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Seismic-Lateral-Studies

High Resolution Seismic Reflection Project

by

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AECL Radioactive Waste Disposal Program

Technical Memo: 3034240-01/79

Seismological Service of Canada

Internal Report #79-1

Division of Seismology and Geothermal Studies
Earth Physics Branch
Department of Energy, Mines and Resources
Ottawa

February 1979

Introduction

During the month of October, 1977 a seismic study was conducted by Earth Physics Branch (EPB) personnel at the Chalk River Nuclear Laboratory site. This study had the following five specific goals:

1. Measure the horizontal velocities of seismic P, S and surface waves as a function of azimuth from a centrally located, drilled hole.

2. Determine the effect of tidal stress on these velocities and on the attenuation of seismic waves.

3. Relate horizontal velocities to vertical velocities, obtained in situ and to velocities of core samples.

4. Attempt to relate velocity variations and attenuation as a function of azimuth to the pore pressure and to the distribution of cracks and joints in the rock body.

5. Using high resolution reflection/refraction techniques, attempt a structural interpretation as revealed by profiles near the drilled hole.

The first four objectives required innovative field and data processing techniques and are reported on elsewhere. The fifth objective, the subject of this report, required the application of a standard, oil industry, technique, known as the common reflection point (CRP) method.

While the technique is widely used as a means of delineating strata within a sedimentary basin, it's utility in mapping the boundaries of, or the fracture/shear zones within, a granite batholith had not heretofore been tested. Granite batholiths in the upper crust may be "floored" and the ancient, deeply eroded, crust of the Canadian Shield may be a patchwork of diapiric intrusions floored, in some cases, at shallow depth. The delineation of the macro-features of the batholith may be possible with the CRP seismic technique, subject to the following considerations.

The CRP method enhances seismic energy returned from near-horizontal acoustic discontinuities. In the vicinity of vertical or steeply dipping discontinuities, however, the assumptions inherent in the "stacking" process are violated and rather than a reinforcement of signal, interference will occur. This same result will occur with the use of linear arrays of seismometers for each trace. The linear arrays are designed to attenuate energy travelling, near-horizontally, in-line with the array, while enhancing the near-vertical reflection energy returned from a near-horizontal interface.

Dips greater than about 15^{o} will not, normally, be well accommodated by the method, requiring modified field procedures and migration techniques in the data processing stage. Both of these operations, however, are based on a knowledge of the target, that is unavailable to the initial field experiment.

The resolution capabilities of this technique depend on the wavelengths of seismic energy, reflected from acoustic discontinuities within the earth, that can be recorded at useful signal to noise ratios. In a sedimentary basin, the highest, useful frequencies recorded are about 50 Hz and in rock material with a typical P-wave velocity of 5 km/s the corresponding wavelength is 100 m for this energy. The useful resolution of the technique can be extended to some, unknown, fraction of this shortest wavelength by studying the variations in form and time, as a function of horizontal distance, of correlatable, reflected energy, transients.

In a granite batholith, P-wave velocities will be typically 6 km/s but useful recorded frequencies may be as high as 200 Hz to yield wavelengths as small as 30 m.

We might expect, therefore, that acoustic discontinuities such as may be caused by, fractures, shear zones, changes in rock type or even a change in the pore pressure within the rocks, may be detectable if their vertical extent is of the order of several meters. The amount of energy reflected will depend on the density and velocity differences of the interface, however, strong reflections are often produced by interlayered bedding, with layer thicknesses of a small fraction of the wavelength and with small reflection coefficients. The lateral extent of the discontinuity must be sufficient to allow correlatable wave shapes to be recorded, as a function of distance along the surface profile, a matter, resolvable to some extent, by the choice of field recording geometry.

Field Procedure

A contract, awarded to the University of Manitoba, provided a 24 channel, Geo Space 211-T, binary gain, digital recorder, and an experienced technician, plus associated equipment, including cables and a recording truck.

A contract awarded to Mark Products, Calgary provided 36 linear arrays of seismometers. Each array was composed of nine (L15, 10 Hz, 600 ohm) elements, equally spaced over a cable length of 50 m, connected in series/parallel and damped to 0.6 critical.

A contract with Environmental Research Insitute of Michigan, provided a "thumper" unit, two technicians and a service truck. The thumper unit provided a source of compressional energy, produced by a 1 1/2 ton weight, dropped a vertical distance of about eight feet onto a steel pad previously hammered into the ground. An accelerometer, fixed to this pad, provided the zero-time signal to the recording equipment.

The field parameters chosen were:

1. A spacing between center points of each array of 30 m.
2. A digitization rate of 1000 Hz.
3. A recording duration of six seconds per thump.

4. Split-spread, roll-along profiling with a thumper to nearest recorded channel distance (minimum offset) of 90 m, i.e. for each thump, 12 recordings spaced over the distance 90 to 420 meters ahead of the thumper position and 11 recordings (one channel inoperative) from 90 to 390 meters behind the thumper, were obtained. Six thumps at each site were recorded, then the complete array and thumper moved ahead by 30 m.

5. No high-cut filtering other than the alias filtering supplied with the recording equipment, i.e. - 3 db. at 125 Hz to -80 db. at 250 Hz.

6. Low-cut filtering was provided by the seismometers with 12 db. per octave attenuation below the 10 Hz resonance.

7. 1200% common reflection point (CRP) stacking capability, i.e. thumper site and array site spacings are equal for 24 channel recording.

8. 600% stacking capability of successive thumper blows at each thumper site.

The two profiles indicated in Figure 1 comprise approximately 130 sites. It required approximately 60 hours of field work to complete these lines.

Horizontal and Vertical Control

Array centerpoint, distances were obtained to precisions of approximately 0.1 m using a surveyors chain. These measurements were related to topographic markers and plotted on a large scale (1" - 400') base map. Errors, relative to this map, proved to be less than ± 2 m. Coordinates east and north for each position from an origin (Figure 1) were measured from this base map. Elevations were obtained by linear interpolation of the contours of the base map to a precision estimated to be within ± 1 m.

As vertical velocity for compressional waves in the surface low-velocity-layer (LVL) is approximately 2 km/s and the highest frequencies recorded are approximately 200 Hz, one wavelength of this energy is approximately 10 m. An elevation precision of ± 1 m is therefore adequate for our data processing procedures that will use this statistic. As horizontal velocity is approximately 6 km/s (this energy travels beneath the upper layer) and the wavelength for 200 Hz energy is therefore, about 30 meters, a precision in lateral distance of ± 3 meters is adequate.

As the original base map is scaled in feet per inch, the position data of eastings, northings and elevations given in Table 1 have not been converted to metric measure, and have been "rounded" to the nearest 5 feet in elevation and 10 feet in lateral distance.

Data Processing

At each position along a profile, six, 24 trace (23 seismic plus 1 accelerometer) recordings were obtained. These were of six second duration, digitized at 1000 Hz. Approximately 800 of these recordings were obtained in traversing the two profiles.

These data were recorded on 9 track, 1/2 inch tape in SEG-A format, a standard of the oil exploration industry. Recording equipment malfunction rendered these tapes unreadable by standardized commercial computer programming. The data were therefore, reformatted by the University of Manitoba into block form. Individual blocks were read, demultiplexed and when necessary corrected, using a PDP-11 mini-computer at the EPB. These corrected data were then, again, reformatted to allow manipulation by the EMR, Cyber computer, a necessary procedure as memory requirements during one step of this manipulation required a storage capacity of approximately 5,000,000 computer words.

Equivalent traces (time-series) of the six recordings obtained at each position were amplitude normalized, shifted to make each time-series begin at the zero-time indication of the accelerometer and then added to each other. This procedure should, theoretically, improve the signal to random noise ratio by a factor of $\sqrt{6}$. This step reduced the data to 65 x 24 traces for Line 1 and 66 x 24 for Line 2. This is still a formidable number of data samples (65 x 24 x 6000 for line 1) and a reduction to a duration of 3 seconds (the first 3000 samples) from the 6 seconds recorded was adopted for subsequent manipulations. These "equivalent trace" stacks have been stored on magnetic tape as an "indexed sequential file" (see Appendix A for details of the format and calls required to access these tapes).

Displays of 0.5 seconds of these traces were obtained and served the dual purpose of, allowing an edit to remove poor traces from subsequent processing steps and allowing "first event" time picks and intercept times to be obtained. These displays are shown in Appendix B. The traces are individually normalized, and plotted at fixed gain, unfiltered. They are time shifted by a factor of $T - X/6000$, where T is the recorded sample time after the thumper pulse and X is the straight-line distance, in meters, between the thumper and recorder positions. Any correlatable event with an apparent velocity of 6 km/s will, therefore, be lined up vertically on these displays and it is apparent that the first events are very nearly so. Intercept time of each record was obtained from these plots by interpolation, to the thumper position, using the time picks of the adjacent traces. An estimate of the thickness of the low velocity layer (LVL) at each thumper position can thus be obtained, by multiplying half of the intercept time by an assumed velocity of 2 km/s.

These results for Profiles 1 and 2 of Figure 1 are shown plotted in Figure 2 and Figure 3. They provide a basis for computing time delays in the LVL and to a datum plane for a ray path travelling nearly vertically, beneath the thumper and recording positions, corrections that are required in subsequent processing.

The indexed sequential files for each line are searched for common reflection point (CRP) traces and written to tape. These "CRP gathers" have been retained (see Appendix A for details). The time series samples, of each trace are amplified by a varying gain function based on the computed power within a 200 sample (0.2 seconds) moving window. A time shift is then calculated and applied to correct each trace for its thumper and recorder position elevations relative to a datum plane and for the LVL delays at these points. A variable time shift (normal moveout) that, effectively, corrects each wave trajectory from the slanting paths required by the field geometry (thumper to reflector to recorder) to a vertical trajectory are then applied. Each trace is then filtered (Fourier transformed to the frequency domain, normalized to a desired pass band, then transformed back to the time domain). Data samples at these corrected times, common for each trace of the CRP gather are then summed to produce one composite trace. These resulting traces are then normalized to a common maximum amplitude, related in position to the mid point between thumper and recorder positions and, finally, plotted.

The processing, simply described in the foregoing paragraph, is in fact a rather time consuming, expensive computer operation. The plots of Figures 4 and 5 cost approximately $400.00 each to produce from the CRP gather tapes.

The processing steps described are standard techniques. The programming software developed at EPB to achieve these steps may be found in Appendix A.

Discussion

Figures 4 and 5 are the result of a 1200%, CRP stack using a filter (BPNORM) that shapes the frequency spectrum of each trace to unity between 24 and 48 Hz and applies a cosine weighting function to reduce the spectral amplitudes to zero at 12 and at 96 Hz. This filter forces all traces to have the same frequency spectrum but does not alter their phase spectrum. It's effect is to, generally, increase the high frequency content of the recorded time series within the selected passband.

There appears to be no correlatable energy, as a function of distance, on these plots.

The 1200% gather traces are composites made up of corrected time series recorded with thumper to recorder position offset distances varying from 90 m to about 400 m. It is quite possible that, within this range of distance, significant lateral variations in velocity and structure could occur that would destroy the value of the CRP stacking process. We can reduce this range of offset distances by using only the recorded traces nearest the thumper position. Figure 6 is a 600% stack wherein the range of distance within each gather is from 90 m to just over 200 m. Again, there appears to be no useful correlations.

This really, is not too surprising as, in the short discussion on the resolution of the method, it was suggested that to detect an acoustic discontinuity its vertical dimension should be some reasonable fraction of the wavelength of the highest recorded frequency. The filter used for these sections begins attenuation of frequencies above 48 Hz and this frequencies wavelength is approximately 120 m in the batholith. To seismic energy with wavelengths of this dimension and greater, the rock structure in this area at Chalk River appears virtually, homogeneous, to the full depth of these sections of approximately 9 km (3 seconds ÷ 2 x 6 km/second). A negative result perhaps but, in fact, one that would be considered as favorable insofar as the qualifying of a radioactive waste disposal site was concerned.

Figures 7 and 8 are the results of a 600%, near-trace, CRP stack and a filter with a pass-band of 80 to 200 Hz. We violate a principle here by forcing the pass-band to 200 Hz as, during the recording, we used an alias filter that attenuated frequencies above 125 Hz. We therefore, are introducing non-seismic noise in the range above about 150 Hz. It is interesting noise however, and indicates how one could be misled by an artifact of the field and processing sequence. The correlatable transient at about 0.4 seconds, probably results from some low-level switching noise in the recorder. The fact that this noise stacked in phase for all of Line 2 but only the left half of Line 1 was due to a change in the field operation. The right half of Line 1 was recorded first and, during this period, the time shifts of individual recordings to the zero instant were obtained by analysis of the accelerometer wave-form. The zero instants were randomly distributed over the first half second or so of the recording interval whereas the switching transient was, apparently, fixed in relation to the start of the recording cycle. Stacking of the six recordings at each position with randomly distributed time shifts would therefore stack the switching transients out of phase. During the recording of the last half of Line 1 and all of Line 2 we were able to operate (properly) using the accelerometer signal to trigger the recording cycle. As no time shifts were therefore required, the transient then stacked in-phase and our illegitimate, filter pass-band has made visible this instrument noise.

Ignoring the transient, we can see no useful, correlatable seismic energy on these plots, nor have we been able to detect any on plots using filters with legitimate, but necessarily lower, band-passes.

The data can be subjected to further processing steps such as "Fan" filtering and deconvolution. These procedures will be time consuming and expensive as they require fairly major modifications to some of our existing software and a more or less "cut and try" approach to data enhancement. This work will be done as time permits.

Conclusions

We have discussed the physical size and nature of a discontinuity that would be expected to be revealed by the CRP method. The "first event" data (Appendix B) indicate no significant velocity variation for the near-horizontally travelling seismic energy, i.e. we detect no lateral heterogeneities of sufficient size and velocity difference to affect the CRP stacking process. We must therefore conclude that the Chalk River batholith, beneath a shallow LVL, in the area traversed by the two profiles, appears virtually homogeneous to seismic energy in the frequency range up to 125 Hz, with the field parameters employed. Discontinuities almost certainly exist, within a depth interval and lateral distances of a kilometer or so, but are beyond the resolving power of the method employed.

Recommendations

We can not be sure, after this first survey, that the resolving power of the method, as used, requires vast improvement for the surveying of other sites. Increased resolution involves much higher cost and should be carefully balanced against the objective. For the first step in the site selection process our concern should be with the detection and mapping of major discontinuities, at all sites, at a reasonable cost. The second step, for sites not disqualified by step one, to be the application of a much higher resolution field procedure.

As the number of sites to be investigated may be large and the time available short, this seismic reflection work should be contracted to Industry.

A contract with Geoterrex to evaluate a field technique (Mini-Sosie) differing from that described in this report only as to the much lower energy of the source and much higher "equivalent trace stacking" employed has been let for short surveys at Pinawa, Man. and at Chalk River, Ont. At Chalk River, over part of Line 1, we will evaluate the use of much higher resonant frequency seismometers, higher recorded pass-band, 10 m spacing of recording sites and no in-line seismometer arrays but with horizontal noise reduction achieved using a moving source.

The real test of the method should occur at W.R.N.E., Pinawa, Manitoba in Jan.-Feb. 1979. A shear zone has been discovered, by drilling, at about the 400 meter depth. The contracted, Mini-Sosie reflection profiling, will attempt to map this known discontinuity. If the technique is unable to clearly delineate this zone, we must reconsider the probable potential of the CRP seismic method as a tool for site selection.

TABLE 1

Measurements in feet

LINE - 1

Origin: 16,735,000 N/1,023,000 E

EAST	NORTH	ELEVATION	POSITION
1790.	6100.	40[illegible].	1
1740.	5990.	398.	2
1720.	5770.	398.	3
1720.	5650.	395.	4
1720.	5540.	392.	5
1690.	54[illegible].	390.	6
1640.	53[illegible].	389.	7
1600.	5[illegible].	388.	8
1610.	5110.	395.	9
1670.	5010.	395.	10
1770.	4950.	395.	11
1880.	4910.	395.	12
1950.	4850.	395.	13
2030.	4750.	395.	14
2060.	4630.	390.	15
2100.	4[illegible]0.	390.	16
2170.	4440.	395.	17
2260.	4360.	400.	18
2360.	4300.	400.	19
2460.	4260.	400.	20
2550.	4200.	400.	21
2650.	4130.	400.	22
2720.	4060.	405.	23
2820.	4000.	405.	24
2890.	3880.	405.	25
2930.	3780.	405.	26
3010.	3700.	405.	27
3110.	3640.	410.	28
3210.	3600.	410.	29
3320.	3570.	420.	30
3400.	3470.	420.	31
3480.	3410.	415.	32
3550.	3310.	415.	33
3590.	3200.	415.	34
3630.	3090.	415.	35
3660.	2980.	415.	36
3690.	2840.	410.	37
3730.	2740.	405.	38
3770.	2640.	405.	39
3790.	2520.	405.	40
3790.	2400.	405.	41
3790.	2280.	405.	42
3780.	2170.	405.	43
3790.	2050.	400.	44
3830.	1960.	395.	45
3890.	1860.	395.	46
3970.	1770.	390.	47
4050.	1690.	390.	48
4140.	1590.	390.	49
4210.	1490.	390.	50
4280.	1400.	395.	51
4350.	1320.	395.	52
4440.	1230.	395.	53
4520.	1140.	395.	54
4570.	1060.	400.	55
4650.	980.	405.	56
4720.	930.	410.	57
4800.	840.	410.	58
4910.	800.	415.	59
5020.	770.	420.	60
5140.	710.	425.	61
5240.	640.	430.	62
5330.	560.	430.	63
5410.	490.	430.	64
5520.	420.	430.	65
0.	0.	0.	66
0.	0.	0.	67
0.	0.	0.	68
0.	0.	0.	69
0.	0.	0.	70
0.	0.	0.	71
0.	0.	0.	72

LINE - 2

Origin: 16,729,000 N/1,025,000 E

EAST	NORTH	ELEVATION
5790.	7810.	565.
5700.	7750.	555.
5610.	7690.	550.
5510.	7630.	545.
5410.	7560.	540.
5320.	7500.	535.
5220.	7450.	530.
5135.	7380.	529.
5040.	7300.	525.
4955.	7220.	520.
4860.	7150.	515.
4770.	7080.	505.
4670.	7000.	500.
4560.	6920.	495.
4490.	6840.	485.
4400.	6770.	480.
4320.	6680.	470.
4250.	6560.	465.
4190.	6480.	460.
4140.	6370.	460.
4120.	6260.	455.
4100.	6140.	450.
4080.	6020.	450.
4060.	5910.	445.
4040.	5790.	445.
4025.	5680.	435.
4020.	5560.	430.
4000.	5450.	425.
3990.	5340.	415.
3980.	5230.	410.
3970.	5120.	405.
3950.	5000.	405.
3930.	4890.	405.
3920.	4780.	400.
3900.	4680.	400.
3890.	4570.	400.
3870.	4450.	400.
3850.	4330.	400.
3830.	4210.	400.
3780.	4110.	395.
3720.	4010.	390.
3660.	3910.	385.
3590.	3820.	385.
3510.	3740.	385.
3430.	3660.	365.
3340.	3580.	390.
3260.	3520.	390.
3180.	3450.	390.
3100.	3370.	395.
3010.	3300.	405.
2920.	3210.	415.
2840.	3140.	420.
2740.	3060.	420.
2660.	2990.	420.
2580.	2910.	415.
2490.	2840.	415.
2410.	2760.	415.
2320.	2670.	410.
2230.	2600.	410.
2140.	2510.	410.
2060.	2420.	415.
2000.	2330.	420.
1940.	2260.	425.
1860.	2160.	440.
1770.	2070.	450.
1680.	2000.	457.
1590.	1930.	465.
1480.	1870.	475.
1370.	1840.	483.
1270.	1810.	490.
1160.	1[illegible]10.	495.
1050.	1800.	500.

BASE MAP

Topographic Plan A and C

Chalk River Nuclear Laboratory

by Aero Photo Inc., Dec. 1965

Scale 1 inch = 400 feet

Elevation contour interval = 5 feet

No. X-4500-1

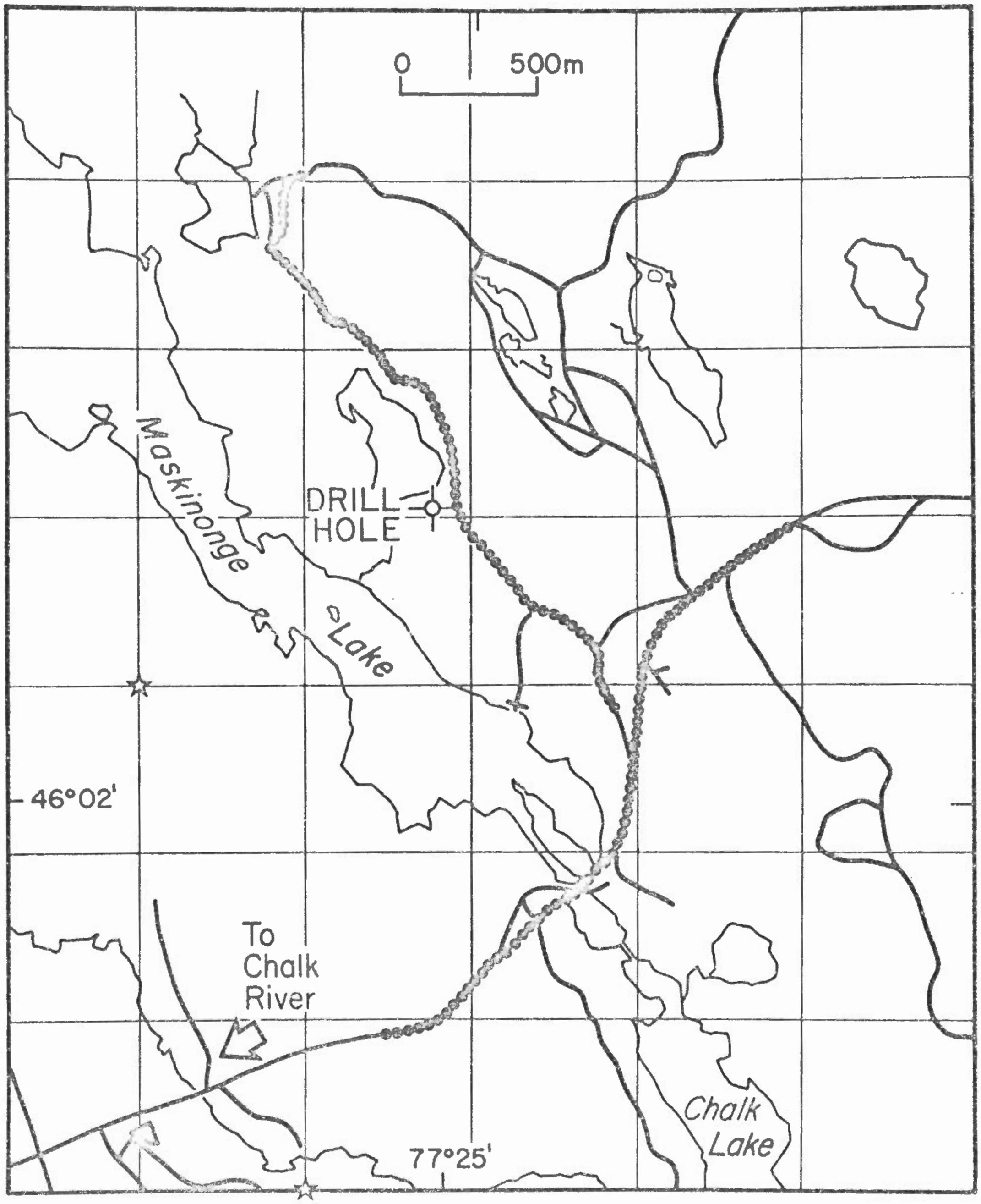

Figure 1: From Aero-Photo Inc., Topographic Plan A and C, Chalk River Nuclear Laboratory, Dec. 1973, Base Map X-4500-1 Thumper and recorder positions are indicated with dots. Profile 1 position 1 at upper left, origin of coordinates (star) at center left.
Profile 2, position 1 at center right, origin of coordinates (star) bottom left.

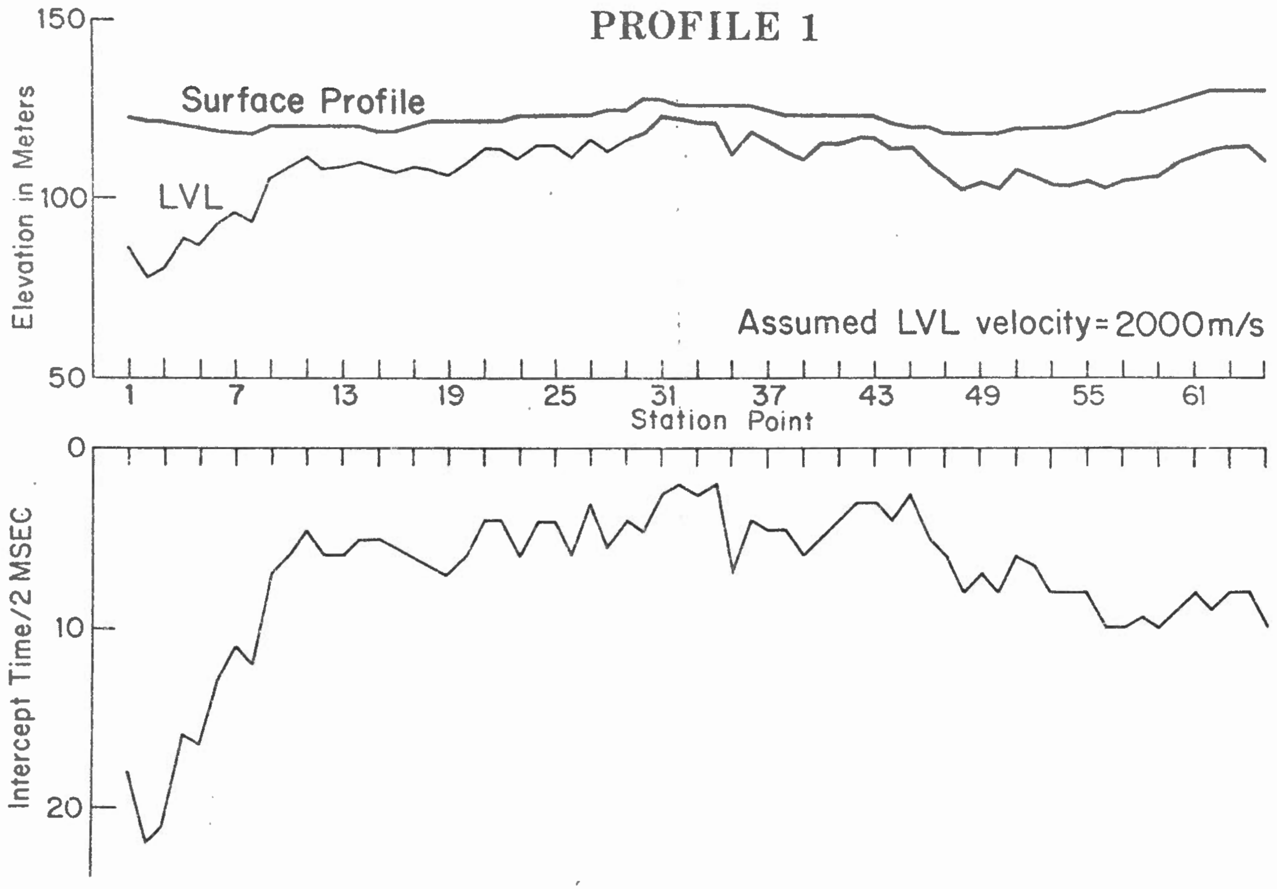

Figure 2: Profile 1, low velocity layer thickness as deduced from intercept times.

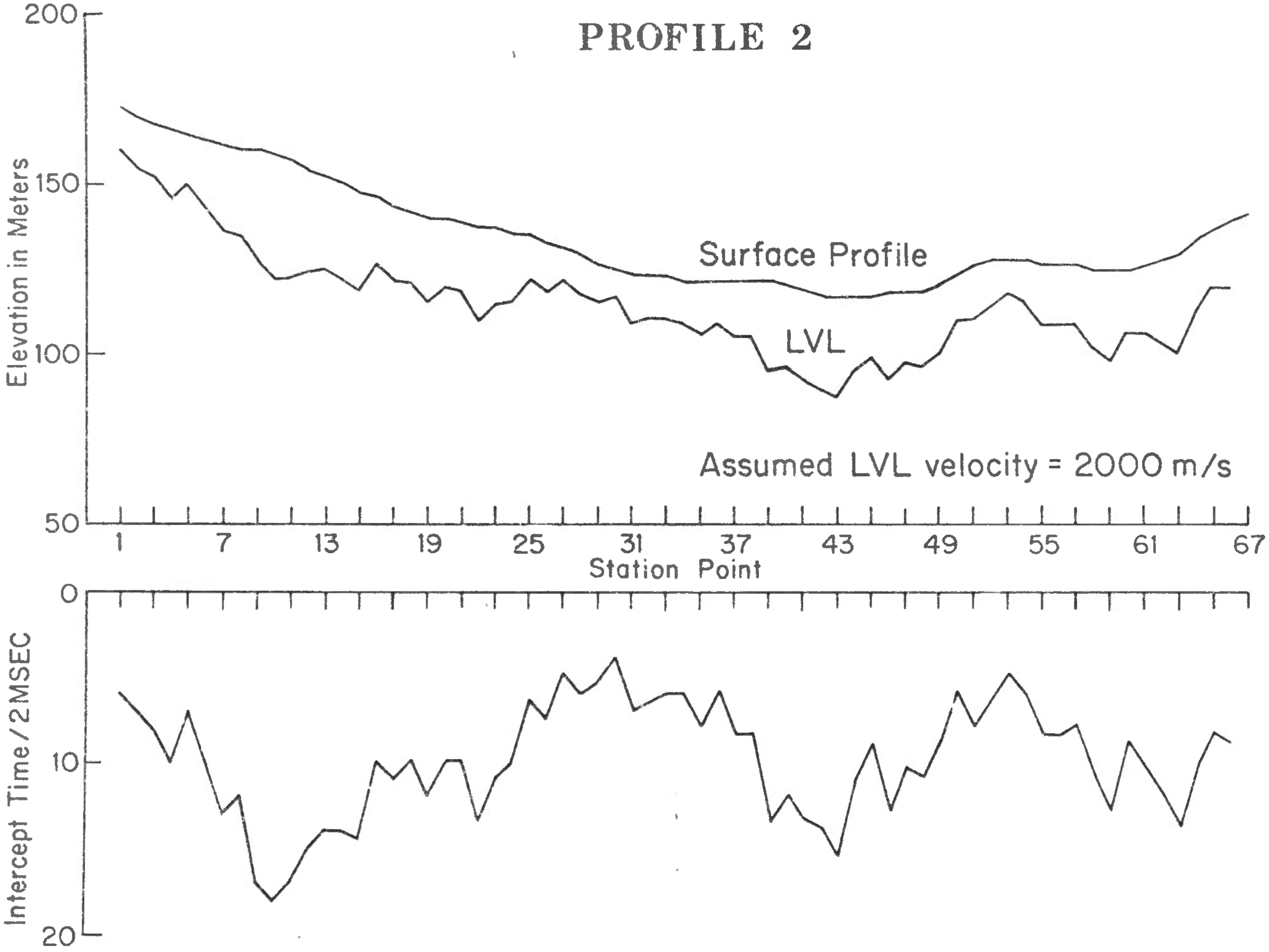

Figure 3: Profile 2, low velocity layer thickness as deduced from intercept times.

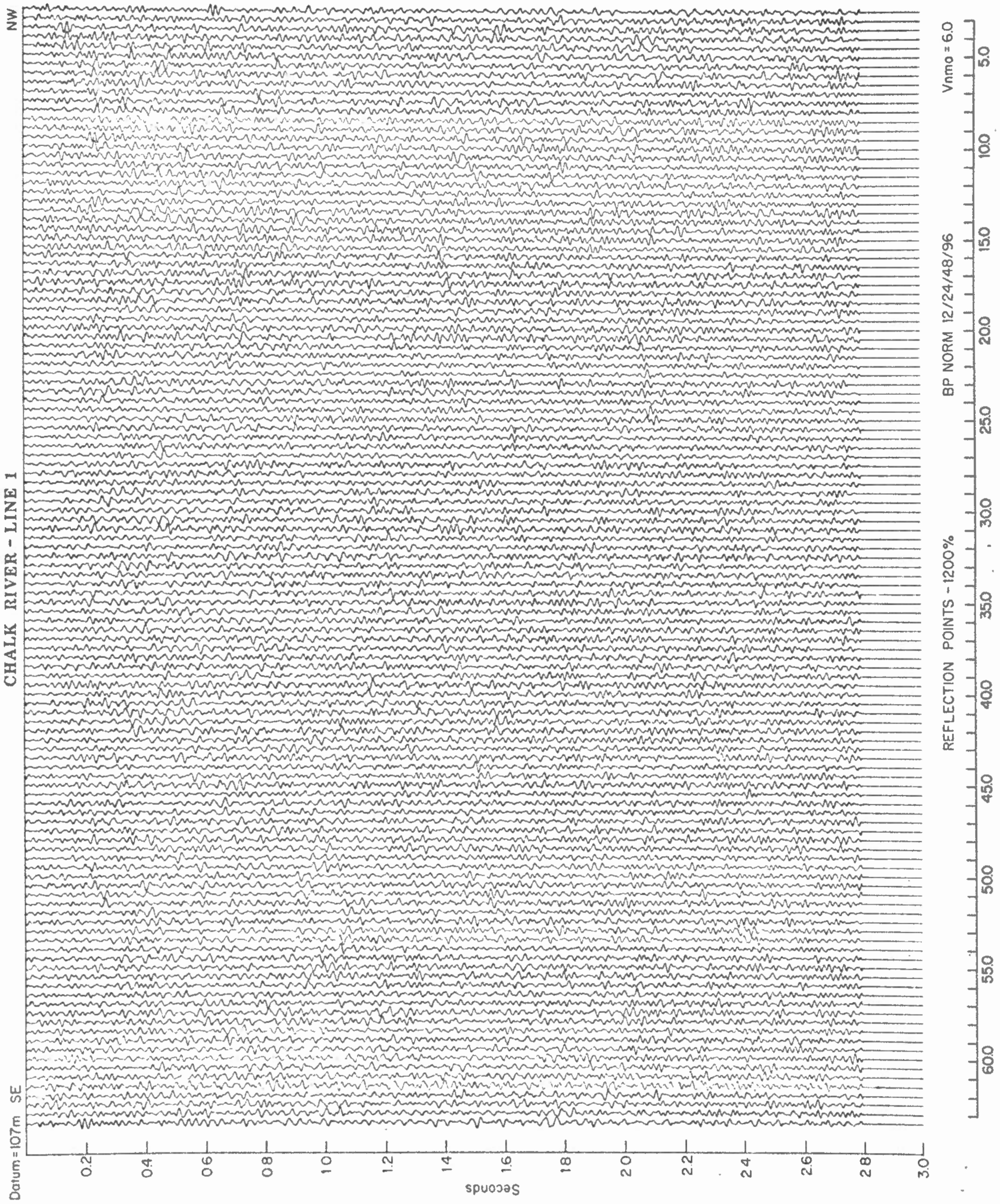

Figure 4: Profile 1, 1200% CRP stack, filtered 12/24/48/96

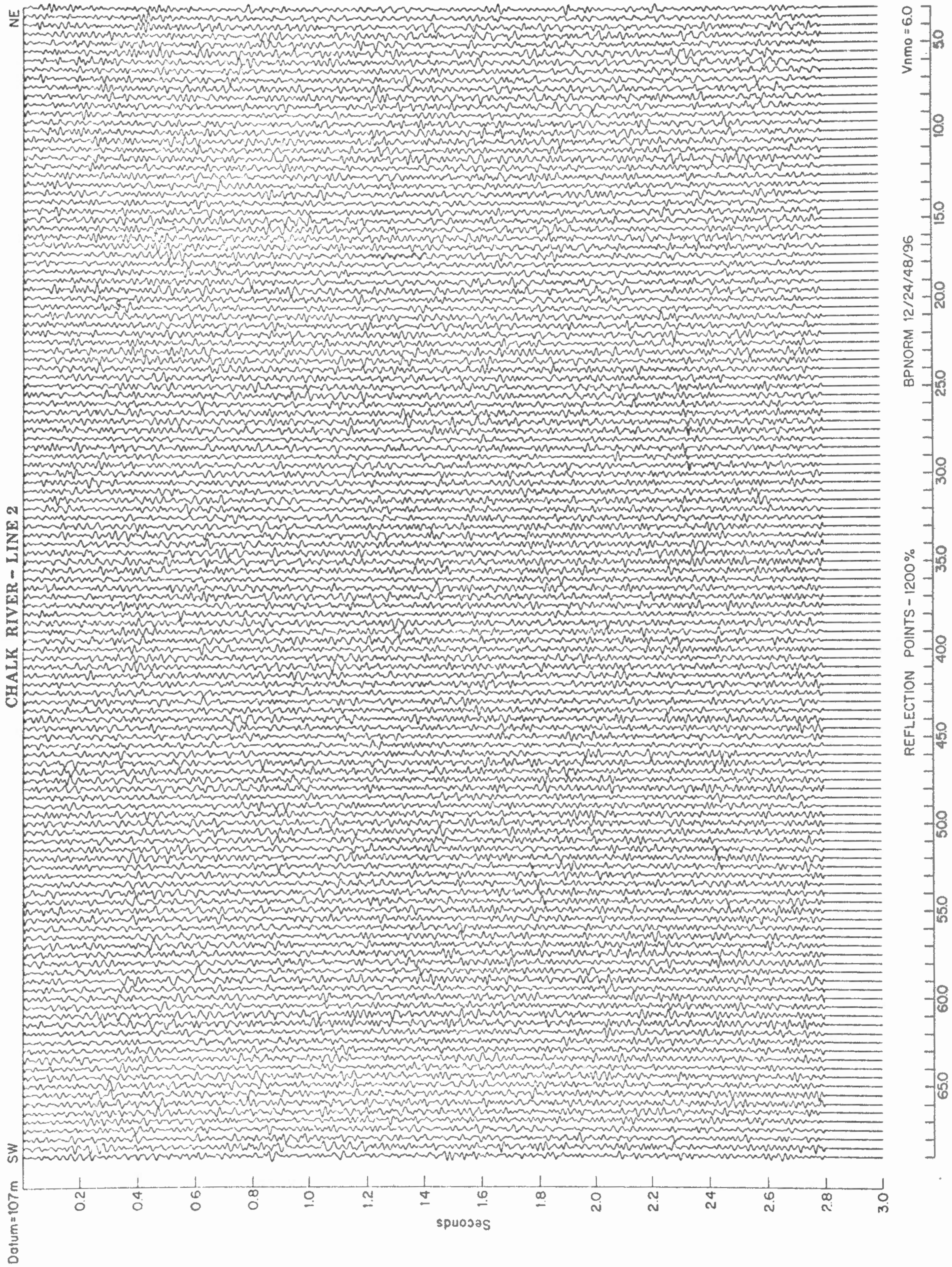

Figure 5: Profile 2, 1200% CRP stack, filtered 12/24/48/96

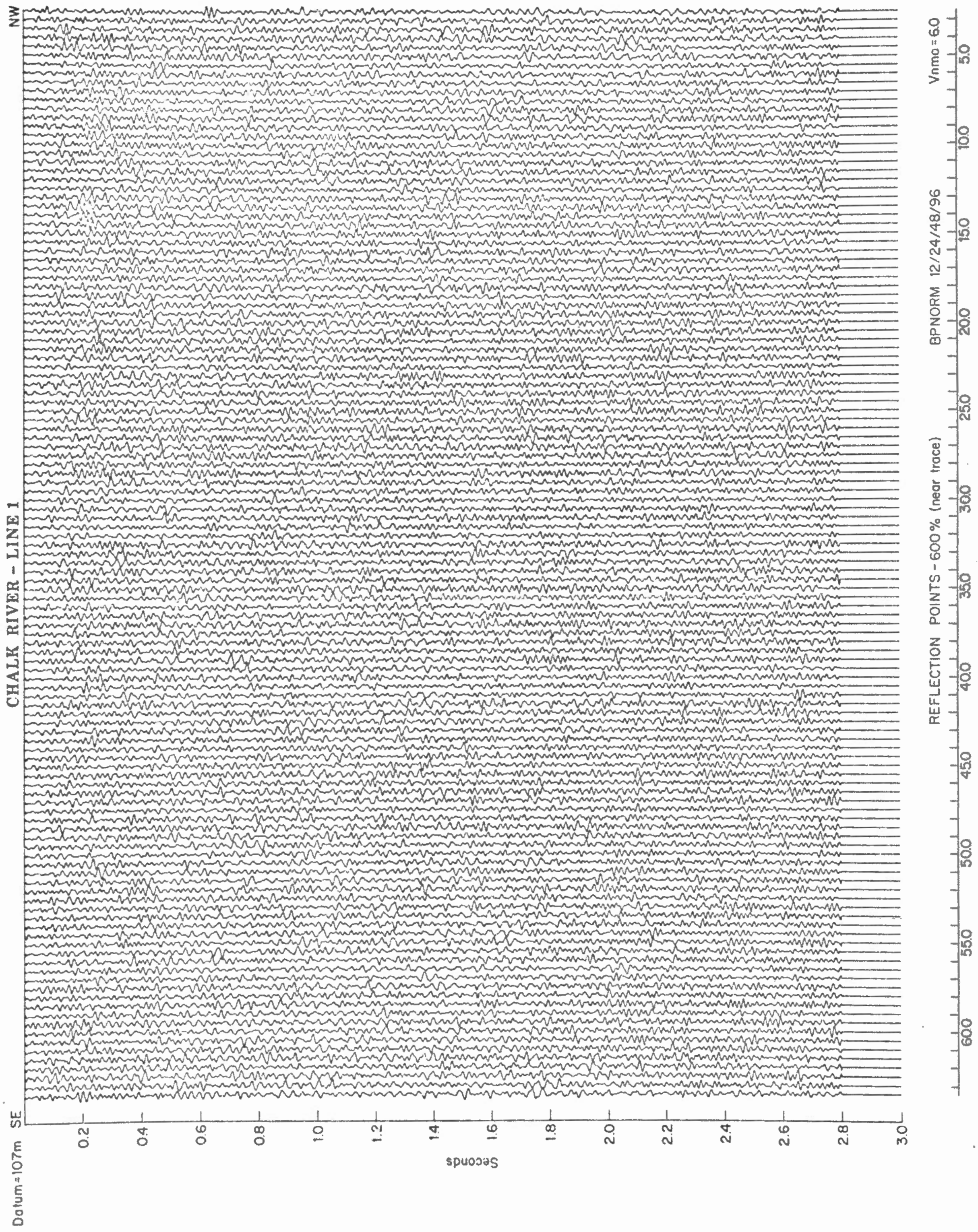

Figure 6: Profile 1, 600% CRP stacked, filtered 12/24/48/96

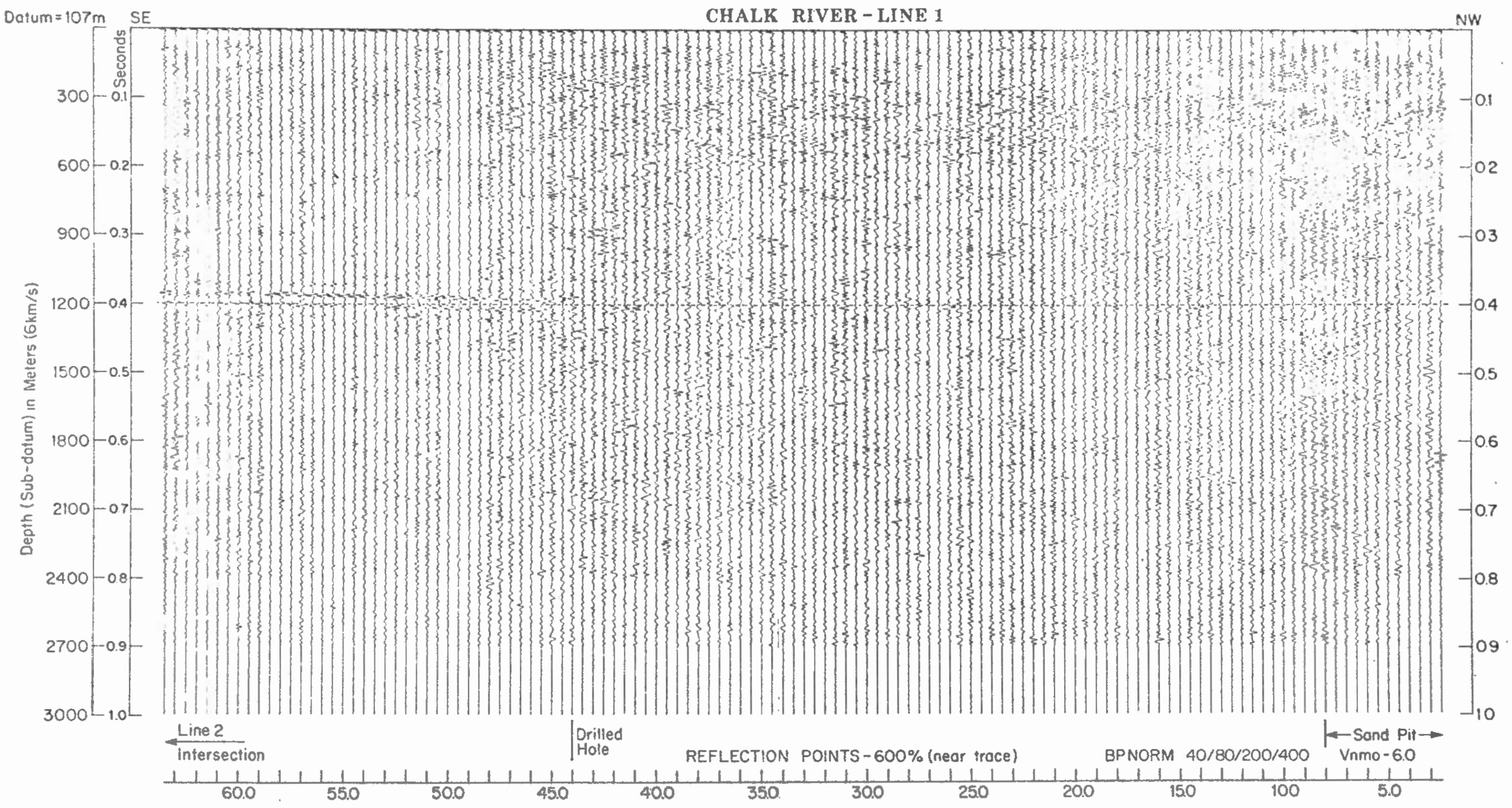

Figure 7: Profile 1, 600% CRP stack, filtered 40/80/200/400

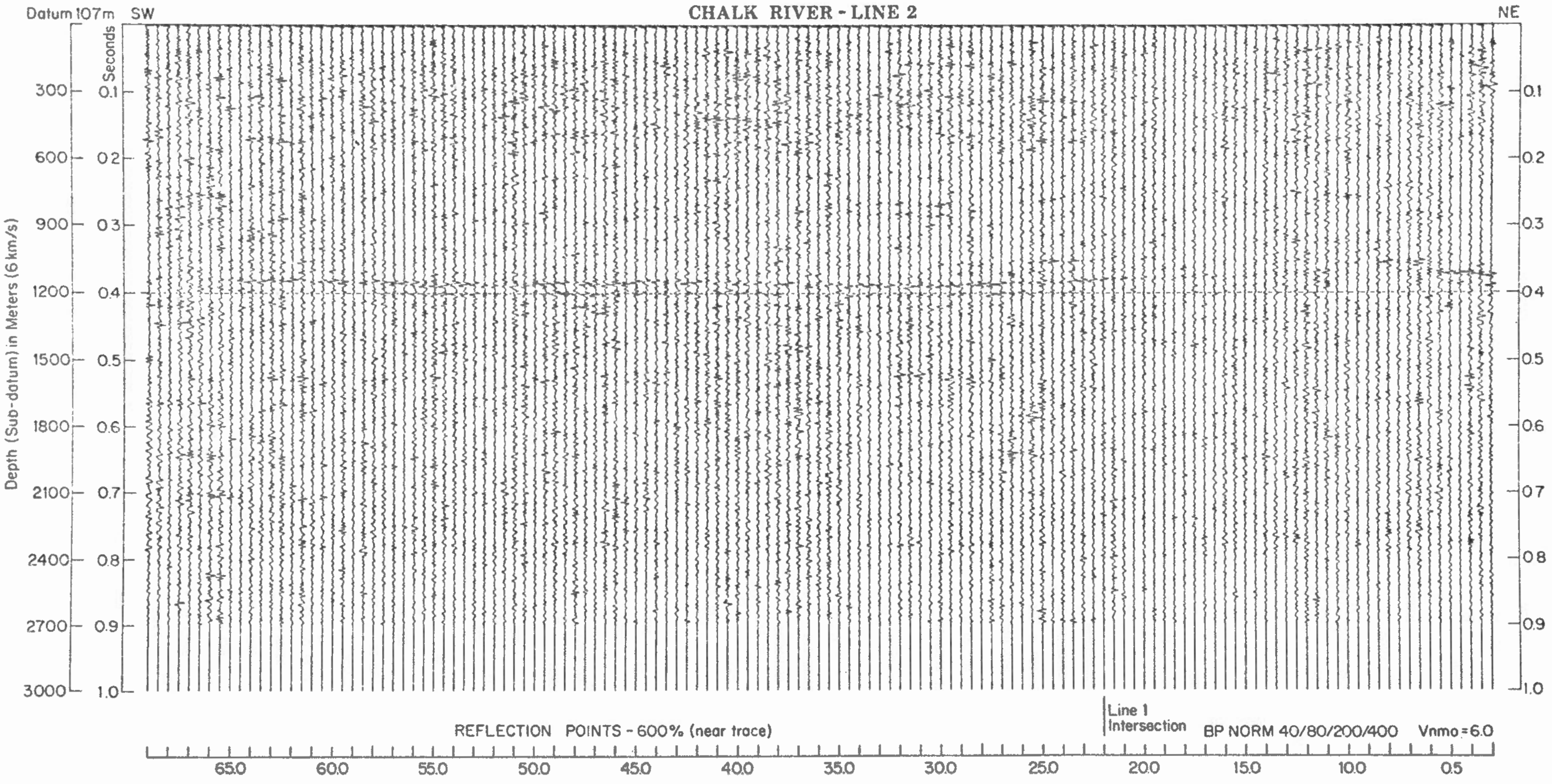

Figure 8: Profile 2, 600% CRP stack, filtered 40/80/200/400