

USING A VERTICAL SEISMIC PROFILE TO INVESTIGATE A MULTIPLE PROBLEM IN WESTERN CANADA

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ABSTRACT

A major benefit of the Vertical Seismic Profiling Method (VSP) stems from its ability to distinguish multiple events and identify the generating system unambiguously. In this study, a VSP was recorded in an area of western Canada where long-period multiples are a particular problem. One of the objectives of the study was to clarify the multiple problem at the zone of interest and evaluate methods of multiple attenuation on the seismic data. Effective attenuation methods in this area would greatly assist seismic interpreters.

By separating the VSP into its up-going and down-going wave components, the major problem was identified as a first-order multiple from a shallow event, followed by a weaker peg-leg. In order to make meaningful comparisons with seismic data, the down-going wavelet character measured by the well geophone was analyzed. This analysis showed major variations in both phase and spectral bandwidth. However, a series of control wavelets measured by a geophone at the surface indicated that these variations were due mainly to changing shot-hole conditions. Hence it was assumed that the wavelet character did not vary significantly with depth and the VSP was deconvolved by using the individual down-going wavelets.

The excellent tie between VSP and surface seismic data, as well as zero-phase synthetic data, confirmed the validity of the deconvolution procedure.

To minimize multiple interference on the seismic data, two techniques were employed. One method used the VSP itself to design the attenuation operator, while the other method used differential moveout in the F-K plane. In each case, the resulting seismic data were evaluated by comparing the seismic response with the VSP response.

VSP FIELD ACQUISITION TECHNIQUE

Energy was provided by shooting 0.25 kg dynamite charges in a 15-m deep, 0.8-m diameter, cased and cemented hole. A 12-m water tamp was maintained throughout the survey. Energy was received by a wall-lock well geophone which was locked in position for every shot at 15-m intervals from total depth to surface casing. The well geophone had a natural frequency of 10 Hz and a frequency amplitude response within 3 db from 8 to 300 Hz. The cable was slacked 8 m at each shot level so cable waves would not be transmitted.

The shot-hole was located 65 m from the well. It was felt that as this area did not have a strong ground roll problem, tube waves would not be significant and thus a short shot-hole to well distance could be tolerated. This proved to be the case as only low-amplitude tube waves were observed on the VSP (Fig. 1).

As the data quality was good, and to minimize rig standby time, each level was shot once. Twelve hours were required to shoot 130 levels. To preserve a quiet environment, all motors on the well site were shut down for the duration of the survey.

The signal was recorded on a four-channel multigain ranging digital recorder at a 1-ms sample rate. One channel was used to record the measurements from a surface reference geophone. Several surface reference geophones with varying natural frequencies and damping factors were used at different times during the survey to test their responses. This was unfortunate, as it complicated the use of the reference signal in determining changes in the source wavelet over time. The problem was alleviated by dephasing all the reference geophone signals at the processing stage.

The 15-m vertical spacing was selected to ensure that a relatively broad-band response would be preserved after F-K filtering.

TEMPLATE SEISMIC

The template seismic line, to be shown in later figures, was shot after the well was drilled. These data were

INTRODUCTION

In March 1981, a Vertical Seismic Profile was shot by Hudson's Bay Oil & Gas Ltd. in an area of western Canada where long-period multiples are a particular problem. It was hoped that by studying the multiple wave train and primary response separately, the multiple generating system could be understood and various multiple removal schemes evaluated.

This paper describes the acquisition, processing and interpretation of the VSP and also evaluates two multiple removal schemes on a template seismic line.

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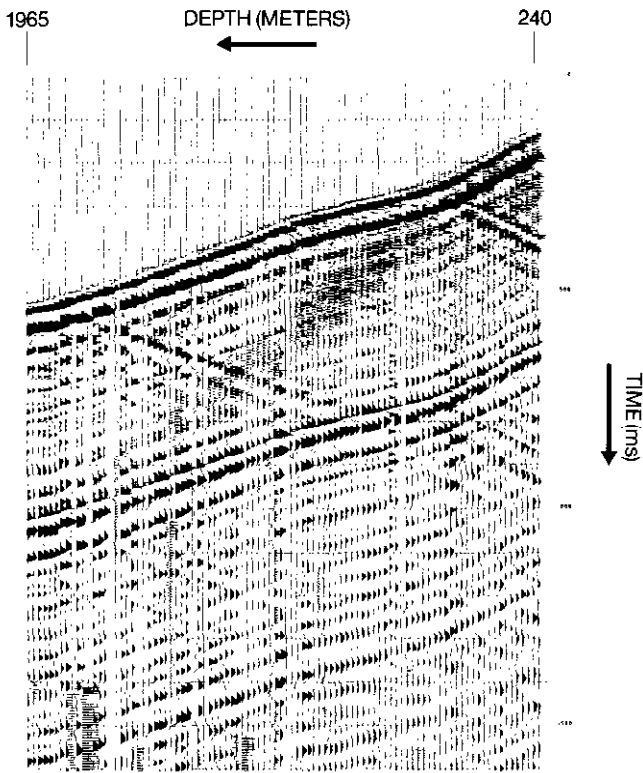


Fig. 1. Vertical seismic profile before processing.

recorded with a 96-channel instantaneous floating-point recording system with a 2-ms sample rate. Recording parameters were: a group interval of 33.5 m, a shot interval of 134 m, offsets from 33.5 to 1609 m on a

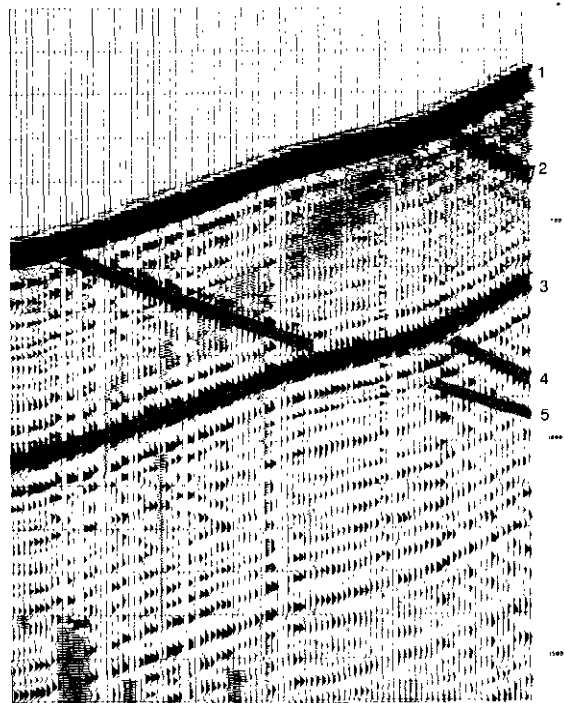


Fig. 2. Interpretation of VSP.

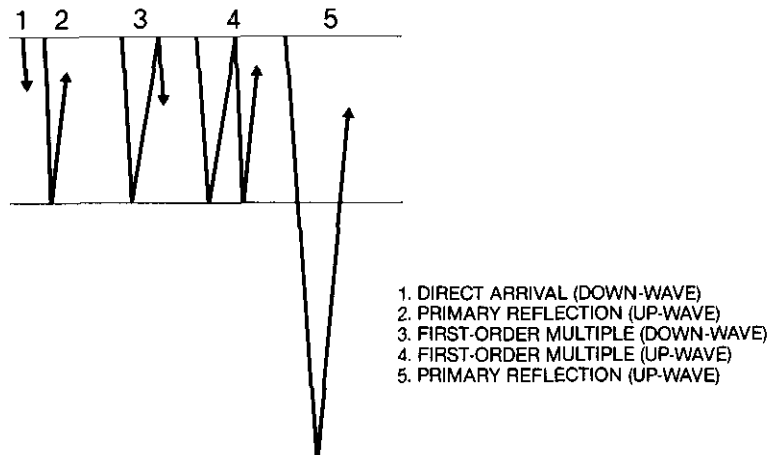
symmetrical split spread, recording filters of out-128 Hz, and a 1-kg dynamite charge in a 14-m shot-hole.

The processing sequence included exponential gain recovery, spiking deconvolution, normal moveout correction, automatic statics, bandpass filter and stack.

PROCESSING

One of the major benefits of the VSP method stems from the fact that, as the receivers are measuring signals at depth, energy is recorded while moving downward as well as upward. As a result, the events recorded on the VSP form a simple pattern as shown in Figure 1 — all events dipping from right to left (such as the first breaks) came from energy moving down through the earth, whereas the events dipping the opposite way were moving upward when recorded. The interpretation of the various events is straightforward and has been discussed by numerous authors (e.g., Kennett, Ireson and Conn, 1980). Basically, if the offset from borehole to shot is small and the reflecting horizons have small dips, all the downward-dipping events are strictly parallel and have a shape that follows the average velocity as a function of depth. Similarly, the updipping events are parallel and have a dip with the same magnitude but opposite sign from the down-dipping events.

Figure 2 shows the interpretation of the major events on the VSP. All the down-dipping events are multiples except for the first breaks. The up-dipping events can be either primaries or multiples — the rule being that if the event extends all the way to the first breaks it is a



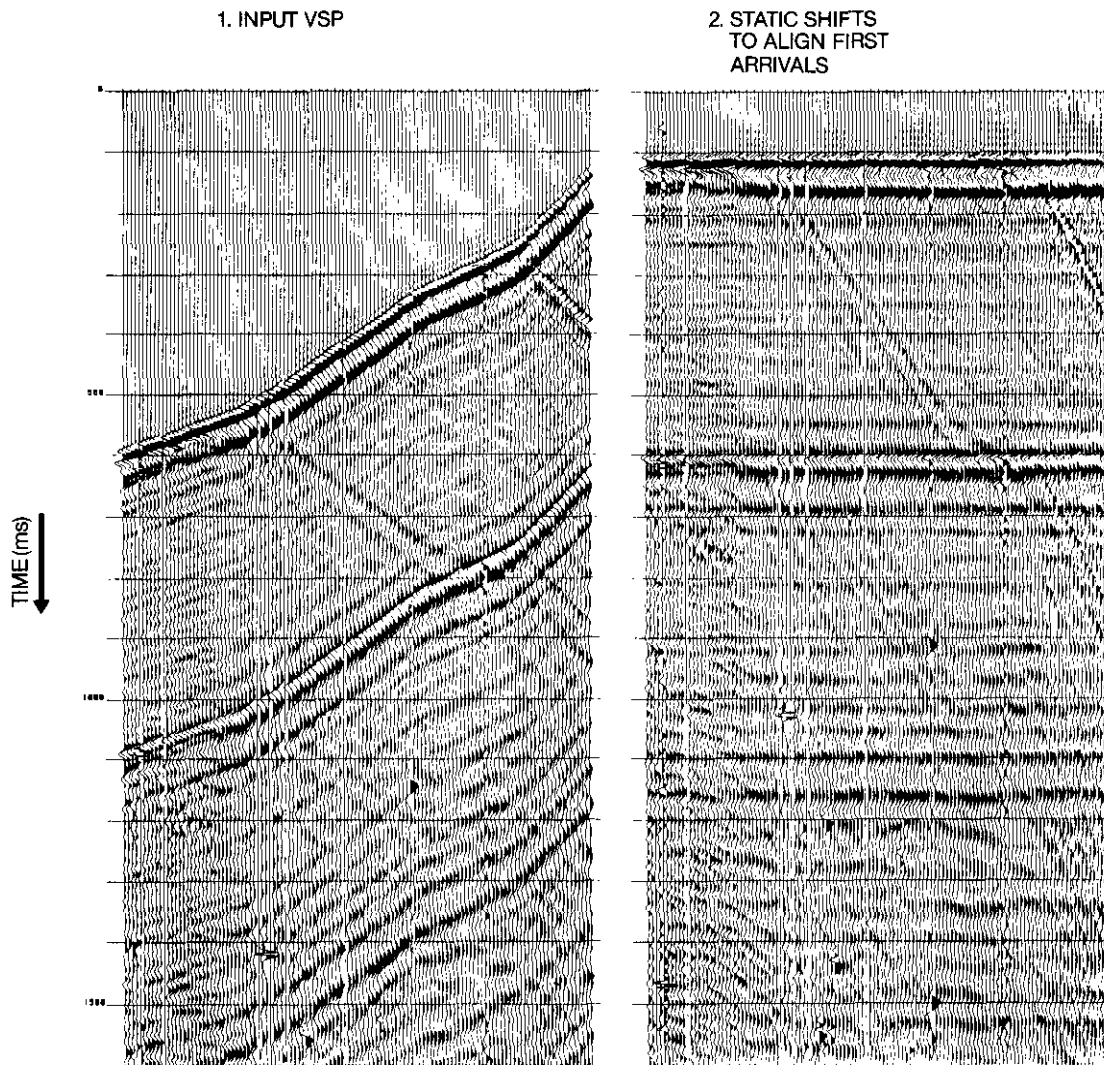


Fig. 3. Producing up-wave section.

primary (as in event 2); otherwise it is a multiple (as in event 4). The deepest primary involved in generating a given up-going multiple is identified by finding the termination point of the multiple event and tracing vertically upward through the VSP to the first breaks, which should coincide with the termination point of a primary. In Figure 2, event 4 is a multiple generated between event 2 and the near surface.

For analysis, it is convenient to separate the VSP into two parts, one of which contains only upward-moving energy, and one of which contains only downward-moving energy. This is achieved by F-K filtering as shown in Figures 3 and 4. In Figure 3, the first breaks of the VSP are aligned by applying a series of static shifts. In the process, the other down-going events are aligned as well, since they are all parallel. In Figure 4, an F-K filter has been applied, which suppresses zero-dip energy, and the original static shifts are removed twice, with the result that the up-going events are aligned. Similarly, the up-going events may be suppressed, leaving the down-going events aligned.

The two resulting displays are shown in Figures 5 and 6. The horizontal axis of the up-wave section (Fig. 5) measures the depth of the receiver, and each trace shows the seismic response that would result if seismic data were recorded with the receivers at that level (and only upward-moving energy recorded). The multiple at 1000 ms is clearly visible, as well as the primary event at 1050 ms. It is also clear that the reflection quality of the primary is affected by the presence of the multiple.

Figure 6 shows the nature of the multiple problem. The interpretation of the down-going wave section is that each trace shows the total incident wavelet at every level. By studying the wavelet change from trace to trace, we can track the change in wavelet character with depth (assuming a constant shot condition). The first breaks in Figure 6 can be thought of as the basic seismic wavelet, while the later events are the multiples that will form the tail of every primary reflection below the receiver. In this case, most of the multiple energy is concentrated about 500 ms after the first breaks, indicating that most of the multiples on the up-wave section (or

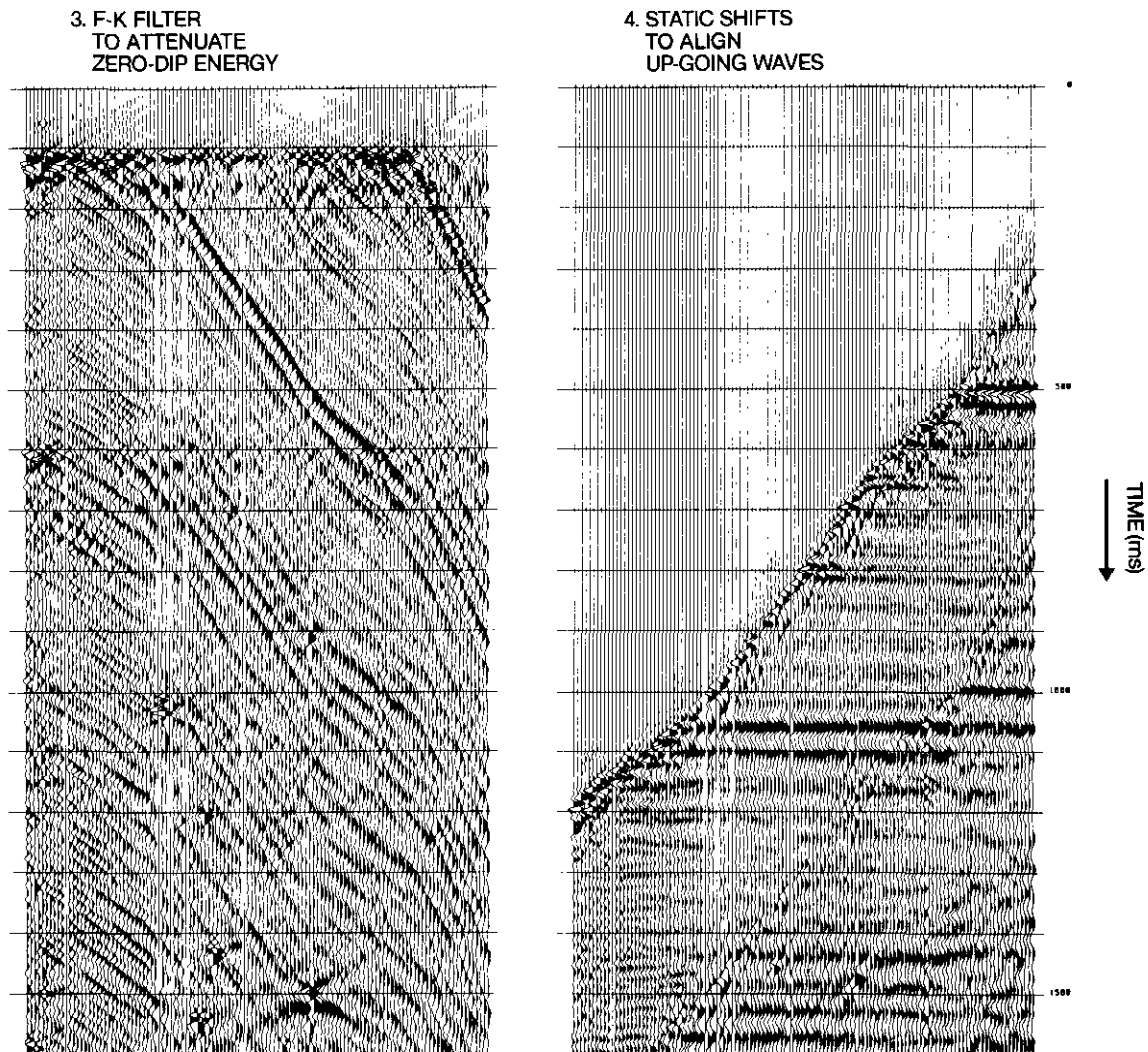


Fig. 4. Producing up-wave section.

seismic data) are caused by the single extra bounce between the primary at 500 ms (top of Wabamun) and the near surface. Other smaller-amplitude events on Figure 6 between 100 ms and 600 ms correspond to shorter-period peg-legs possibly set up between the Wabamun and later events. A multiple that is set up in this way could not be measured as a down-going wave by receivers above the Wabamun, so that such an event should terminate at the Wabamun depth (534 M) on the down-wave section. Although some of the events on Figure 6 (e.g., around 460 ms) do appear to terminate in this way, it is not clear at exactly which depth.

In order to study the basic wavelet character, Figures 7 and 8 show the first breaks (without spherical divergence compensation). Also shown is a plot of the amplitude spectrum of each wavelet in the range 0-100 Hz. The analysis of this display is an important part of the processing, because it is essential to bring the up-going wave VSP as close as possible to zero-phase. On examining the wavelets, it is apparent that they fall into three distinct groups: 1) the wavelets measured above the

Wabamun, 2) the wavelets measured below the Wabamun, but above the level marked "character change" in Figure 8, and 3) the wavelets measured below this level. It is important to determine whether the changes observed here represent real changes in the wavelet character as it moves through the earth, or whether it is the shot condition that is varying.

First of all, the wavelets measured at the deepest levels are apparently of broader bandwidth than the wavelets measured above — that is, opposite to the expected wavelet changes due to absorption or interbed multiple generation. Apparently, the sudden change observed at the deeper level is due to a change in the shot condition itself. Figure 9 tends to support this interpretation. A geophone located on the surface close to the bore-hole was used to measure the direct arrival from some of the VSP shots. The surface geophone was either a 30-Hz or a 50-Hz phone as indicated in the figure, whereas the down-hole geophone was a 10-Hz phone. In Figure 9, the two sets of wavelets are shown, after the appropriate phase compensation for the differ-

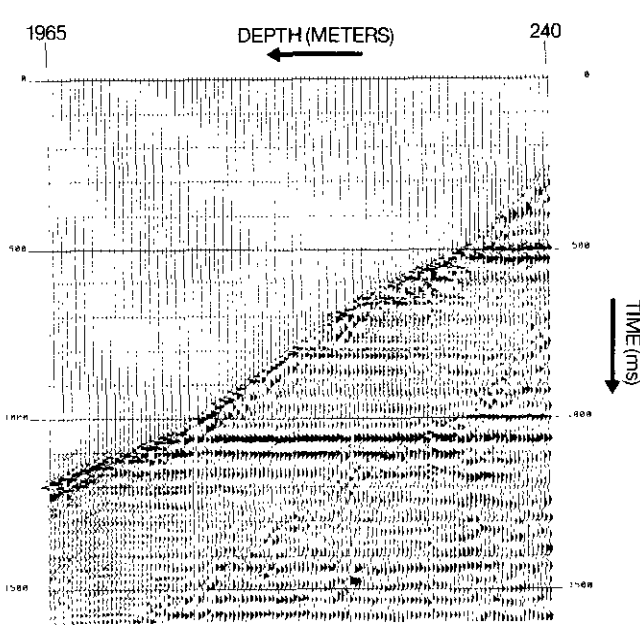


Fig. 5. Up-going wave section.

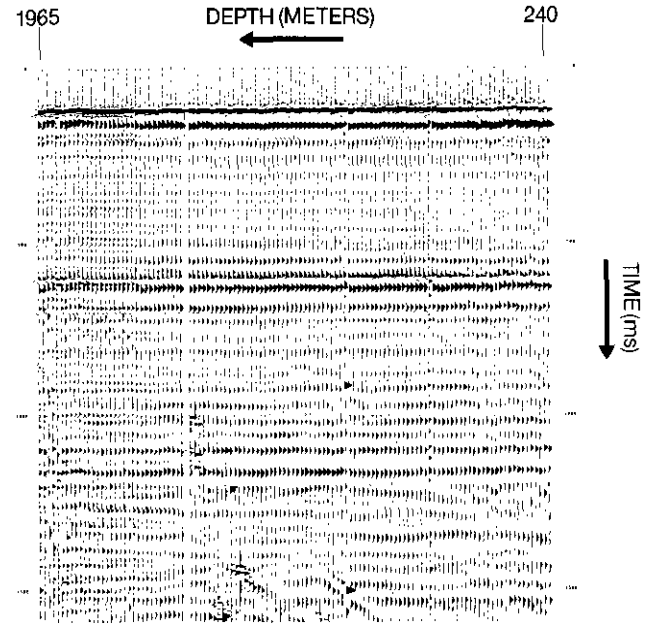


Fig. 6. Down-going wave section.

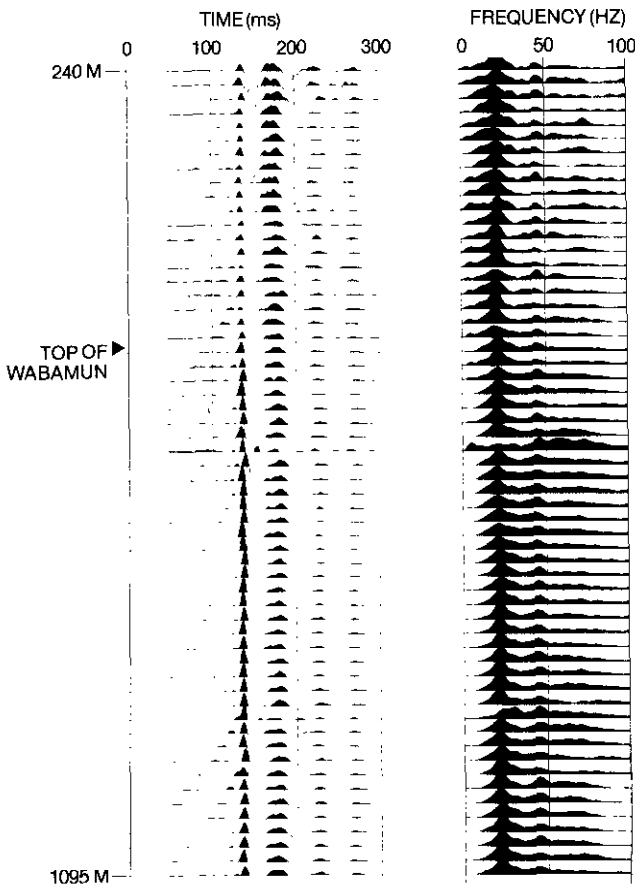


Fig. 7. Down-going waves: depth 240 m to 1095 m.

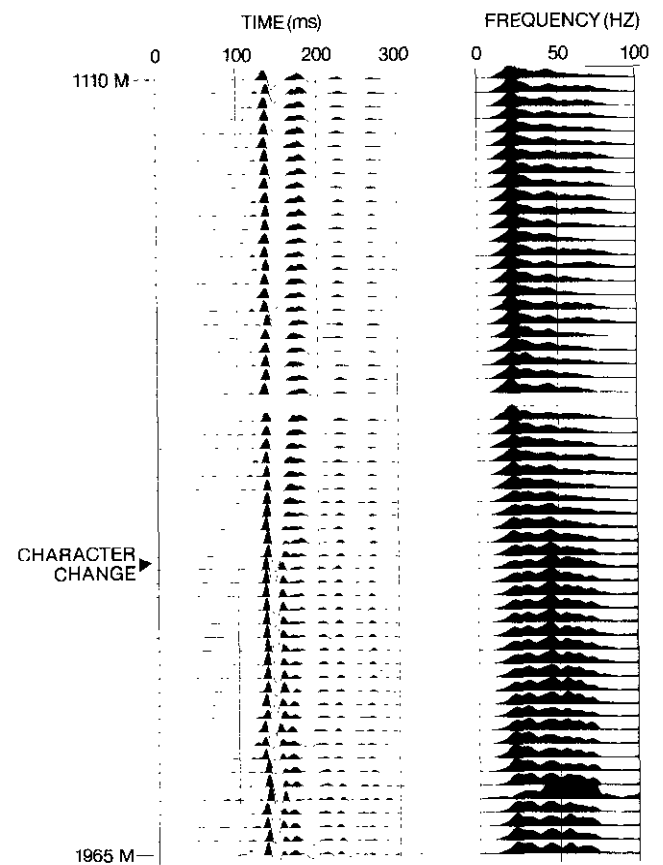


Fig. 8. Down-going waves: depth 1100 m to 1965 m.

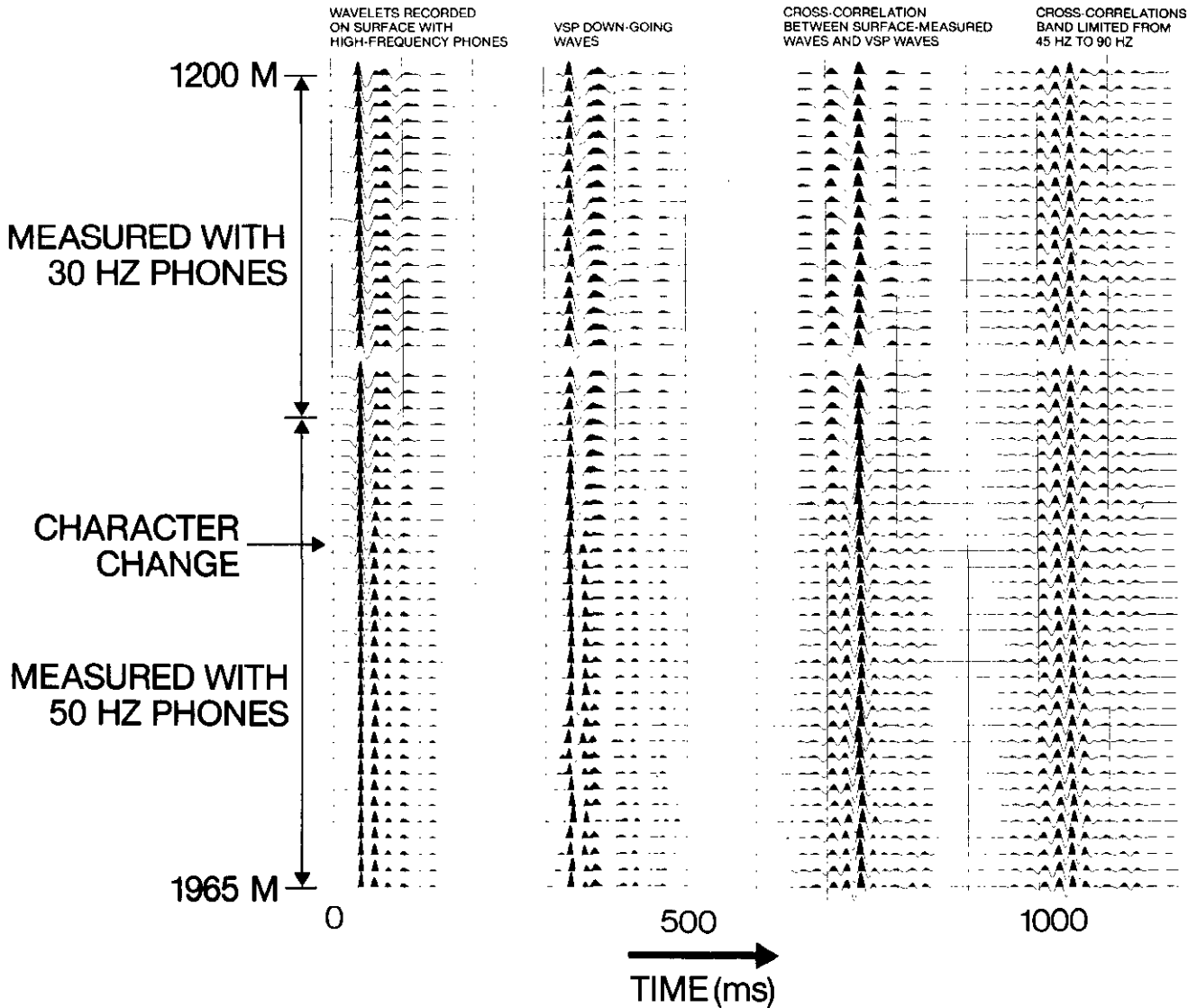


Fig. 9. Comparison between surface-measured waves and VSP waves.

ent geophones. Also shown is the cross correlation between each pair of wavelets and, finally, the same cross correlation band-limited to the range 45 to 90 Hz. It is clear that both sets of wavelets exhibit the same change in character at the same location. The cross correlation, on the other hand, shows that, although there is a measurable phase difference between the two wavelets in each pair, that difference tends to remain constant as the two wavelets change. The band-limited cross correlation shows this consistency even more clearly, as the change in amplitude spectrum is no longer visible. As it happens, the VSP was shot with the receiver moving from the bottom of the hole upward, and the effect we are seeing at depth is a change in the shot-hole condition with time. This interpretation is neatly confirmed by the fact that several widely spaced calibration shots were fired while the geophone was being lowered, and these wavelets show the same character as the

deepest wavelets. One such wavelet is the ninth below the level marked "top of Wabamun."

The explanation for this effect is not entirely clear, but apparently some sort of inelastic deformation of the region about the shot-hole has occurred after about the first thirty or so shots. According to Ziolkowski and Lerwill (1979), the bandwidth of the basic pulse varies inversely with the size of the sphere of anelastic deformation about the shot. The changes observed here would be consistent with the hypothesis that this region of anelastic deformation had suddenly expanded and stabilized at a new value.

The wavelets measured above the Wabamun are apparently of a different character from those measured below. However, the magnitude of the change is so extreme as to make us question the validity of these shallow wavelets. As can be seen in Figure 1, a great deal of high-frequency noise exists in this region, while a close examination of

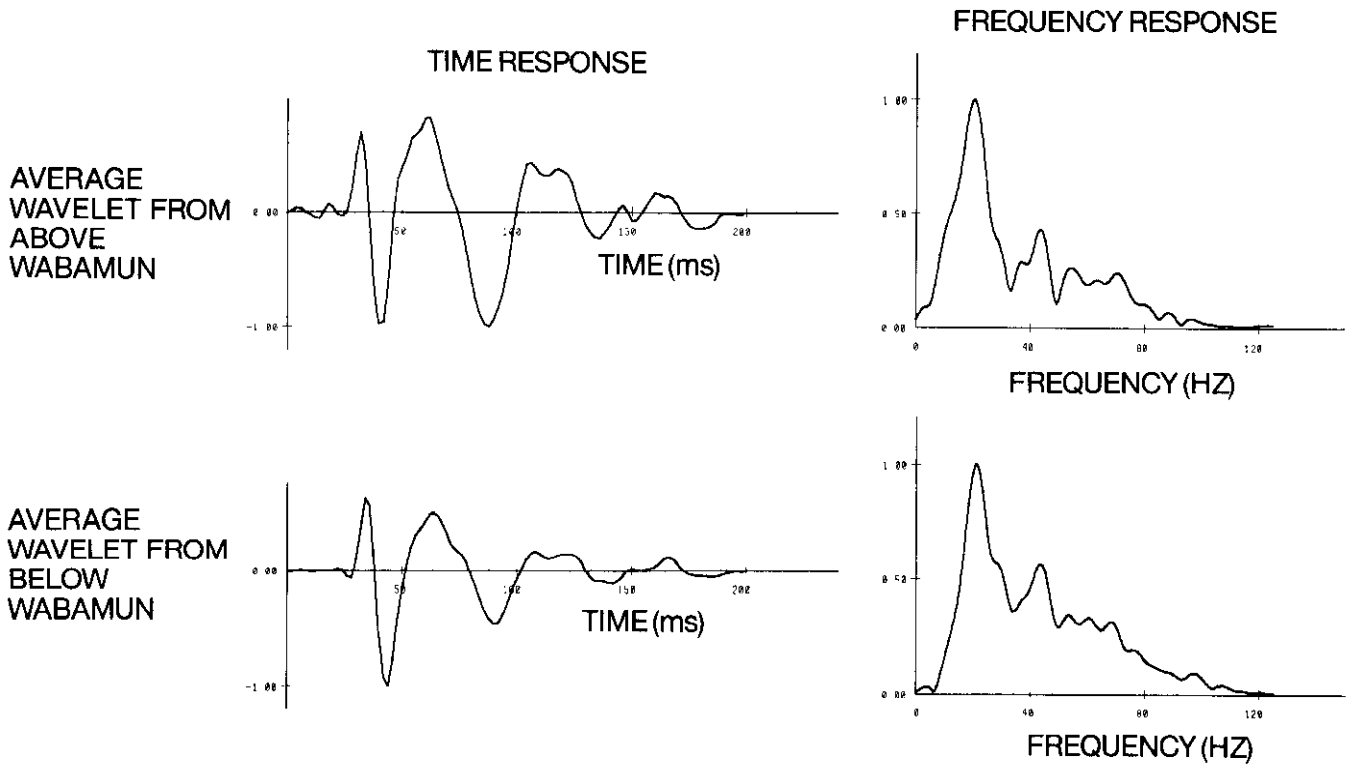


Fig. 10. Average wavelets calculated from first arrivals.

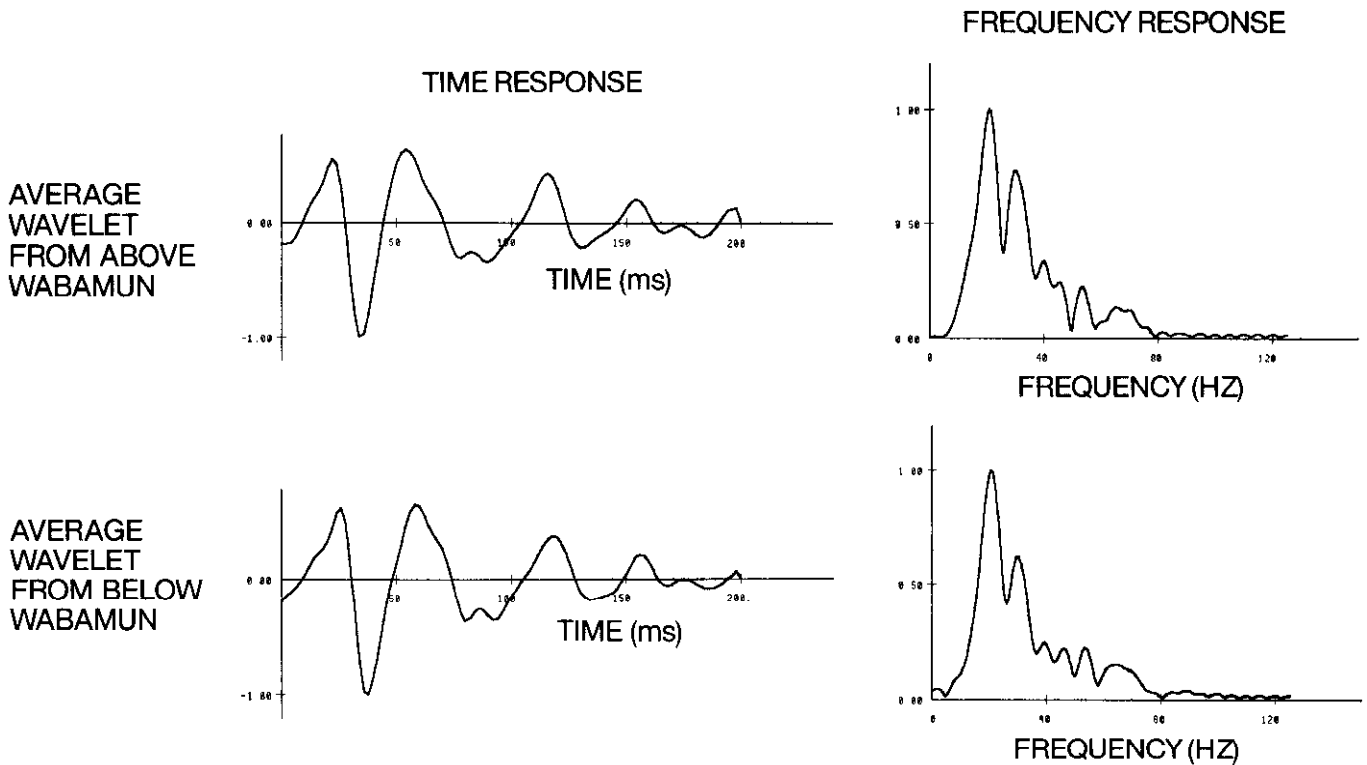


Fig. 11. Average wavelets calculated from first-order multiple.

the first breaks on the inside traces revealed that digital clipping had occurred in many places. Any change in wavelet character on passing through the Wabamun should be observed not only on the first breaks, but also on the first-order multiple on the down-going VSP. Figures 10 and 11 show the average wavelet measured above the Wabamun compared with the average wavelet measured below. The average wavelet from below was calculated by summing the wavelets from the level marked "top of Wabamun" to that marked "character change." Figure 10 shows the result of using the first breaks, while Figure 11 shows that of using the first-order multiple. It is clear from Figure 11 that, aside from a small high-frequency attenuation, the wavelets from above and below the Wabamun are practically identical. For this reason, it was decided to discard the wavelets measured above the Wabamun as unreliable.

Finally, the large group of wavelets from the middle traces of the VSP show a stable wavelet phase with a gradual attenuation of the high frequencies. The very slight degree of high-frequency absorption evident below the Wabamun is consistent with the findings of other investigators such as Hauge (1981), who reported attenuations of less than 0.1-dB wavelength in rocks that were predominantly limestone and shale.

Because the wavelets showed little change with travel-time, it was decided to assume that the down-going wavelet at each receiver level was representative of that entire trace and to deconvolve each trace with its own wavelet. As the wavelets measured above the Wabamun were considered unreliable, the average wavelet measured below the Wabamun was used for these traces. Figure 12 shows the resulting up-wave section

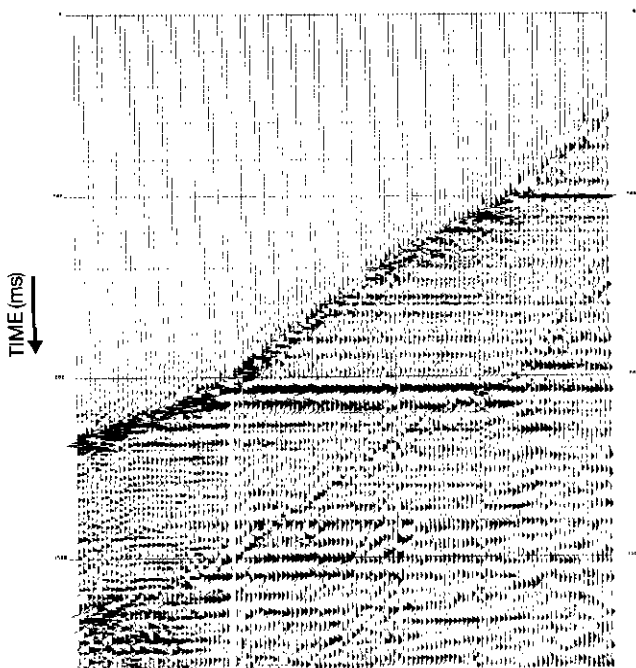


Fig. 12. Final dephased up-wave VSP.

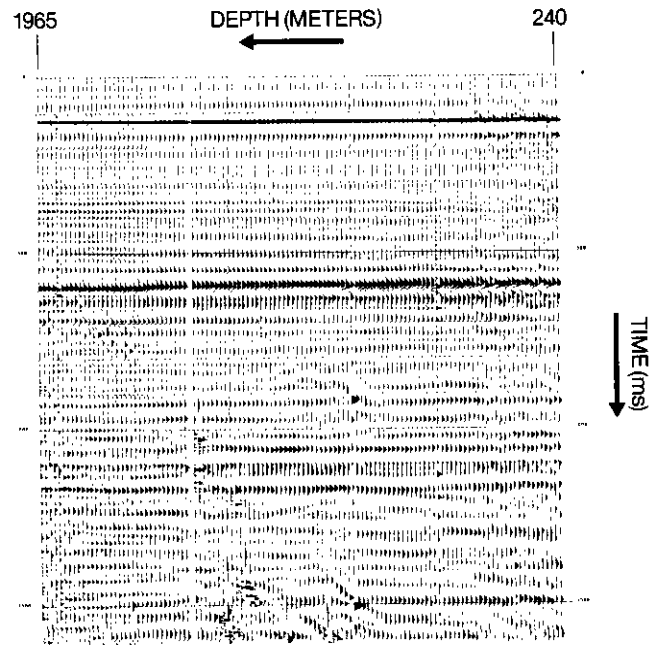


Fig. 13. Down-going waves after dephasing.

after using each down-going wave to correct the trace to zero-phase while leaving the amplitude spectrum unchanged. The Wabamun reflector now appears as a single positive reflection coefficient, as it should. The dephased down-wave section is shown in Figure 13. It is interesting to note that while the first breaks are zero-phase, the first-order multiple is not exactly reversed in polarity. This deviation from reverse polarity measures the phase change in the wavelet due to the two-way travel path between the Wabamun and the near surface.

VSP INTERPRETATION

A major problem for interpreters in the area under investigation has always been the presence of strong multiples at reflection times of interest. Figure 14 shows the lithology in the vicinity of the well, and it is clear that very strong reflections will be generated from the shale-carbonate boundaries. In particular, the upper boundary (top of the Wabamun Formation) has an especially high acoustic contrast with a reflection coefficient of about 0.4.

In order to compare the VSP with surface seismic data, composites of the VSP traces over specific zones were formed. Figure 15 shows one such composite. The narrow area following and paralleling the first arrivals has been called the primary zone because no multiples generated between the Wabamun and the near surface are present in this zone. As this mechanism is responsible for most of the multiple energy, stacking the traces within this zone produces a trace that is relatively multiple-free. Similarly, as shown in Figure 16, stacking those

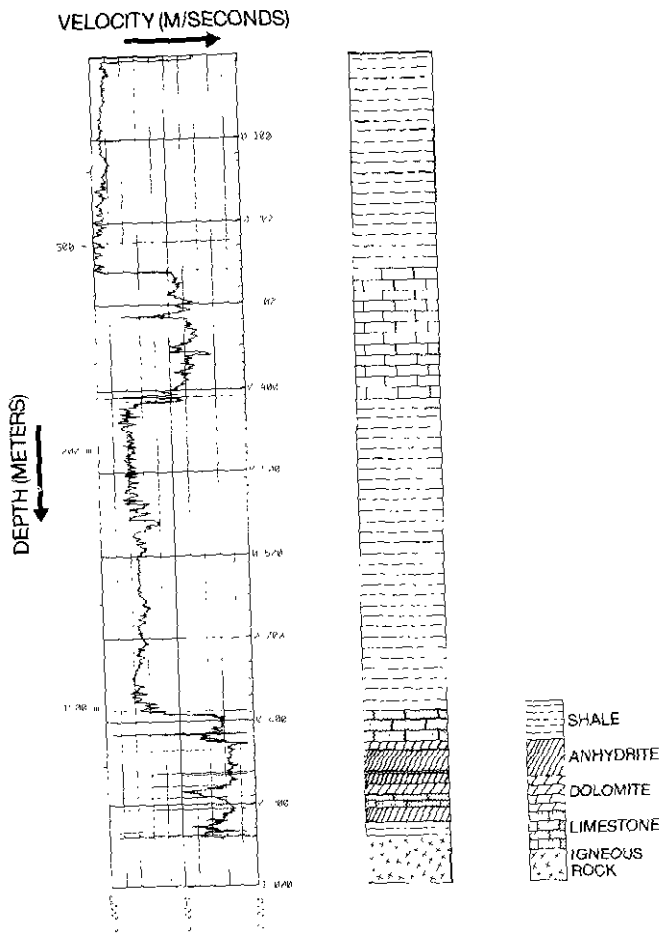


Fig. 14. Stratigraphy of VSP well.

traces recorded above the Wabamun gives a good approximation to zero offset surface recorded data, since all primaries and up-going multiples generated by the Wabamun or lower primaries are included in this stack. By correlating the two composites with the seismic data, it should be possible to distinguish multiples and primaries unambiguously.

On the left side of the up-wave VSP (Fig. 16), two deep primaries can be observed: one at 1.15 s and the other at 1.18 s. The amplitude and structure of these events are critical clues to hydrocarbon accumulations. Both events deteriorate on the right side of the VSP as more multiples are included. Apparently these interfering multiples are generated by primaries below the Wabamun. The primary at 0.65 s, for example, has created a multiple at about 1.15 s as it crosses the appropriate level. This result is not obvious to interpreters (from examining conventional common-midpoint or common-offset seismic stacks). In the next section, this interpretation is confirmed by showing an improvement in the primary response at this level after multiple attenuation.

One of the objectives of the survey was to evaluate the reasons why synthetic seismograms created from sonic logs in this area did not correlate well with the lower part of the seismic section. Figure 17 shows the VSP primary trace correlated with the primaries-only synthetic seismogram after artificial checkshot adjustments to match event spacings and identical filtering. The excellent tie illustrates not only the correctness of our approach in generating a primaries-only VSP composite, but also the good performance of the sonic log. Apparently, much of the difficulty in matching synthetics with conventionally processed seismic data

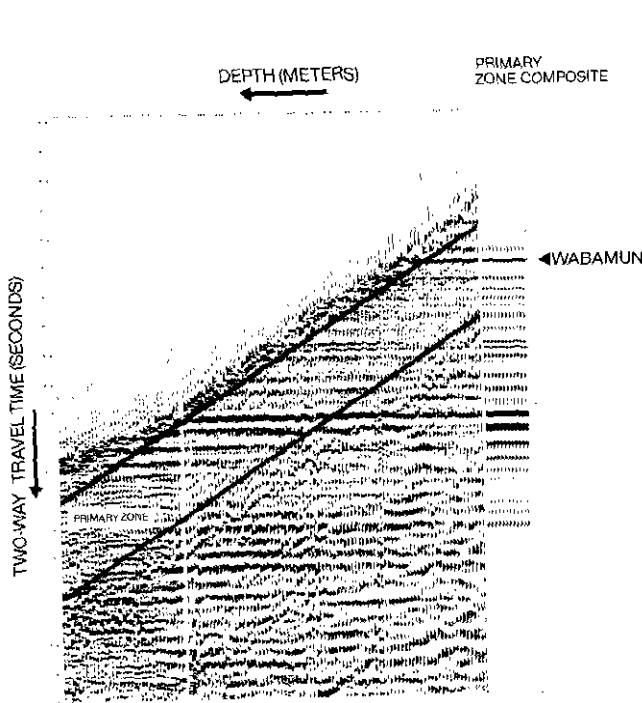


Fig. 15. Up-wave VSP, dephased and filtered 3/8 - 95/125 Hz.

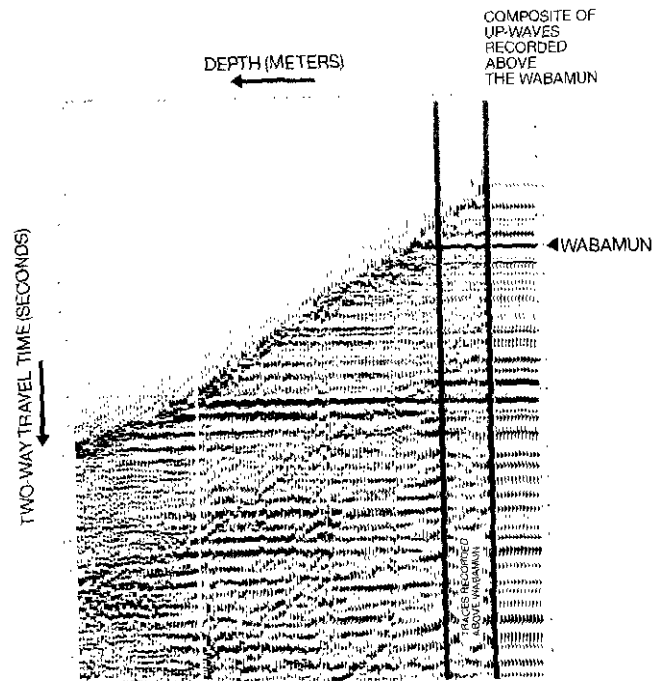


Fig. 16. Up-wave VSP, dephased and filtered 3/8 - 95/125 Hz.

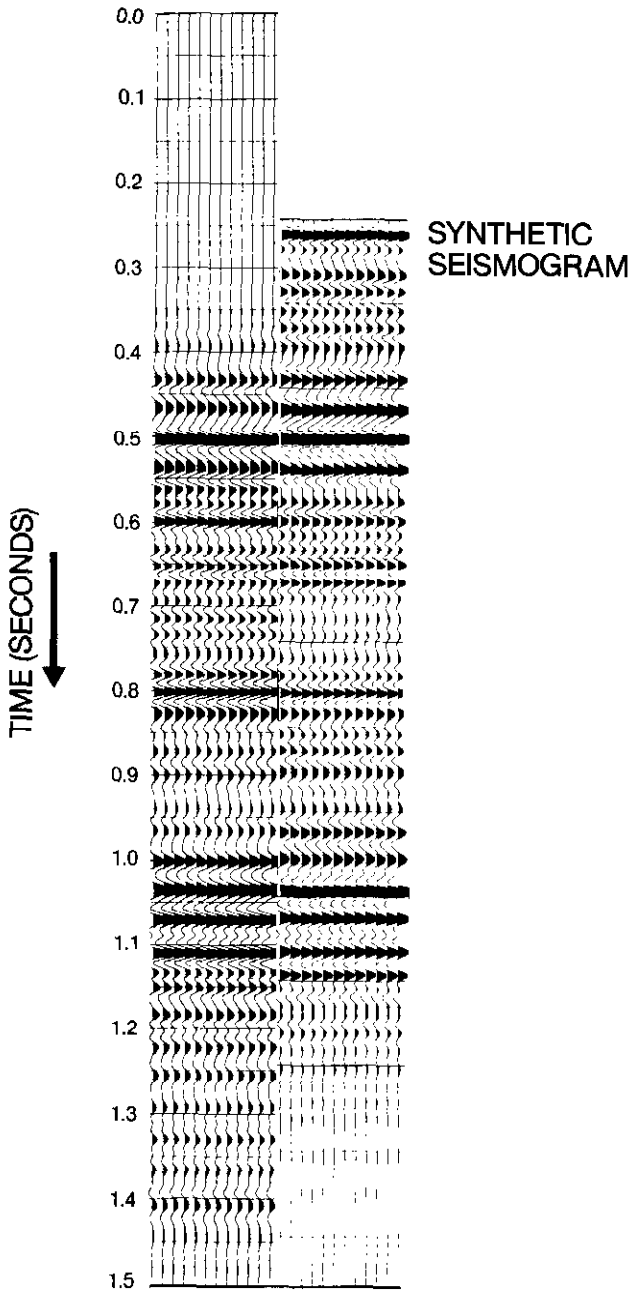


Fig. 17. Primary composite VSP and synthetic seismogram.

in this area can be attributed to the presence of multiples, which of course are absent on the VSP composite.

In order to correlate the VSP composites with the surface seismic data, it is necessary to filter the broad-band VSP to match the relatively narrower band seismic. The result is shown in Figures 18 and 19, where it is interesting to note that the deterioration in primary energy at about 1.1 s on crossing the Wabamun level is no longer as obvious as it was on the broad-band VSP (Fig. 16). Apparently, the 23-Hz low-cut filter applied to the seismic data discriminates against the relatively low-frequency multiples, a result that is confirmed by experienced seismic processors in the area.

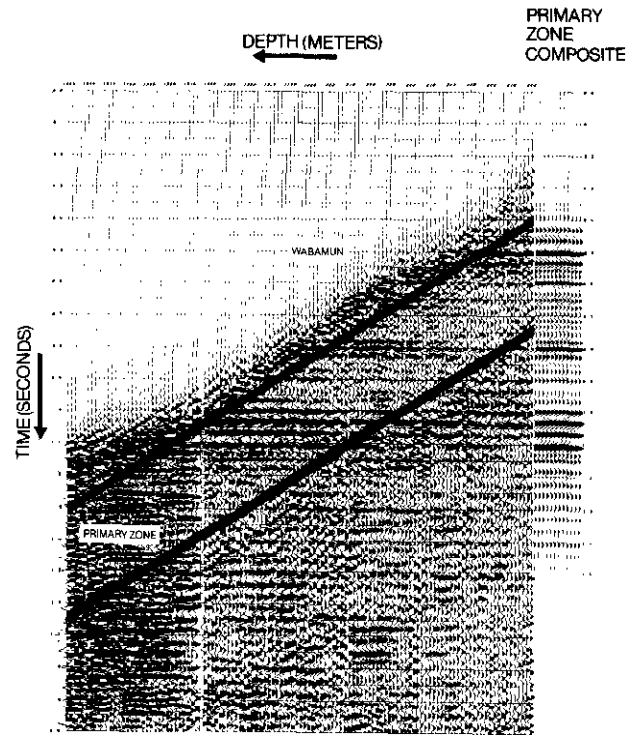


Fig. 18. Up-wave dephased VSP, filtered to match seismic data.

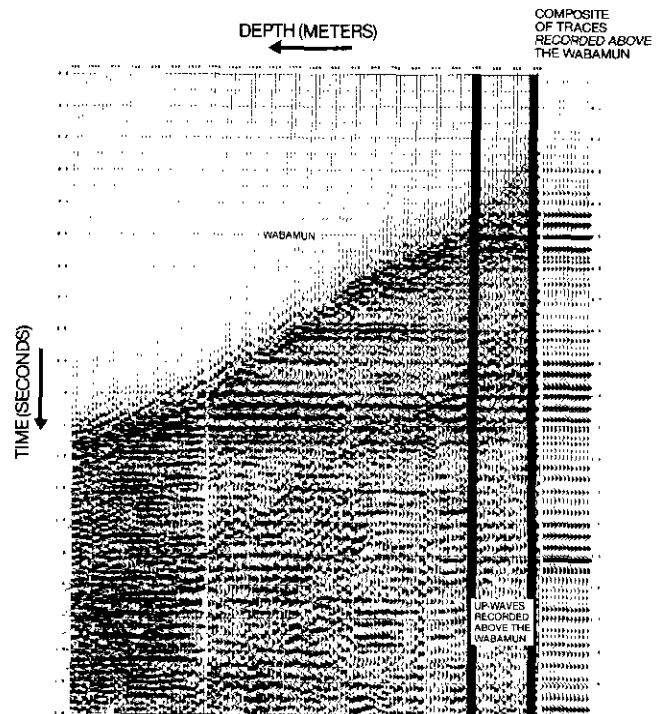


Fig. 19. Up-wave dephased VSP, filtered to match seismic data.

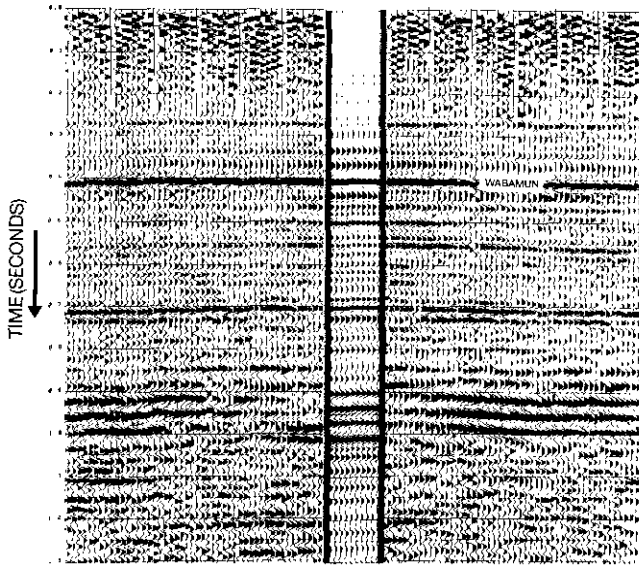


Fig. 20. Seismic data correlated with primary zone VSP composite.

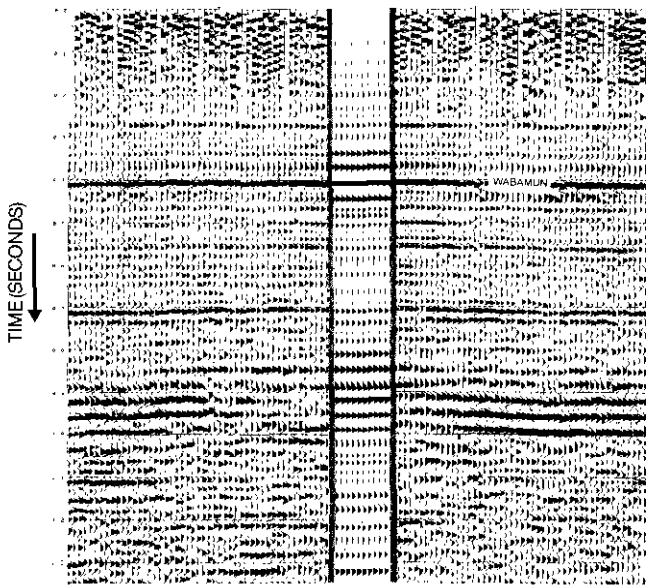


Fig. 21. Seismic data correlated with VSP composite, recorded above the Wabamun.

Finally, Figures 20 and 21 show the correlation between the two VSP composites and the surface seismic data. The composite in Figure 20 is from the primary zone and, in principle, contains no Wabamun-generated multiples. The composite in Figure 21 contains the multiples and should match the seismic data better for this reason. From about 0.8 s down, we see that this is the case, and the event at about 0.85 s can be clearly identified as multiple because it appears on one composite and not on the other. The most interesting feature is the

event that appears at about 1.04 s on the left side of the section and rises rapidly to intersect both composites at around 1.01 s. The fact that it is much weaker on the composite with multiples indicates that a multiple is interfering with this event, and that effective multiple attenuation may improve its continuity on the seismic data.

MULTIPLE ATTENUATION

The interpretation of the VSP suggests that the major multiple-generating mechanism is a simple one: the important multiples are peg-legs generated between the Wabamun and the near surface. As the multiple period is constant, this should be an ideal case for a gapped deconvolution. In practice, predictive decon has proved ineffective in this area for two reasons: 1) because the Wabamun is so shallow, there are usually only a small number of inside traces where it is present without interference from the first arrivals, and 2) because of interference between the primaries and first-order multiple, the design of the decon operator is unreliable. The second problem can certainly be alleviated by using the VSP. Figure 22 shows again the down-going wave VSP. Since only multiples are present in this section, it should be possible to design a very effective deconvolution operator. In order to use this operator on the seismic data, an average operator was calculated by using the time window from 0 to 800 ms and averaging over 16 traces as shown.

Note that these traces came from below the Wabamun level. The operator length is 300 ms and the lag is 400 ms. The effect of using this single operator on the down-wave section is shown in Figure 23. It is especially encouraging to note that the first-order multiple has been significantly attenuated throughout the section and not just within the design gate. The second-order multiple between 1000 and 1100 ms has also been attenuated, but a multiple between 1100 and 1200 ms is still present. This is apparently a long period peg-leg multiple set up between the deep primary reflectors and the interval above the Wabamun. Figure 24 shows the result of using the average operator on the up-wave section. In this case, the operator has been applied only to the traces recorded above the Wabamun. As expected, the multiple has been strongly attenuated, while the primary reflection below remains largely unaffected.

In using the derived operator on seismic data near the VSP well, the assumption is that the change in waveform that occurs as a result of the extra bounce through the Wabamun is constant over an area and is independent of the basic wavelet. The actual operator that is used on each seismic trace can be thought of as comprising three components: the 300-ms operator from the VSP, which contains information about the waveform change; the lag time, which will vary according to position on the seismic data, as well as offset; and the total amplitude of the operator, which will depend on the

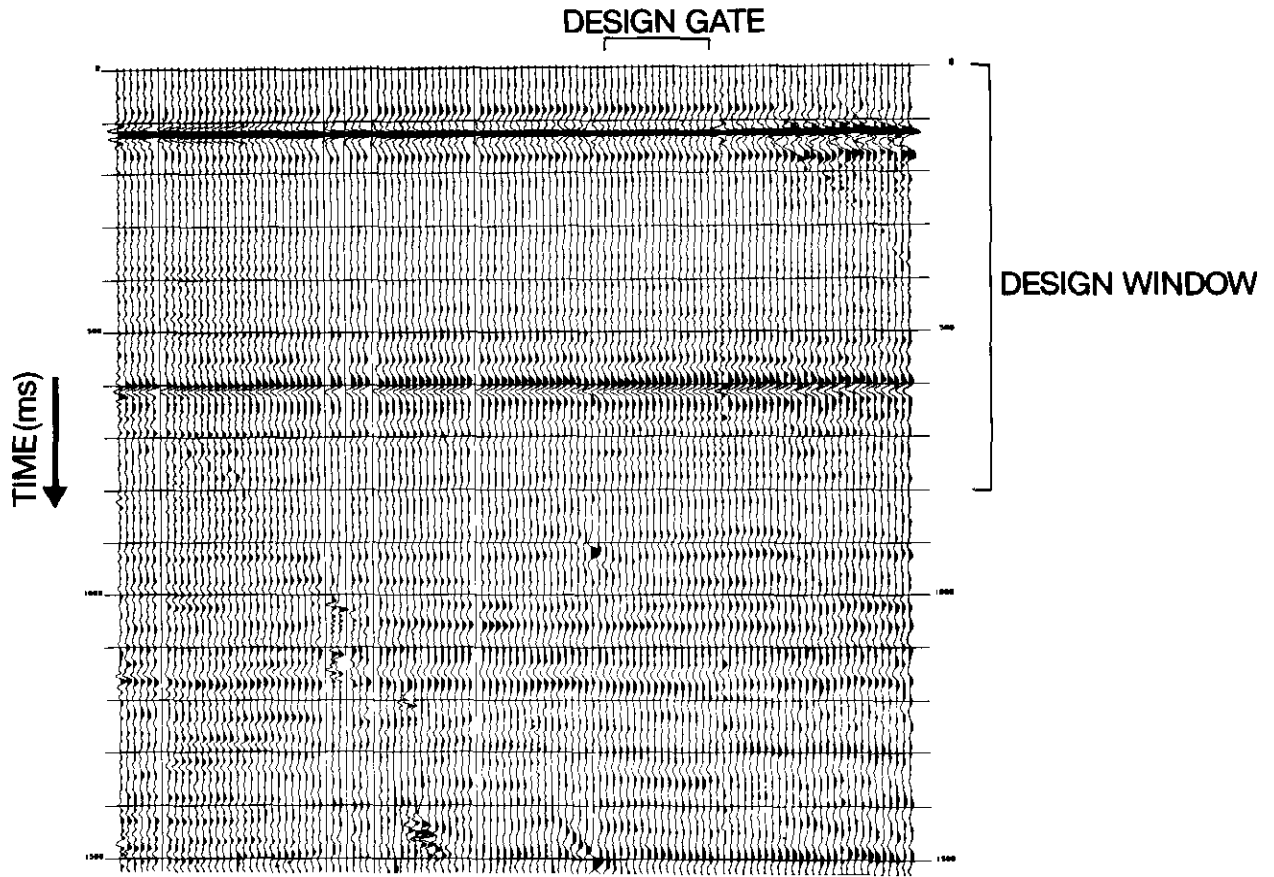


Fig. 22. Down-going waves before multiple attenuation.

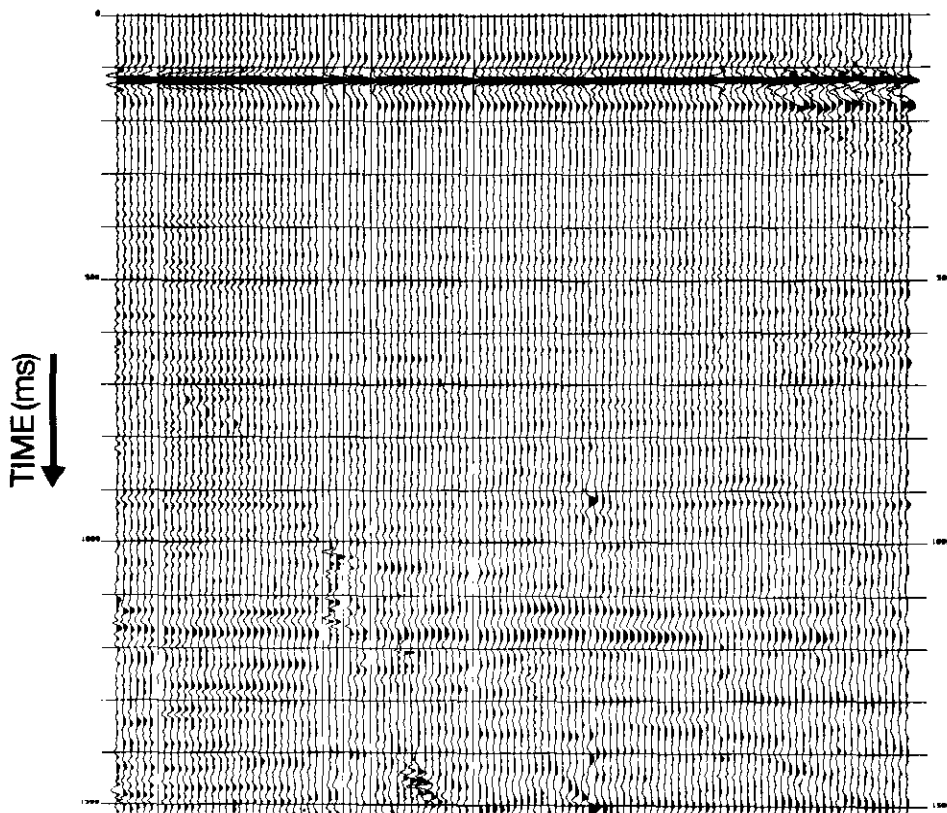


Fig. 23. Down-going waves after predictive deconv with average operator.

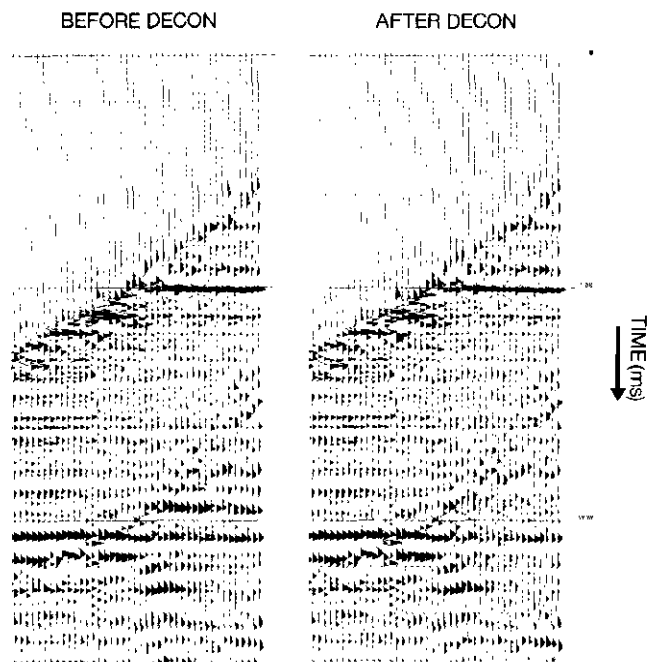


Fig. 24. Use of average predictive decon operator on up-wave section.

gain recovery used in processing the seismic data. The approach used here was to find the optimum lag and amplitude for each trace. The operator was applied to common-depth-point data just before stack and, as the Wabamun reflection had been muted from many of the far traces, a model was formed by stacking several inside traces for input to the decon operation.

Figures 25 and 26 show the seismic data before and after application of the VSP-derived operator. The primary zone composite has been inserted to help evaluate the performance of the operator. Three important features should be noted. First, the event marked "multiple" is part of the first-order Wabamun multiple and has been attenuated by the VSP operator. As a result, primary events between 700 ms and 900 ms are now more continuous. The second point is that the event marked primary D is clearly more continuous after using the attenuation operator. As indicated in the previous section, it appears that a multiple had been generated from the primary at about 550 ms on the seismic data followed by the extra bounce between Wabamun and near surface. This multiple was apparently obscuring primary D, and the attenuation has improved the continuity of the primary. The event ties primary D on the composite trace closely enough to identify it, but the small mis-tie between them implies some wavelet distortion caused either by residual multiple interference or by the attenuation method itself. The improvement in continuity is especially obvious in Figures 27 and 28, which show a portion of the seismic data at an enlarged scale. The third point is that the multiples below the basement have been significantly attenuated.

For the sake of comparison, a second multiple-attenuation technique was tried on these data. The method was similar to one proposed by Ryu (1980) in which F-K filtering was used to eliminate multiples on the basis of differential moveout. In the present case, the multiples all had very similar moveouts at the time of interest, so the procedure was:

- 1) NMO-correct the CDP-gathered data at the multiple velocity.
- 2) Suppress events with close to zero-dip energy by using F-K filtering.
- 3) NMO-correct the data at the primary velocity.

This procedure differs from Ryu's in that only a small segment of the F-K plane is attenuated, rather than an entire quadrant. As the multiple moveout is practically constant over the zone of interest, the NMO corrections mentioned above amount to static time-shifts within the zone of interest.

The resulting section is shown in Figure 29. In many ways, the result is similar to the VSP attenuation. The continuity of primary D has again been improved, although it appears that the continuity of this event on the right side of the anomaly is significantly better on the VSP-attenuated section. The event marked "multiple" has not been attenuated as well as on the VSP section. Primaries A, B and C, on the other hand, appear quite a bit stronger on the F-K filtered section.

In view of the better performance of the VSP-derived operator over the F-K multiple attenuation, it is interesting to note the common offset stacks shown in Figure 30. The common offset stack is formed by adding together sets of traces from nearby CDP locations with the same shot-to-receiver offset. The result is a kind of average CDP gather. The left-hand panel of Figure 30 shows the stack before multiple attenuation, and the multiples can be clearly identified by their residual normal moveout. The common offset stack after the VSP multiple attenuation shows that in fact the method has been most effective on the near traces, while the residual multiples are still strong on the far traces. Even though the F-K method has apparently been more effective over the whole range of offsets, the resulting stacked section was shown to be inferior by using the VSP primary composite to evaluate it. The conclusion is that the near-trace multiples are mainly responsible for the interference on the stack section and that, by attenuating them, the VSP-derived operator has produced an improved stack.

On the whole, the two methods have performed comparably on this seismic line. Where the VSP has been used to identify specific events, the VSP-derived operator appears to have performed slightly better. However, it is not clear to what extent the derived operator can be used on seismic data shot at some distance from the well. Inasmuch as the operator measures the change in wavelet shape without specific reference to lag or input wavelet shape, it is hoped that this quantity will be reasonably constant over an extended area.

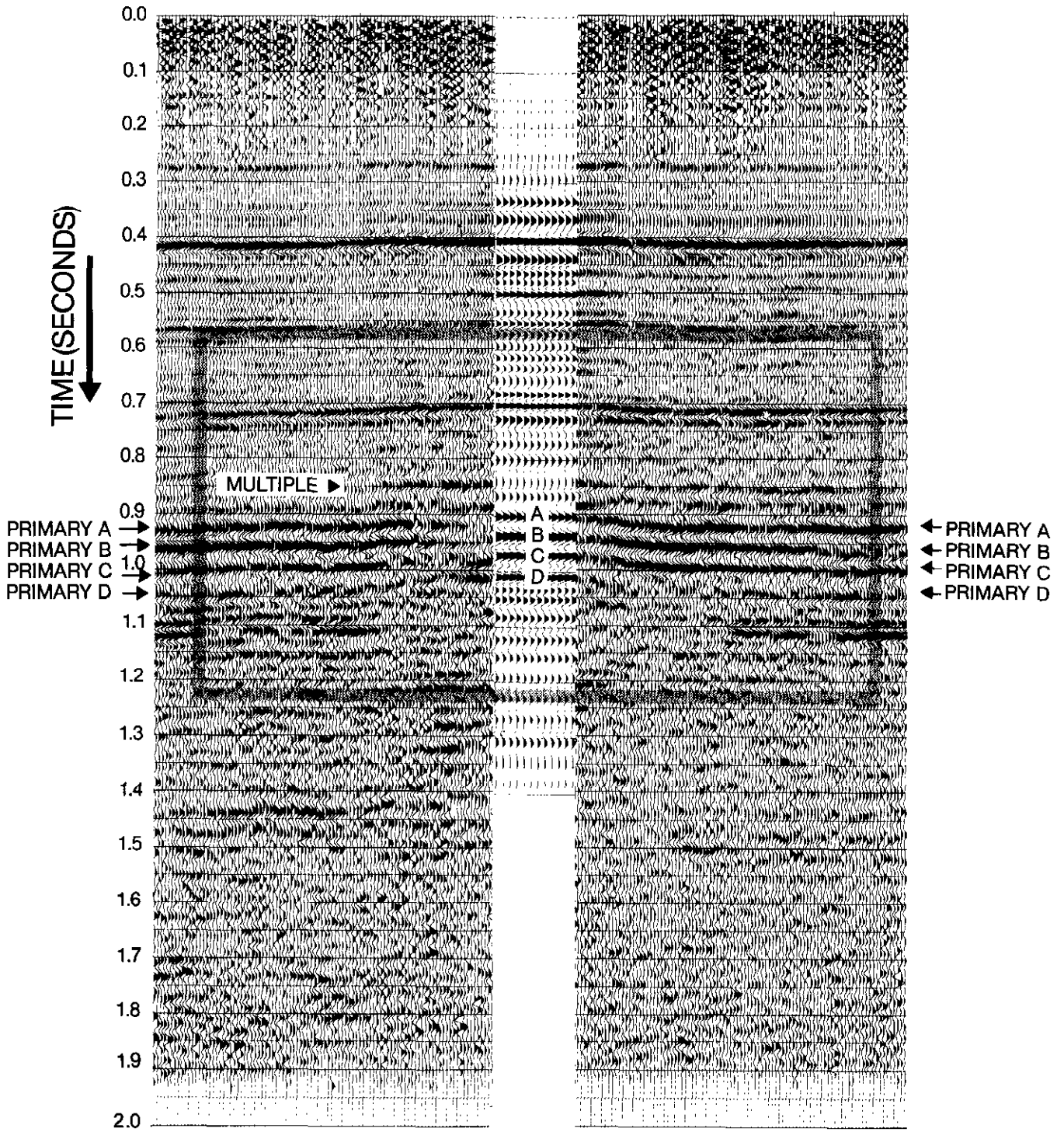


Fig. 25. Primary zone VSP compared with input seismic.

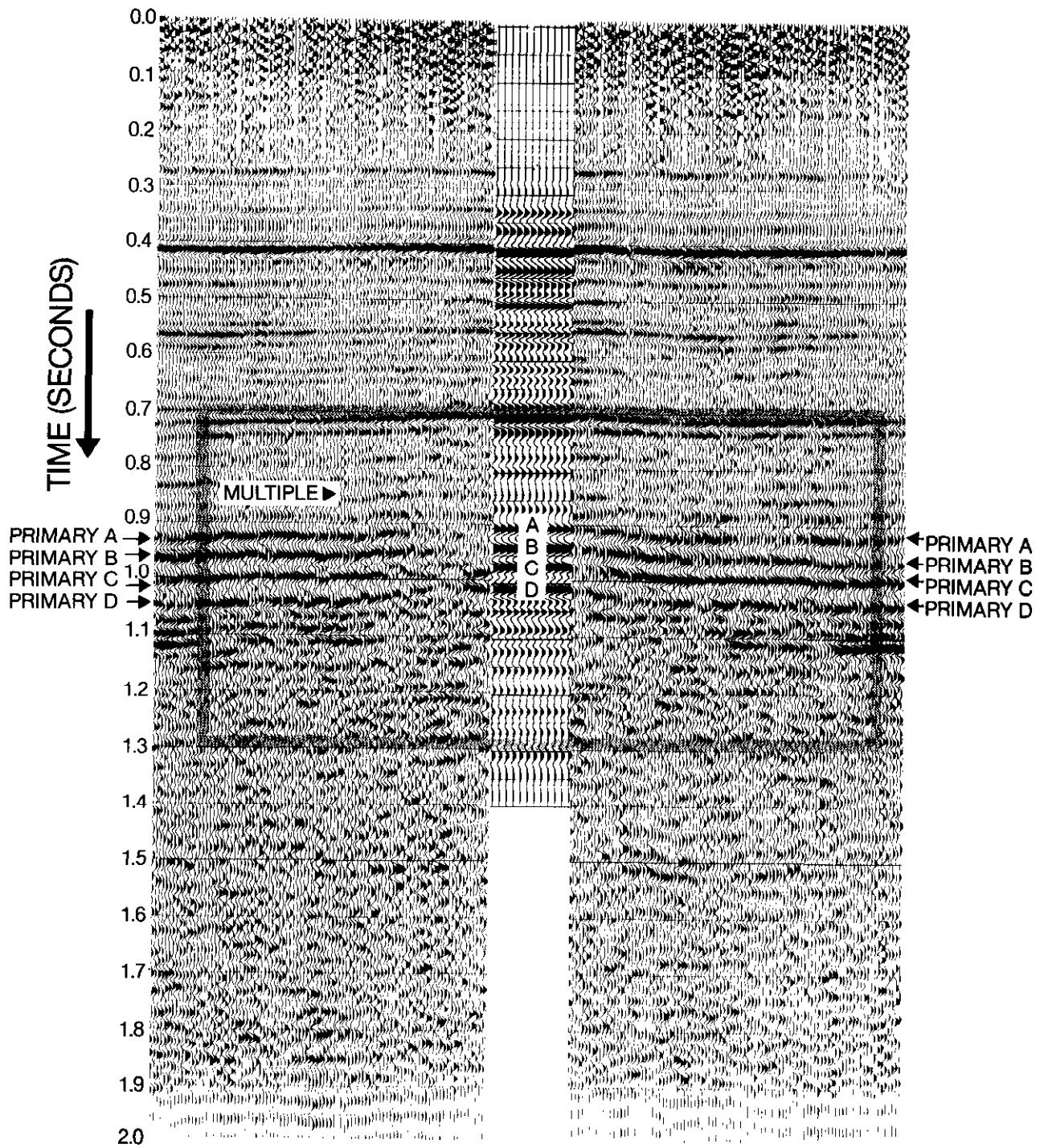


Fig. 26. Primary zone VSP compared with seismic with VSP multiple removal.

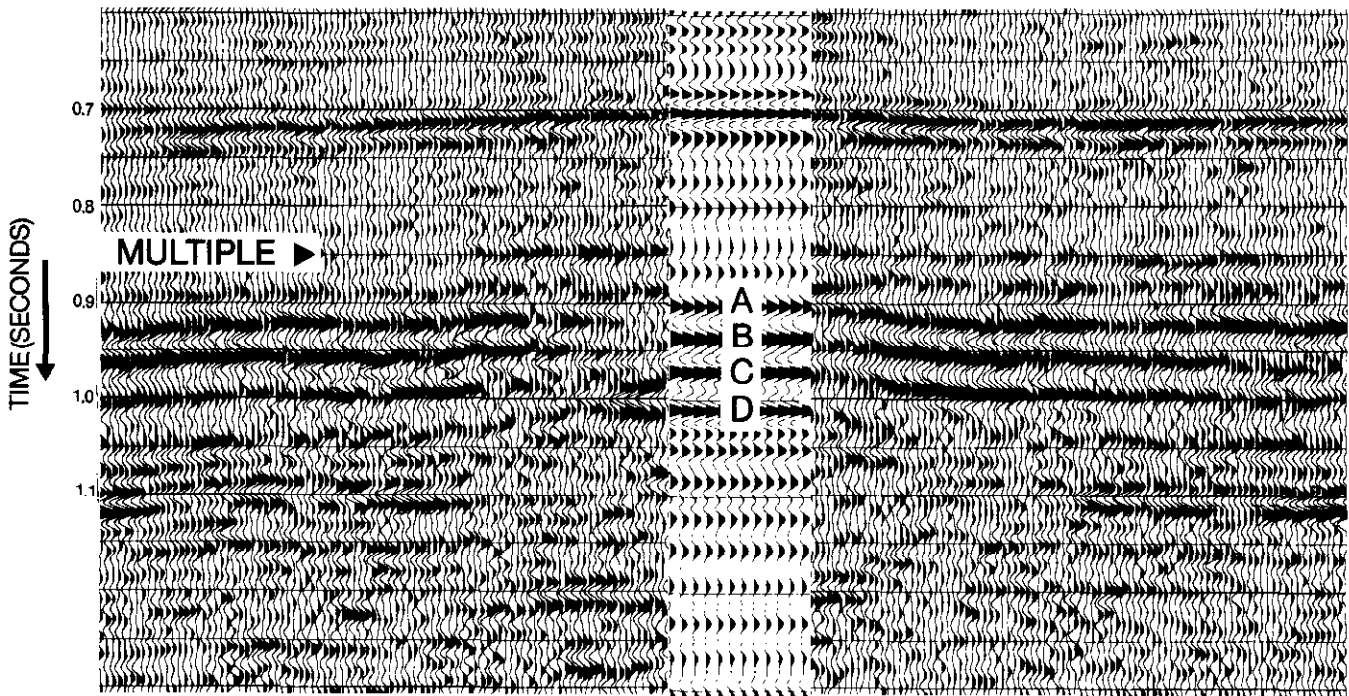


Fig. 27. Primary zone VSP compared with input seismic.

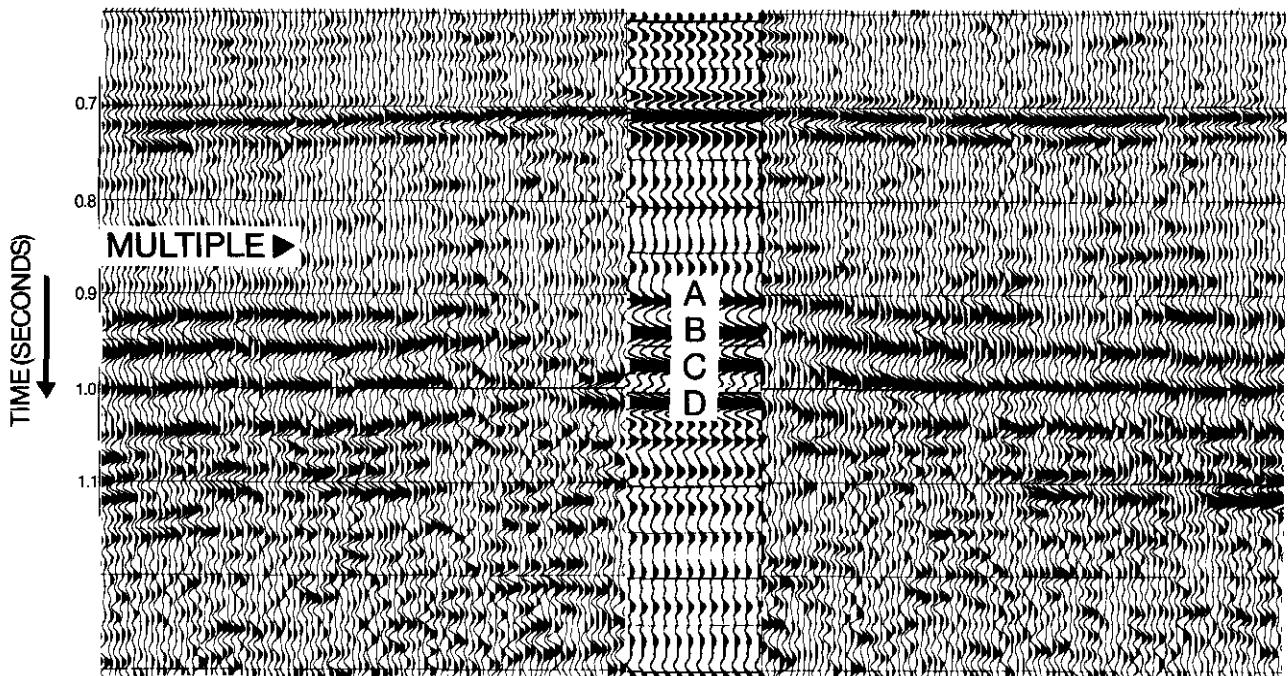


Fig. 28. Primary zone VSP compared with seismic with VSP multiple removal.

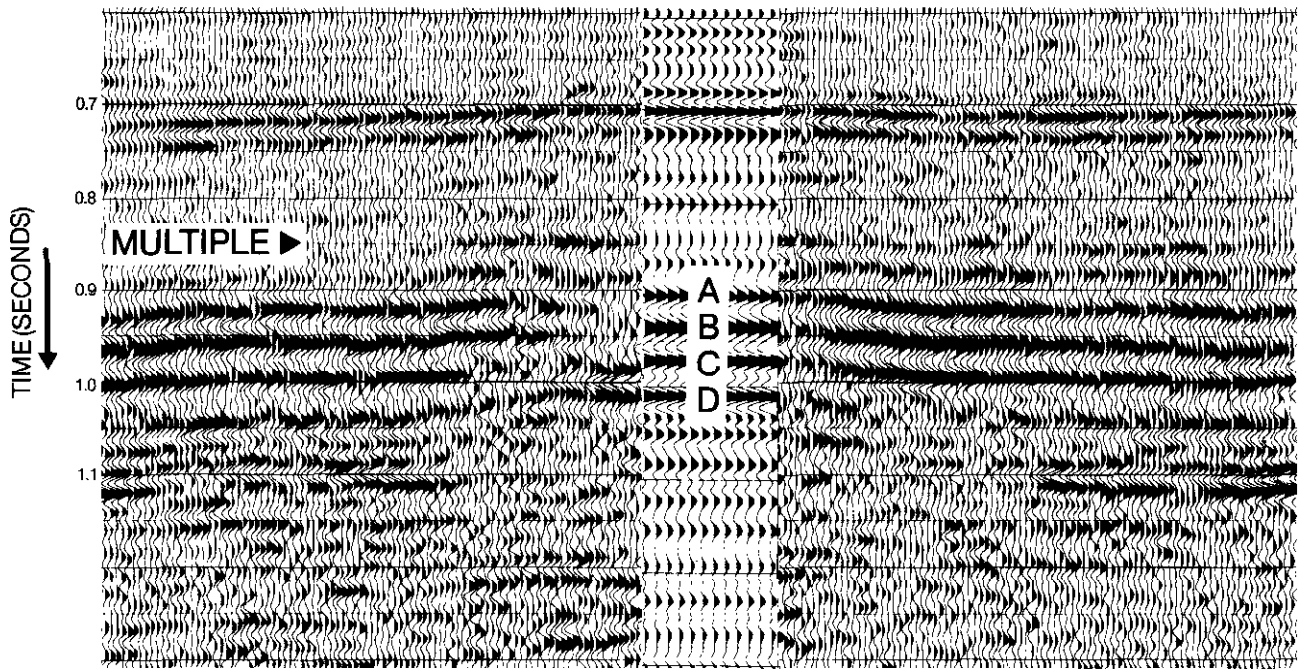


Fig. 29. Primary zone VSP compared with seismic with F/K multiple removal.

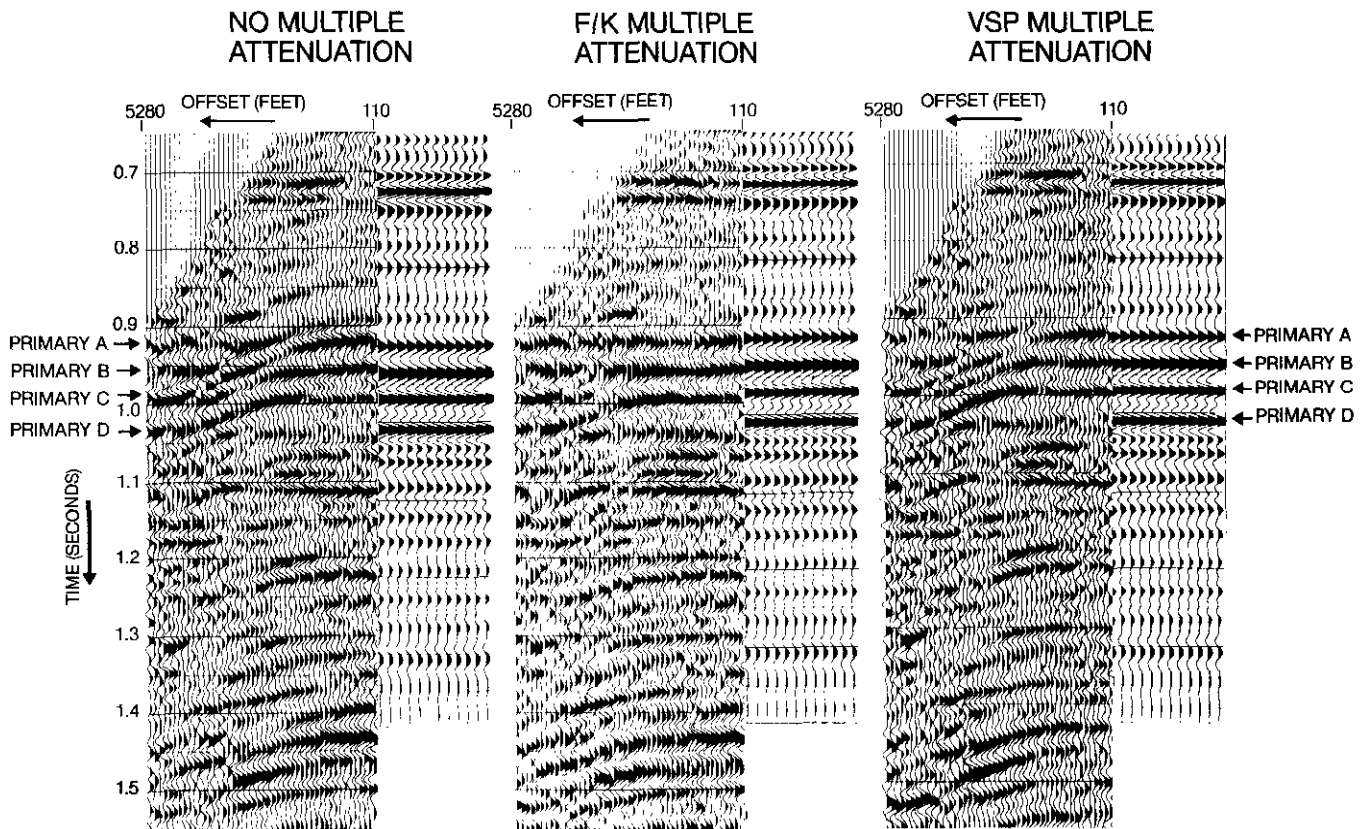


Fig. 30. Common offset stacks.

CONCLUSIONS

The Vertical Seismic Profile is a tool that is well suited to the study of the type of multiple problem that exists in western Canada. In this study we have shown that, by compositing VSP traces to produce the primaries-only and the primaries-plus-multiples responses, residual multiple effects could be unambiguously identified on the seismic data. Information about the wavelet shape from the down-wave VSP was used to design a multiple-attenuation filter, which was applied with some success to the surface-recorded data. A second multiple-attenuation technique based on F-K filtering was tried as well, and the VSP composite was used to evaluate the result. Although the two methods achieved similar results, it was felt that the VSP-derived operator performed better on specific events.

The major difficulty arising from this VSP study came from variations in the source wavelet. An improvement

in this area would have been achieved by using a more repeatable source, such as "Vibroseis"* and monitoring the source wavelet with a single reference geophone at some depth from the shot.

* ®Registered trademark and service mark of Conoco Inc.

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