regions of the rock body. The velocity for profile 2, however, is so much higher than the smooth curves that propagation through a medium of much higher velocity than the gneiss - monozonite body is implied. Near surface velocity measurements on core samples from the gneiss - monzonite body are in the range 4.9 - 5.9 km/s (Simmons, Batzle and Cooper, 1978), which agree well with the velocities of the smooth curves. Further drilling roughly half way along profile 2 intersected gabbro, so that the presence of a high velocity wave guide is also compatible with the geology. Further, the smooth curves show no sharp changes close to CR1, indicating that the cause of the difference in velocities between profiles 2 and 3 is unlikely to be simply a change in lithology close to CR1.

The inferred positions of the uppermost regions of the gneiss-monzonite body (orthogneiss) and the more mafic paragneiss have been plotted on Figure 2 using the geological map prepared by P. Brown. Note that the dip in velocities at the southeast end of profile A is closely associated with the two changes from ortho- to paragneiss. This suggests that the lower velocities are associated with extensive fracturing in the vicinity of the boundary between the two rock types.

Figure 3 illustrates the smoothed velocity curves for profile B, together with the inferred near-surface positions of the lithological boundaries again derived from the geological map of P. Brown. There is obviously no clear correlation between the velocities and the rock type, and profile B lies at the edge of the mapped area. We therefore suggest that the high velocities at the northeast end of the profile are due to propagation through gabbro rather than paragneiss, since the lithological boundaries in this region are unlikely to be accurately defined. The apparent periodicity of the velocities of Figure 3(a) does not correlate well with the features of Figure 3(b). The structure of the smooth curves beyond 300 m from the northeast end of profile B is therefore unlikely to be due to real velocity variations. The only safe inference is that the velocities are on average close to 5.5 km/s with the suggestion of a slight decrease towards the southwest end. The average P velocity for profile 1 of Lam and Wright (1979), which is almost parallel to profile A but displaced a kilometre to the west, is also included in Figure 3. Lam and Wright have already argued that the high velocity of 6.56 km/s implies that the seismic energy has travelled largely through gabbro.

Discussion

The most puzzling result is the quasi-periodic nature of the P wave velocities along profile B that is present for one method of analysis and not for the other. The change from method (a) to method (b) of Figure 1 causes a relative shift of 100 m in the regions of the rock body sampled by the forward and reversed profiles. Each forward or reversed profile yields an apparent velocity (V_u or V_d) averaged over a distance of about 200 m, or about two thirds of a wavelength of the apparent periodic variation. It thus appears that the observed periodic change in velocity is an artifact produced by a combination of the method of analysis and the manner in which the original profiles were subdivided.

The measured velocities in the rock body are fairly scattered, but have a smoothed average that is generally close to 5.5 km/s; this is consistent with the presence of fractured gneiss or monzonite over most of the area sampled. We note also that the northeast end of profile B and profile 1 of Lam and Wright (1979) yield velocities of about 6.5 km/s, which seems to indicate the presence of gabbro.

Recommendations

The two experiments at Chalk River were not undertaken to obtain detailed seismic velocities, so that the results presented are essentially an unplanned bonus that complements the other reports. Thus the shot-recorder configuration would have been quite different in a planned velocity profiling program. Detailed surface refraction profiling over short distances of a few hundred metres is useful for measuring overburden thickness, but suffers from the disadvantage that the underlying refractor velocities are measured only for the uppermost weathered and fractured regions of the rock body. For the 'RADWASTE' program, however, it is the seismic velocities at depths greater than 100 m or so that are important.

Since extensive fracturing and geological and structural complexity are likely to be closely associated, relative simplicity and homogeneity of structure appear to be a requirement of a waste disposal site. Detailed surface refraction work is generally unnecessary, except where overburden thicknesses are required, since a relatively simple shot-recorder configuration with recording at depth in a borehole can determine whether or not a site is seismically homogeneous. More detailed surveys would be valuable, however, in mapping geologically complex areas, should such sites be considered suitable for radioactive waste disposal.

References

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Telford, W.M., L.P. Geldart, R.E. Sheriff and D.A. Keys. *Applied Geophysics*, 860 pp., Cambridge University Press, Cambridge, 1976.

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Figure Captions

Figure 1: (a) and (b) illustrate the two schemes that were used for reversing the refraction profiles using six recorders for each shot position. The shot-recorder positions are shown on the surface of a medium of P velocity V_1, below which there is a sloping interface dividing it from the rock body of velocity V_2.

(c) shows a plan of 16 stations equally spaced, but not in a straight line. A and B correspond to the projections of forward and reversed shot points on to a line XY joining the end stations of the network. The refractor velocity between A and B was plotted at the mid-point of AB, which is marked by a star.

Figure 2: Plot of velocity as a function of distance from the station at the northwest end of profile A. (a) and (b) display data derived according to the methods of Figure 1 (a) and (b) respectively.

Smoothed P velocity curves for profile A and the average velocities for profiles 2 and 3 of Lam and Wright (1979) are also shown.

Figure 3: Plot of velocity as a function of distance from the station at the northeast end of profile B. (a) and (b) display data derived according to the methods of Figure 1 (a) and (b) respectively.

Smoothed P velocity curves for profile B and the average velocity for profile 1 of Lam and Wright (1979) are also shown.

Figure 4: Map of the Chalk River area showing the location of the two reflection lines and the shot and recorder positions for the experiment described by Lam and Wright (1979).

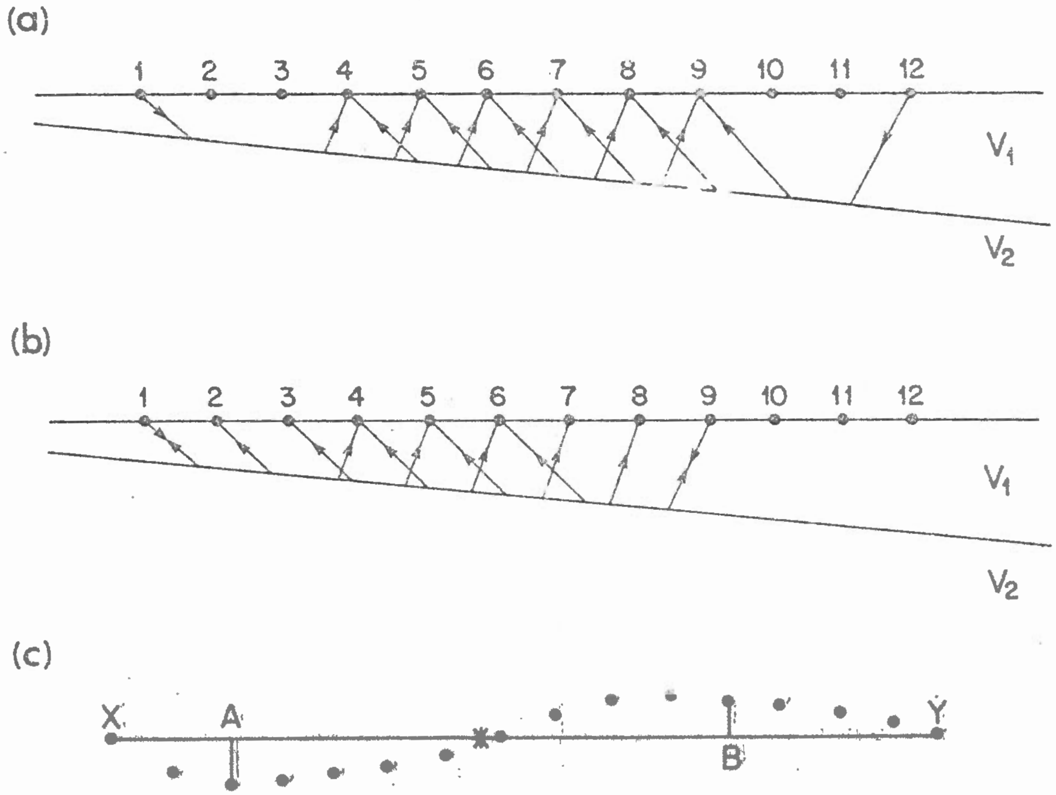

FIG. 1

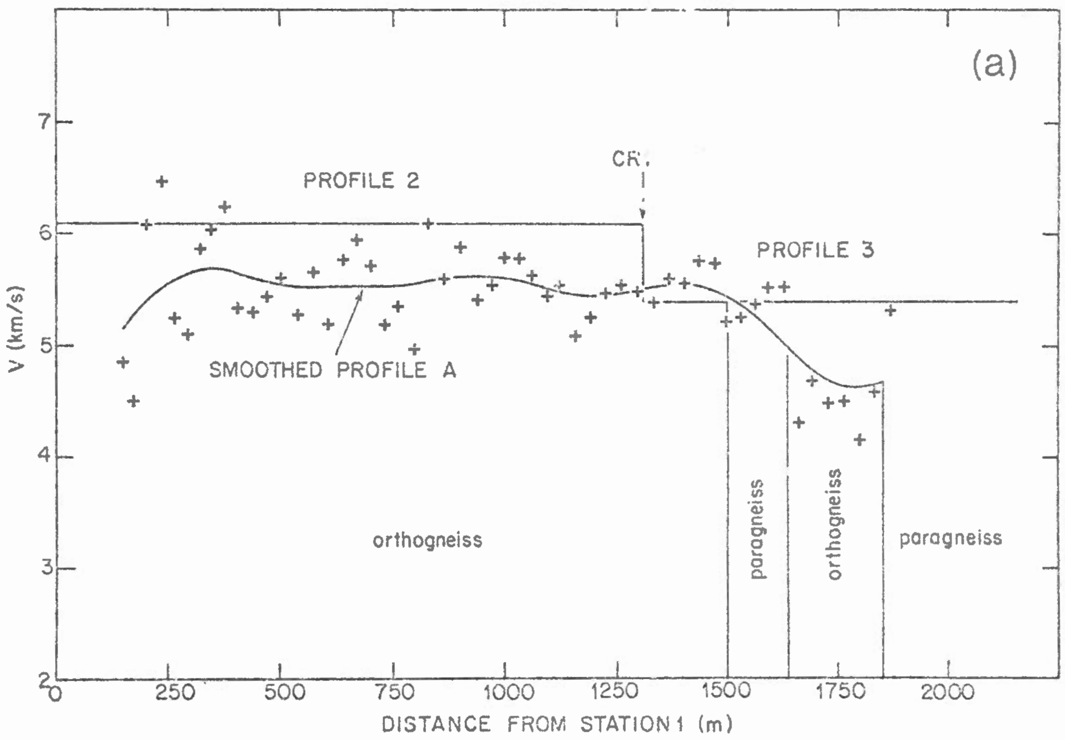
(a)
7
6
5
4
3
2
V (km/s)
0
250
500
750
1000
1250
1500
1750
2000
DISTANCE FROM STATION 1 (m)
PROFILE 2
CR.
PROFILE 3
SMOOTHED PROFILE A
orthogneiss
paragneiss
orthogneiss
paragneiss

Fig. 2 (a)

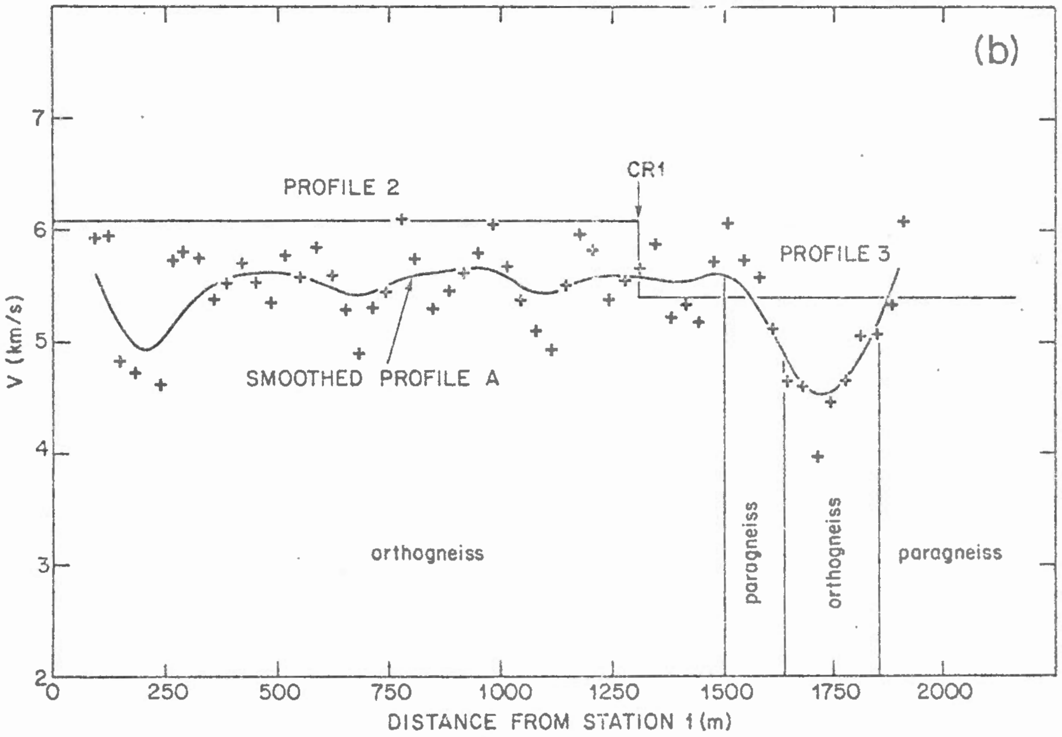
(b)
7
6
5
4
3
2
V (km/s)
PROFILE 2
CR1
PROFILE 3
SMOOTHED PROFILE A
orthogneiss
paragneiss
orthogneiss
paragneiss
0
250
500
750
1000
1250
1500
1750
2000
DISTANCE FROM STATION 1 (m)

Fig. 2 (b)

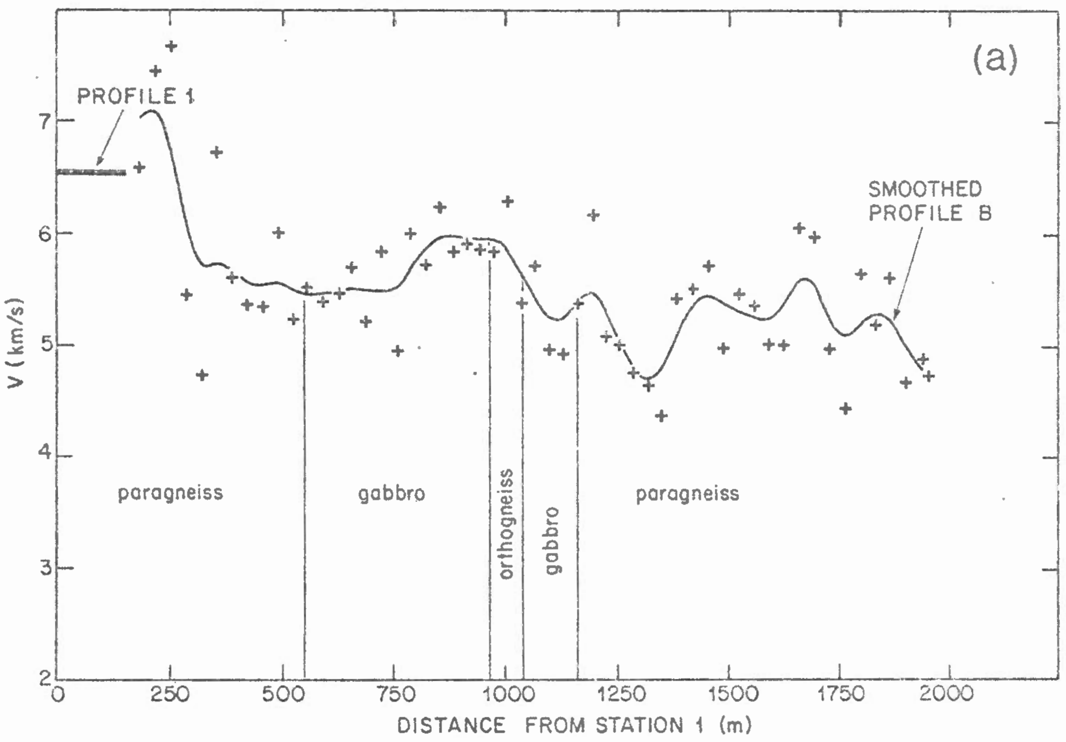
(a)
PROFILE 1
SMOOTHED
PROFILE B
V (km/s)
2
3
4
5
6
7
0
250
500
750
1000
1250
1500
1750
2000
DISTANCE FROM STATION 1 (m)
paragneiss
gabbro
orthogneiss
gabbro
paragneiss

FIG. 3(a)

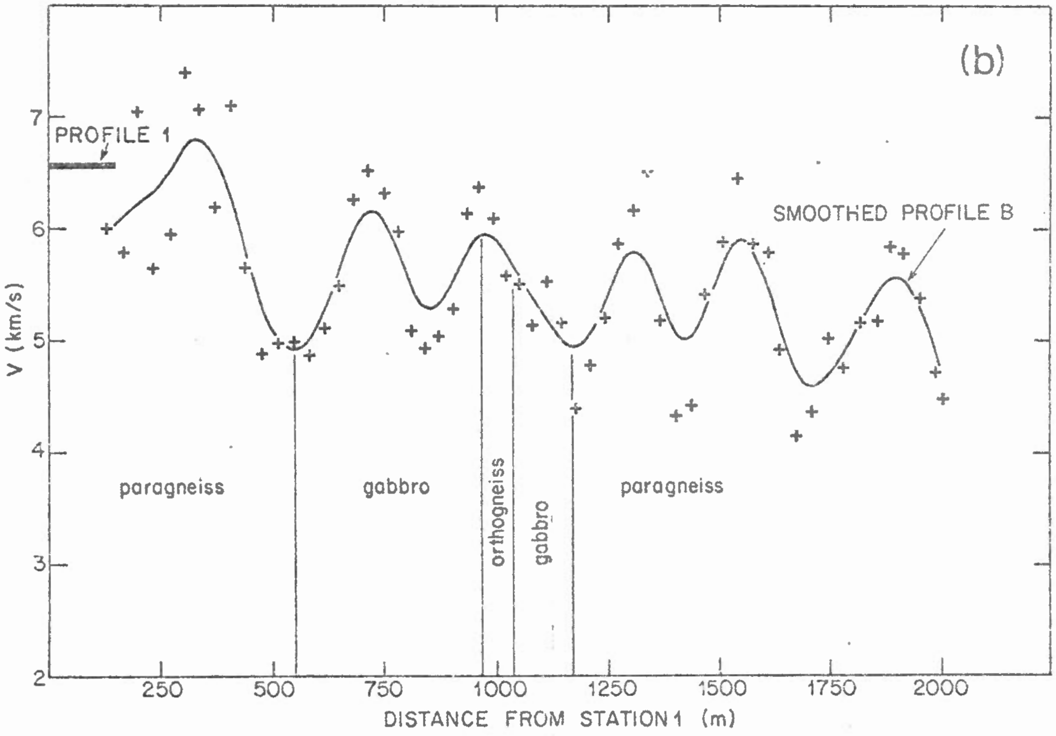
(b)
PROFILE 1
SMOOTHED PROFILE B
V (km/s)
7
6
5
4
3
2
250
500
750
1000
1250
1500
1750
2000
DISTANCE FROM STATION 1 (m)
paragneiss
gabbro
orthogneiss
gabbro
paragneiss

FIG. 3(b)

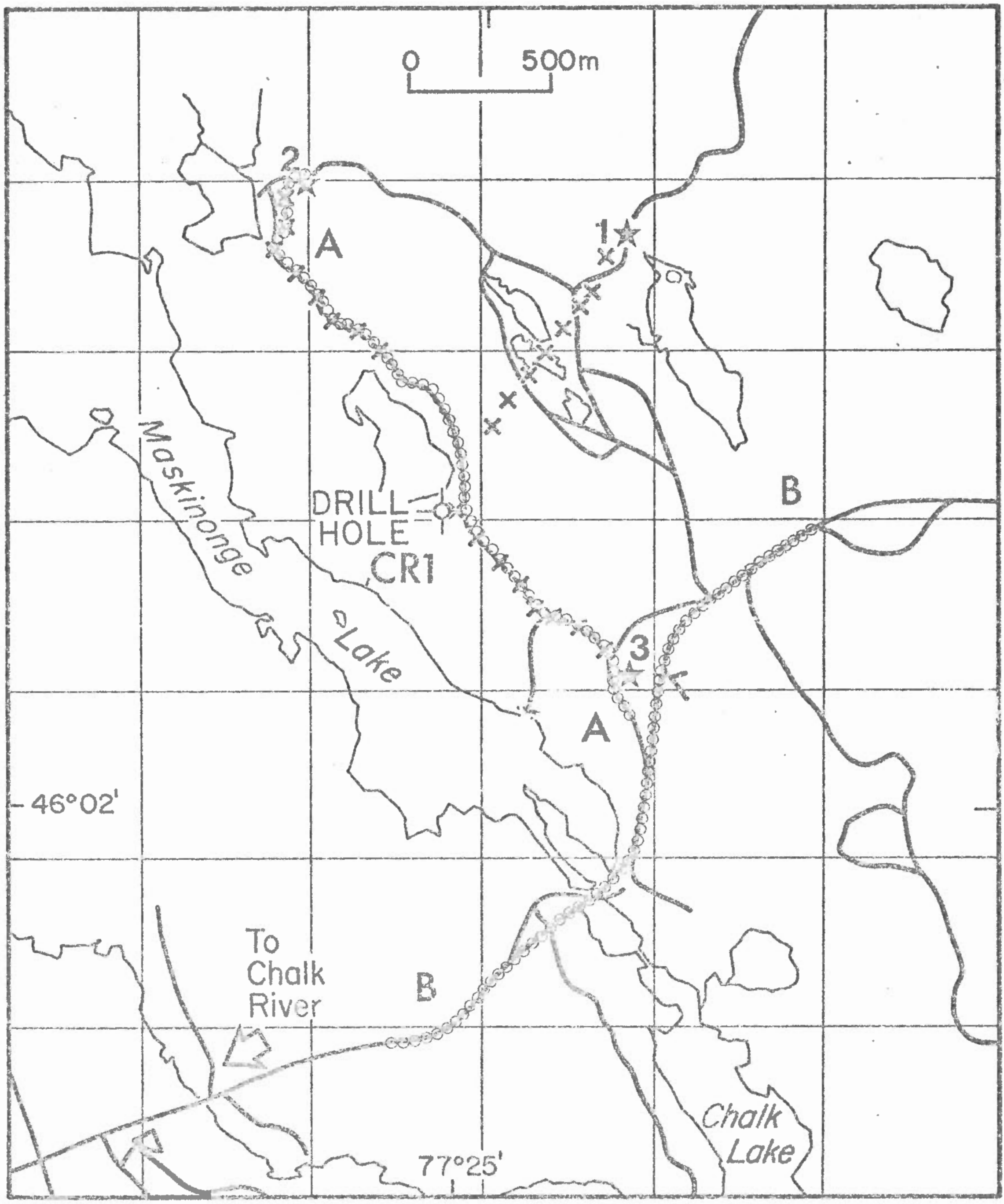

FIG. 4

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