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VSP DETECTION OF INTERBED MULTIPLES USING INSIDE-OUTSIDE CORRIDOR STACKING

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ABSTRACT

Conventional surface reflection methods for detecting and suppressing short-period interbed multiples in Devonian reef exploration often face difficulties. Predictive deconvolution and CDP stacking of surface reflection data sometimes do not suppress the multiples that obscure primary reef reflections. A vertical seismic profiling (VSP) method which can help to differentiate primaries and multiples is corridor stacking of VSP reflection data over selected windows. Using an idea proposed by Hardage (1983), the "outside corridors" should be dominated by primary reflection energy, while the "inside corridors" should contain interbed multiples as well as primaries. Differences between these "inside" and "outside" corridors can indicate the presence of interbed multiples. Autocorrelations from the corridor stacks can also be useful in designing predictive deconvolution filters for both the VSP and surface reflection data. The overall assimilation of VSP corridor stacks, range-limited stacks of surface data, and synthetics derived from well logs aid in the interpretation of possible interbed multiples.

INTRODUCTION

One of the most difficult problems in the exploration of Devonian reefs is the separation of primaries and short period interbed multiples. This is especially true in cases where weak primary reflections from porous reefal carbonates can be easily masked by interbed multiples generated from stronger shale/carbonate reflections above the reef. This problem of primary-multiple separation is difficult since there are small normal moveout differences between the primary and short period multiple reflections so stacking might not be as effective at suppressing multiples as one would hope. Also, predictive deconvolution may be ineffective if it is difficult to design an accurate prediction distance for the deconvolution filter. The ineffectiveness of stacking and deconvolution in some cases has caused us to look for other alternatives. A recent paper by Lines (1996) advocates the use of shaping deconvolution and inversion methods which utilize well log information. Since reliable well log data are not always available, we examine a VSP corridor stacking method for multiple identification proposed by Hardage (1983, p. 154-155) which obviates some of the conventional problems and which does not require well log data.

METHODOLOGY AND RESULTS

Vertical seismic profiling (VSP) involves a fixed near-surface seismic source and downhole geophones (detectors) secured at various depths as shown in Figure 1. Thorough descriptions of VSP methods and their advantages are outlined by Hardage (1983). Unlike surface recorded data, the geophones respond to both downgoing and upgoing energy allowing insight into fundamental properties of propagating wavelets and reflective/transmissive earth processes. *Multiples, mode conversions, and wavelet modifications* can be identified to improve the structural, stratigraphic, and lithologic interpretation of surface seismic data. Resolution is improved in a static sense by involving only a one-way near-normal path through the weathered layer, and frequency content does not suffer from Q effects of a full two-way travelpath. In some cases reflectors can be identified far below the well bottom, and vertical (corridor) stacking may be used to improve the signal to noise (S/N) ratio and discriminate against multiples. It is in fact the corridor stacking idea that we use here in the suppression of multiples.

VSP processing creates wavefields that are expressed in terms of different time coordinates, or time frames. Figure 2 (left) shows that the arrival times for downgoing arrivals will increase as the depth of receivers increases. On the other hand, upgoing reflection times from a subsurface horizon will decrease with increasing receiver depth since the receiver is moving closer to the reflector. The slopes for arrival times of downgoing and upgoing arrivals will have different signs – making their separation much easier than with conventional surface reflection profiling. In field record time (FRT), downgoing compressional energy has opposite time-dip from upgoing energy. Consider TT to be the first arrival traveltime for downgoing arrivals. As shown in Figure 2 (middle), a time frame advanced by first arrival

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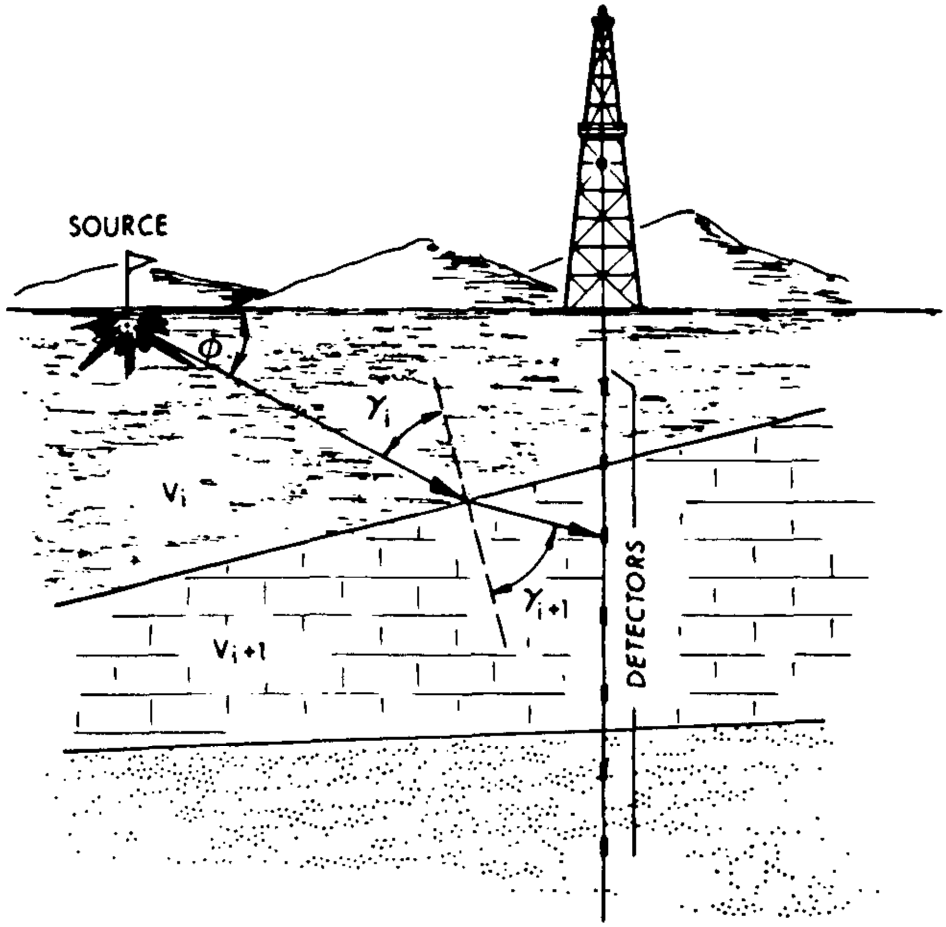

$$\frac{\sin \gamma_{i+1}}{V_{i+1}} = \frac{\sin \gamma_i}{V_i}$$

Fig. 1. Vertical seismic profiling recording configuration – from Lines et al. (1984).

time, by subtracting time TT, would flatten the downgoing wave and steepen the slope of upgoing energy – possibly causing aliasing of upgoing energy. Similarly, a time frame delayed by first arrival time (+TT) would flatten upgoing energy for zero source-to-receiver lateral offset and horizontal reflectors, as shown in Figure 2 (right). This effectively places the upgoing compressions in a two-way time frame comparable with CMP data. It is in the +TT time frame where corridor stacking is carried out. In this domain, corridor stacking involves summation of the upgoing reflection energy along a line of constant time.

The essence of VSP processing involves separation of the upgoing and downgoing wavefields. Figure 3a shows data at the various processing stages for the downgoing wavefields in the domain where first arrival times have been subtracted. The application of f-k filtering separates out the upgoing reflected wavefield and leaves the downgoing wavefield. Median filtering effectively enhances signal-to-noise ratio and waveshaping the downgoing wavelet produces a deconvolved downgoing wavefield , as shown in Figure 3a (right).

Figure 3b shows essentially the same processing steps for the upgoing wavefield section in the domain where first arrival times have been added. Let us take a closer look at Figure 3b. On the processed upgoing reflection wavefield, it is interesting to note that there are reflection events which are relatively strong across the entire array of VSP traces. These are probably primary reflections. On the other hand, there are deeper events at 1130, 1150, and 1170 ms which are weaker for the "outside corridor" traces. By "outside corridor" traces, we refer to those events which are earlier in time for a given trace depth. This "outside corridor" region of earlier arrival times at given receiver depths is also called the "front" or "short" part of the VSP data. One could consider the "outside corridor" to be in the early mute zone of the data. The "inside corridor" region of later arrivals for given trace depths is often termed the "back" or "long" part

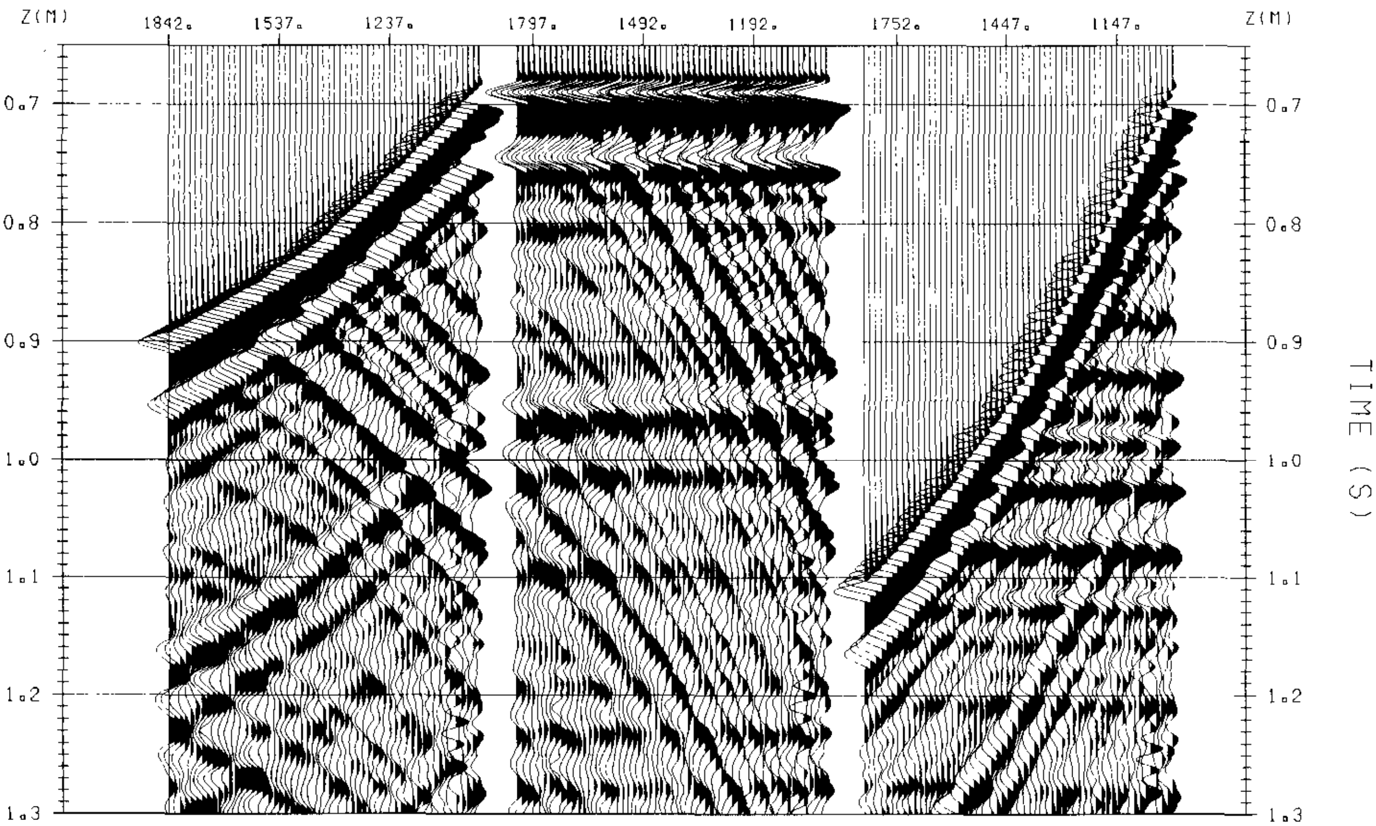

Fig. 2. Various processing time frames for the reef VSP. From left to right is field record time (FRT), first break advance time (–TT), and first break delay time (+TT). In –TT time, downgoing VSP events are delayed relative to the initial downgoing compression by the TWT between the generating interface and the deeper reflector. These events are recorded only at depths below the generating interface. In +TT time, upgoing VSP events are positioned to the TWT at which they are recorded. First breaks were optimized by correlation statics, and bulk has been applied to match surface data.

of the VSP data. Corridor stacking can be applied to this upgoing wavefield section in order to enhance reflections in various zones.

Corridor stacking of VSP gathers is applied to the upgoing wavefield. For an incident source, horizontal layers without structure, and a non-deviated borehole, upgoing events are aligned in the +TT time frame along lines of constant time. As in CMP stacking, the addition of traces with coherent energy in phase causes the signal level of that energy to be increased over random noise by the square root of the number of input traces. The object is the same in stacking upgoing VSP energy, but the primary objective is to enable distinction between primary and multiple events. There are essentially two regions of the VSP over which corridor stacking can take place – termed "outside" and "inside" regions by Hardage. Because multiples are delayed in time relative to the interbed interface primary reflections, stacking within a time window delayed slightly from the first break trajectory will represent all primaries as well as any interbed multiples with periods less than or equal to the time window length. This is called the "outside" corridor stack. These stacks should be dominated by primaries. The stacking of arrivals that appear later in time will be called the "inside" corridor stack. These stacks should show the presence of strong interbed multiples. In comparison, the full VSP stack contains all upgoing energy so that longer period multiple effects may be identified. The regional division between "inside" and "outside" stacks should hopefully lead to discrimination between primaries and multiples. In our case, we use a slight variation on the method advocated by Hardage (1983). We use "outside" corridor stacks with various "mute zones" and compare these to the full corridor stack rather than the "inside" corridors. (In some sense, the full corridor stack is a limiting case of the largest "inside" corridor stack.) We shall now show the effectiveness of these corridor stacks in the discrimination between primaries and multiples on a Devonian reef well. Figure 3c shows the upgoing VSP wavefield compared to impedance logs in time and depth. The "outside" and "inside" corridors are defined by a line running parallel to the mute zone as also shown in this figure. Some of the formation tops are identified. The corridor, as marked in this figure is a zone of about 150 ms.

We are particularly suspicious of the existance of a multiple when we see strong arrivals on the full corridor stack without a corresponding strong arrival on the outside corridor stack. This can be verified by comparing synthetics with primary reflections to synthetics with primary plus multiple reflections for a given well. The existance of some multiple arrivals is confirmed by this comparison. In some cases, our sonic logs do not go deep enough to verify the existance of

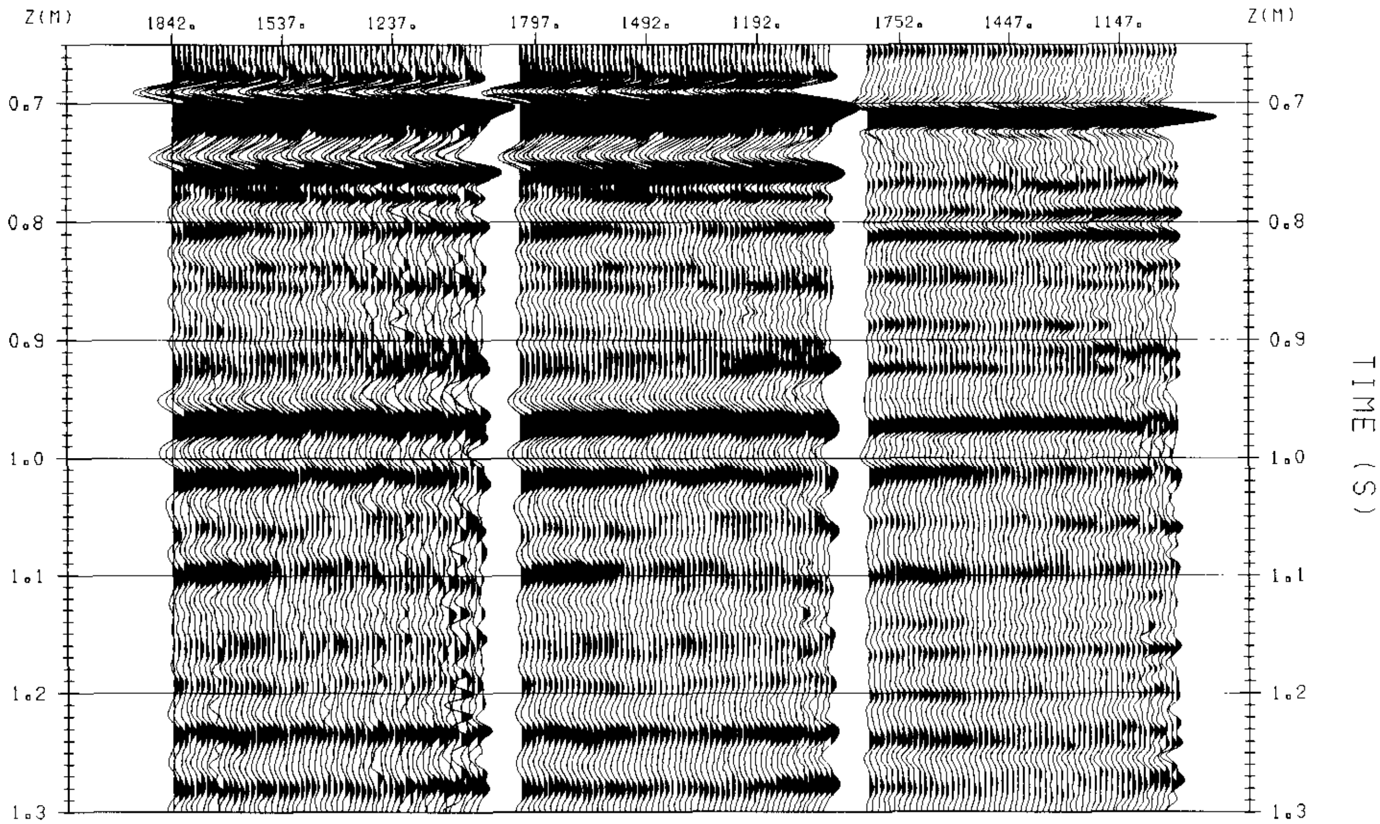

Fig. 3a. Processing stages for the downgoing wavefield (–TT). From left to right is the f-k separated wavefield, output from median filtering, and finally waveshaped using the average wavelet contained within an 80 ms window starting at the first peak.

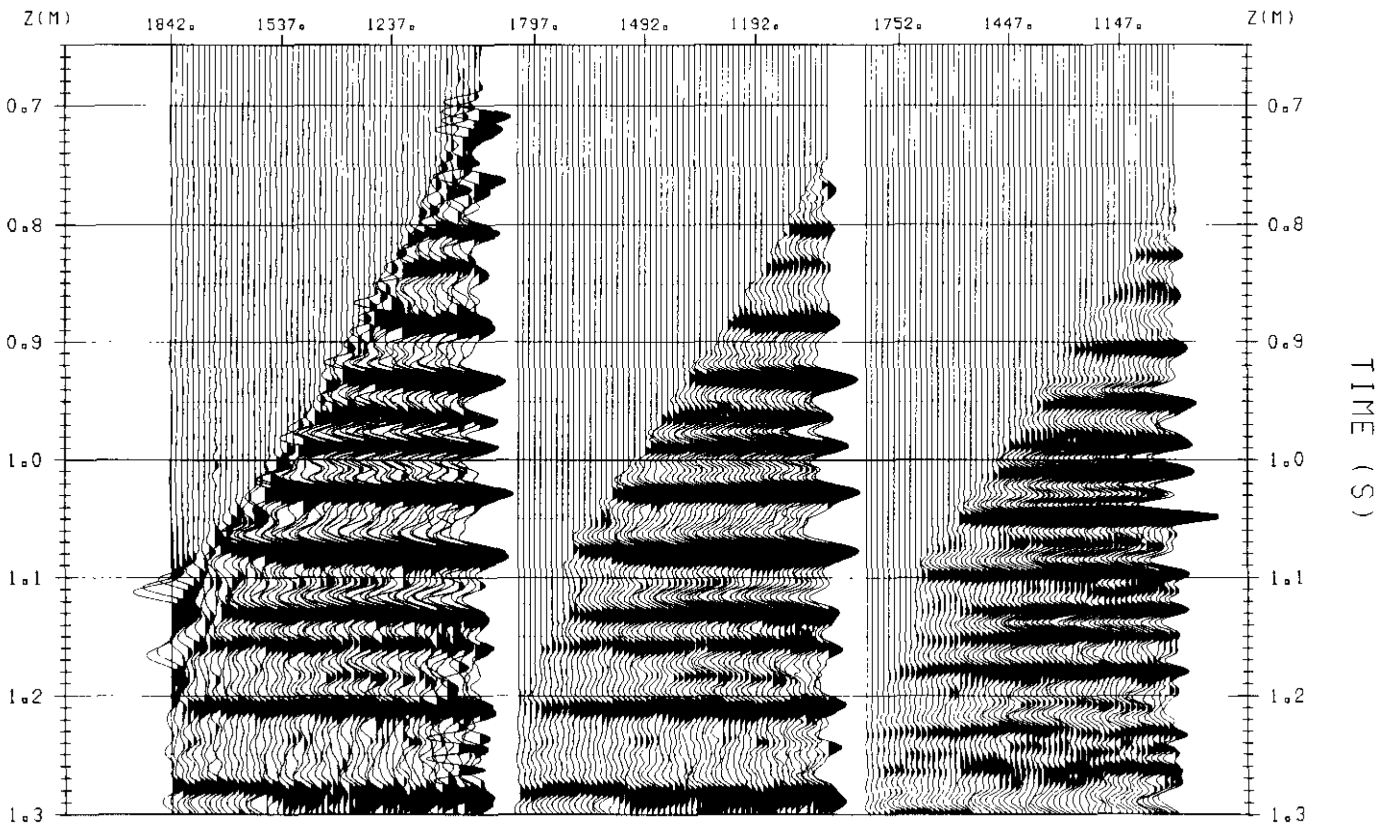

Fig. 3b. Processing stages for the upgoing wavefield (+TT). From left to right is the f-k separated wavefield, output from trim statics and median filtering, and finally waveshaped using the downgoing compressional wavefield. The outside corridor stack can be produced by muting all data below a delayed first break trajectory before stacking. Note that residual f-k energy was muted near the edges of the record.

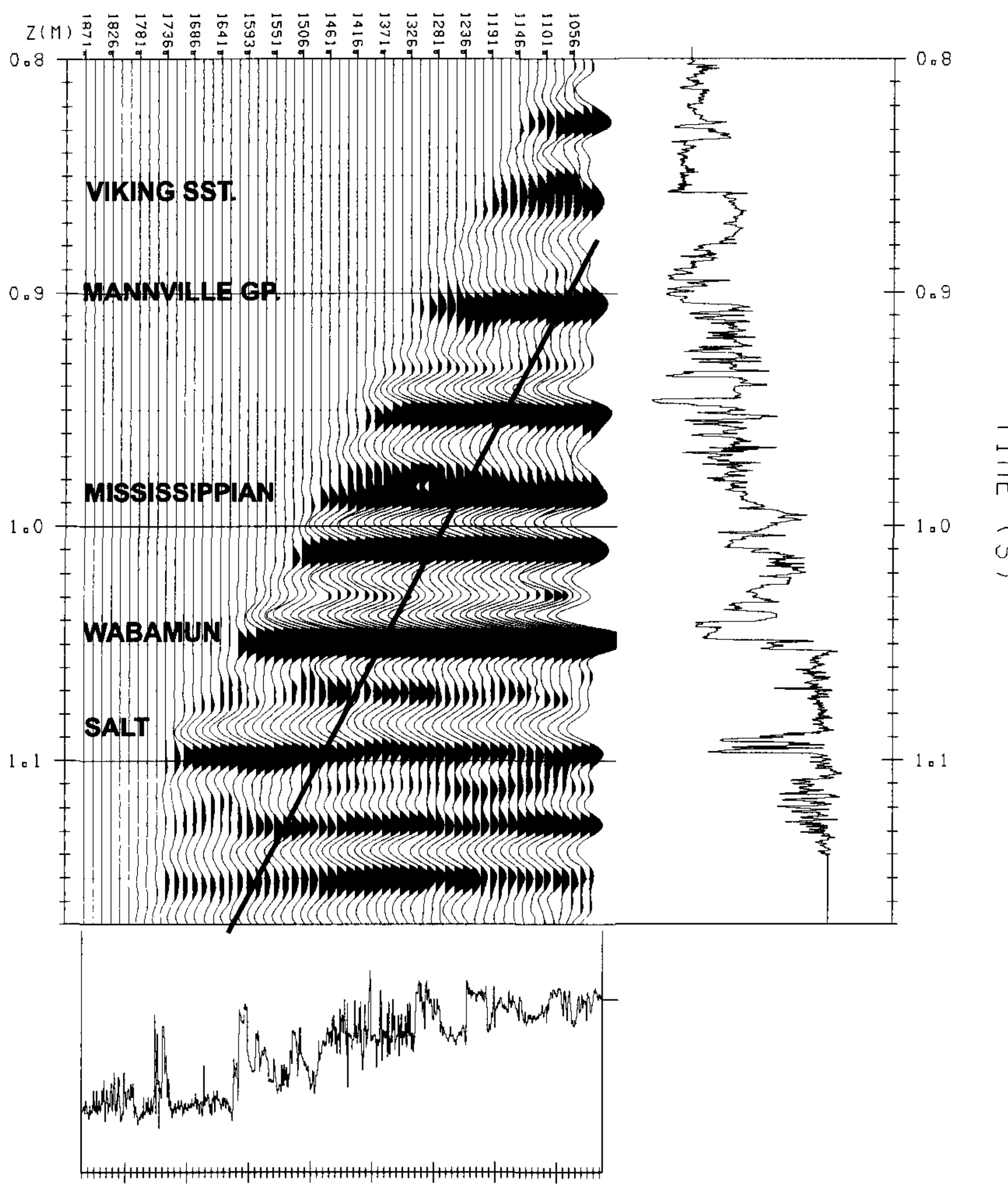

Fig. 3c. Waveshaped upgoing VSP wavefield (+TT) compared to impedence logs in time (constrained by corrected checkshots) and in depth (TVD, SRD = 900 m). The concept of inside corridor stacking is illustrated by the mute zone. Some geologic entities are identified.

primary reflections. For this reason, we also include the plots of far, near, and full stacks for surface reflection data. In cases where there are significant event timing differences between near and far stacks caused by normal moveout differences, we may suspect the existence of a multiple.

For a Devonian reef well, we examine the assimilation of model synthetics, VSP corridor stacks, and range limited CDP surface data stacks in order to detect differences between primaries and multiples. In Figure 4, there is a strong arrival on the impulse response synthetic at 1170 ms and also on the full corridor stack, but the event is practically missing on the outside corridor stacks – suggesting that this event is an interbed multiple. Outside corridor stacks for windows of 200 ms and 60 ms show a disappearance of

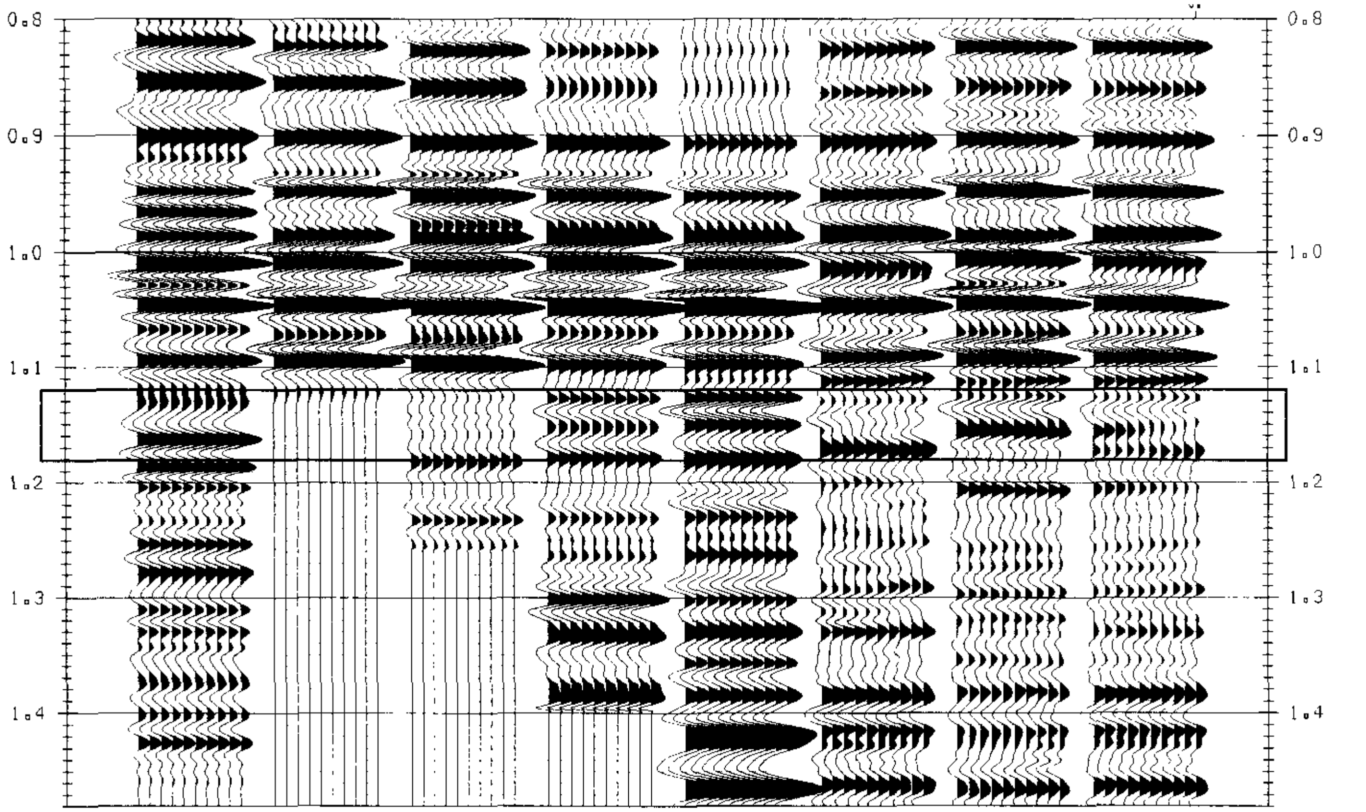

Fig. 4. Assimilation of data for the reef well. From left to right is the primaries plus all interbed multiples synthetic (impulse response neglecting surface reflector), primary synthetic (35 Hz Ricker), outside VSP corridor stack (60 ms window), outside corridor (200 ms window), full VSP corridor stack, far stack (1000-2000 m), near stack (200-1000 m), and full CDP stack (200-2057 m).

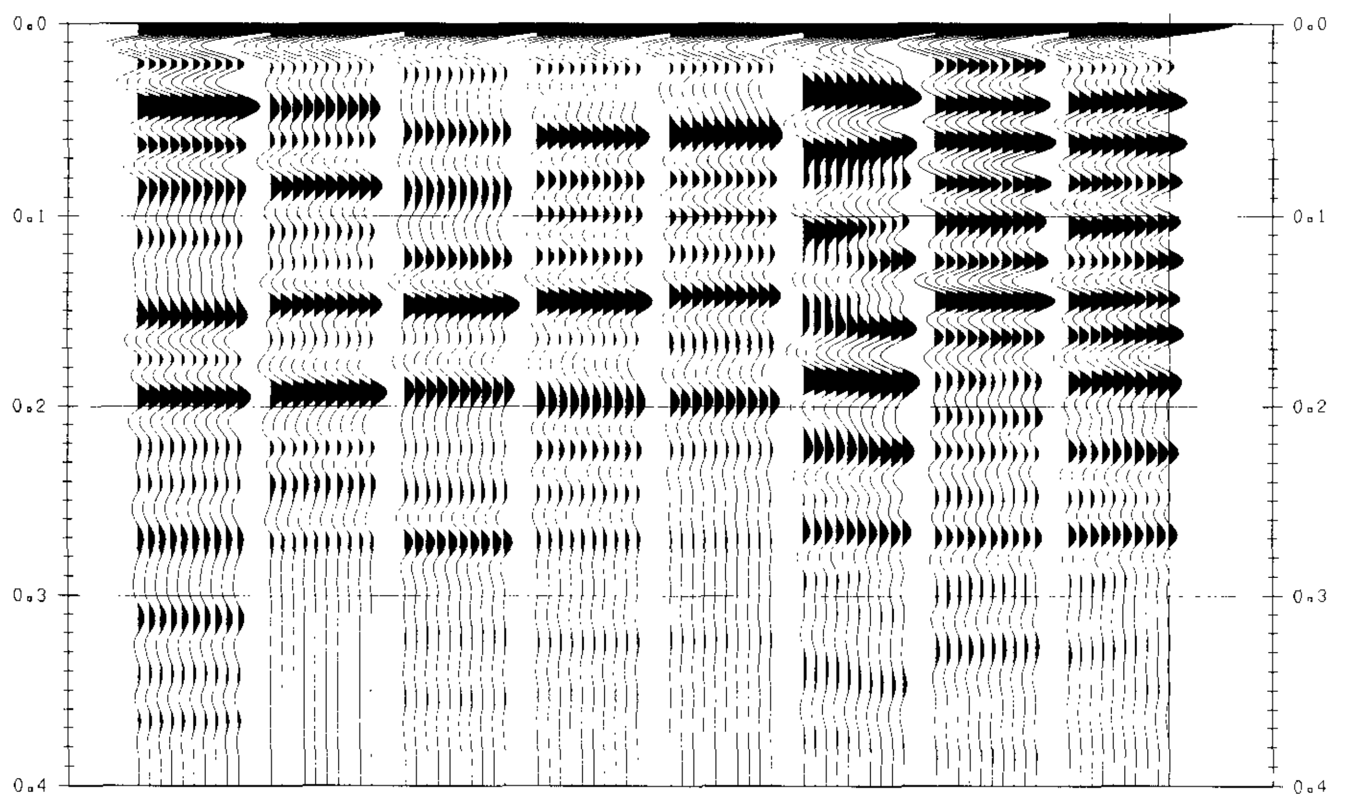

Fig. 5. Autocorrelations of assimilated data for the reef well. The calculation window ranges from 0.8 s to 1.2 s. From left to right is the interbed multiples synthetic, primary synthetic, 60 ms corridor, 200 ms corridor, full VSP corridor stack, far stack, near stack, and full stack. Prediction distance can only be chosen based on the VSP.

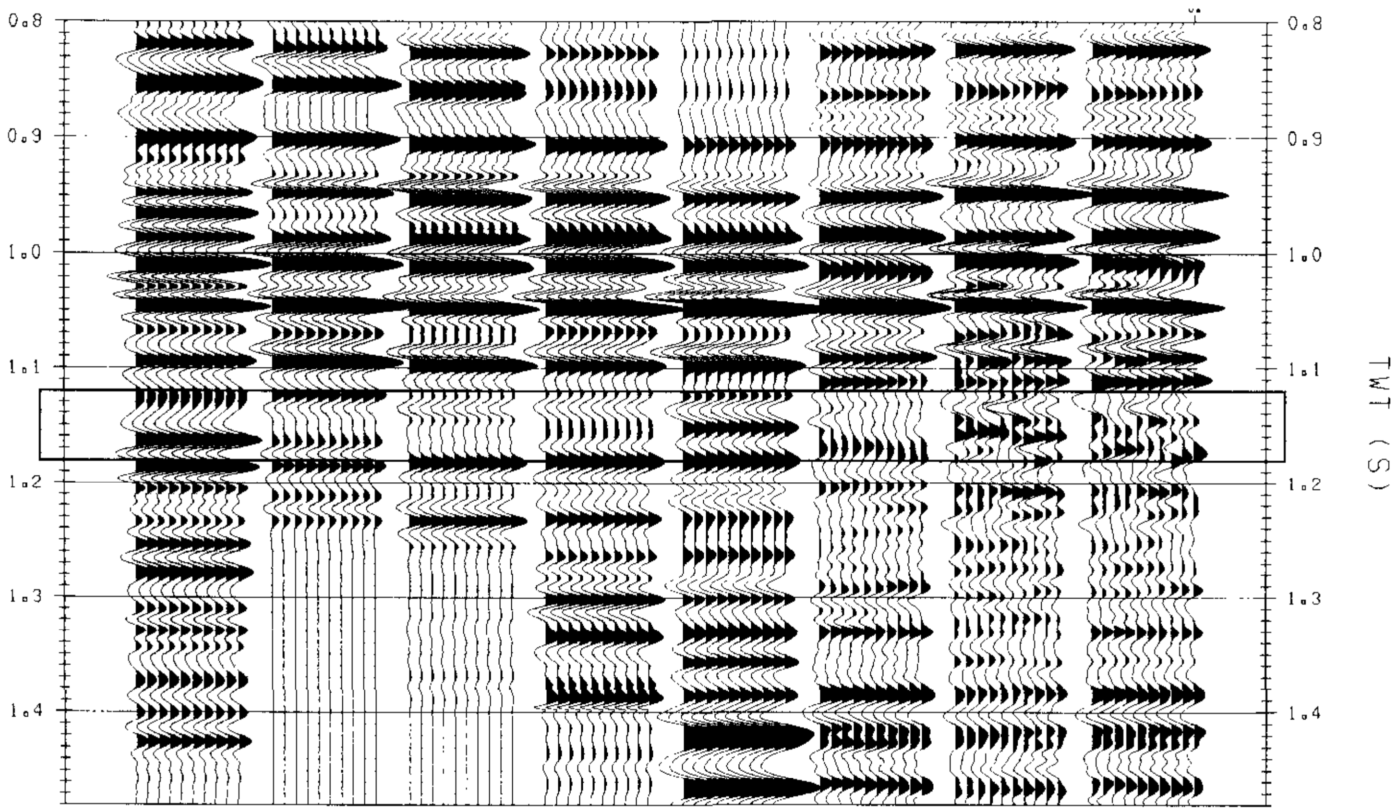

Fig. 6. Assimilation of data for the reef well following predictive decon using 60 ms operator length and 90 ms prediction distance. From left to right is the impulse response synthetic, primary synthetic, 60 ms corridor, 200 ms corridor, full VSP corridor stack, far stack, near stack, and full stack.

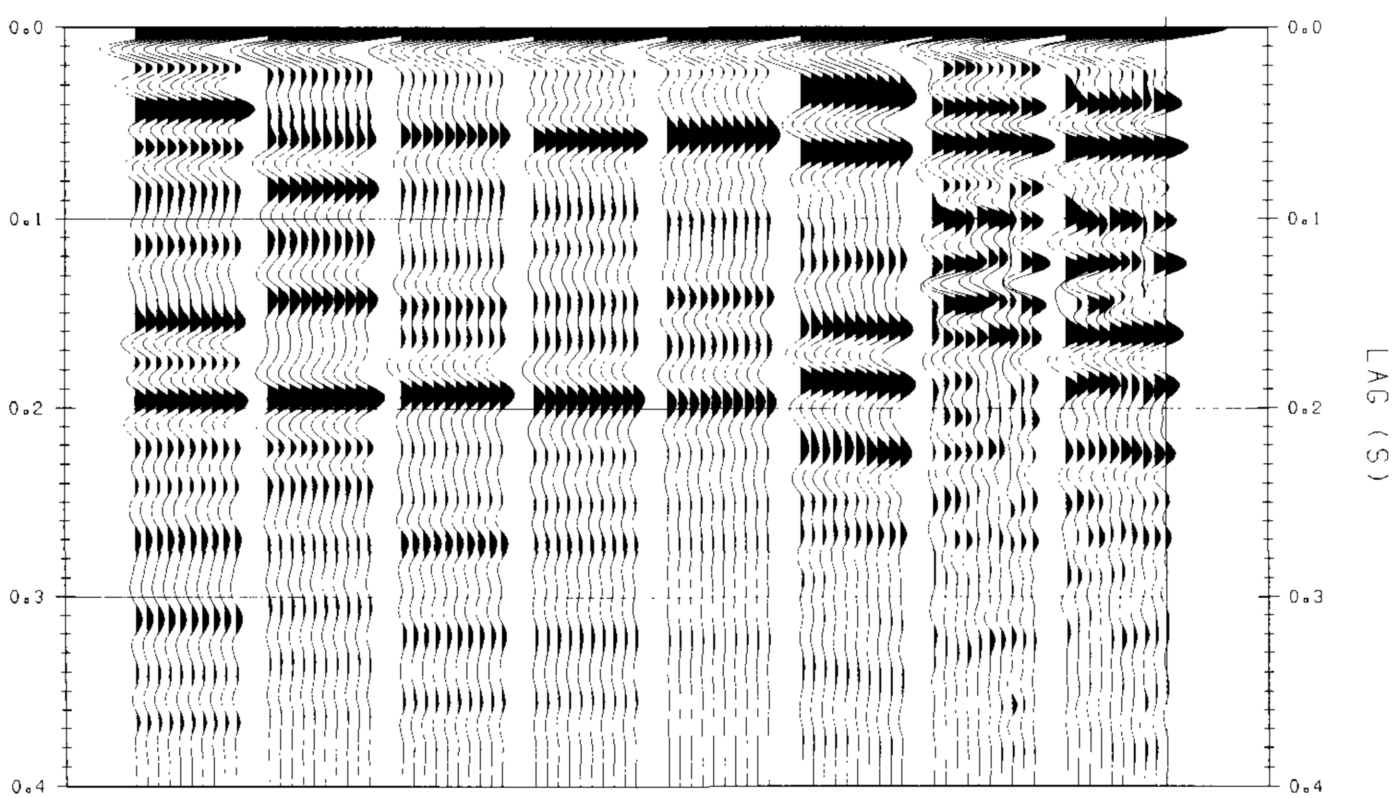

Fig. 7. Autocorrelations of assimilated data for the reef well following predictive decon using 60 ms operator length and 90 ms prediction distance. The correlation window ranges from 0.8 s to 1.2 s. From left to right is the impulse response synthetic, primary synthetic, 60 ms corridor, 200 ms corridor, full VSP corridor stack, far stack, near stack, and full stack.

multiple energy between 1130 and 1170 ms as the outside corridor becomes tighter. Unfortunately, the sonic for the "primaries-only" synthetic seismogram does not go deep enough to confirm whether the arrival is a multiple. The box in Figure 4 outlines the area of interbed multiples. In addition to the identification of multiples, it is very encouraging to note the generally excellent agreement between the "primaries-only" synthetic and the outside corridor stack.

However, the impulse response synthetic of primaries and multiples does show a multiple at 1170 ms (below the well TD). Moreover, the far range stack for the surface reflection data shows a delay or residual moveout relative to the near range stack. Model synthetics, range-limited stacks of surface seismic data, and the VSP corridor stacks all suggest that the events between 1130 and 1170 ms are dominated by interbed multiples.

The autocorrelations of VSP corridor stacks are also useful in designing predictive deconvolution filters for both the VSP and surface reflection data. Figure 5 shows the autocorrelations of these data for model synthetics, VSP corridor stacks, and the surface reflection data. Such autocorrelations are used to estimate the prediction distance and operator lengths for prediction error filters (Peacock and Treitel, 1969). For the autocorrelations of the corridor stack, we see significant differences between the outside corridor case and the full corridor stack which suggest a prediction distance of 90 ms and a prediction operator length of 60 ms. It is not as easy to estimate these parameters from the surface data alone. These predictive deconvolution parameters are used in predictive deconvolution of the data in Figure 4 to produce the deconvolution results of Figure 6. A comparison of Figure 6 with Figure 4 shows significant reduction in the multiple energy between 1130 and 1190 ms. The autocorrelations of the deconvolved output of Figure 7 show the effects of the predictive deconvolution. As expected from the discussions of Peacock and Treitel (1969), these autocorrelations of the deconvolutions show a decrease in autocorrelation values for times between the prediction distance (90 ms) and the prediction distance + operator length (150 ms). The VSP autocorrelations may prove useful in estimating predictive deconvolution operators for both VSP and surface reflection data.

Conclusions

Experience has shown that short-period multiples are difficult to suppress using conventional methods of deconvolution and stacking. It is to our advantage to consider all tools in our multiple suppression toolbox – including the use of VSPs. Thus far, we have found that the use of windowed corridor stacks advocated by Hardage (1983) may prove useful in the identification of multiples. These identifications using VSP corridor stacks are generally in agreement with range-limited CDP stacks and model synthetics. It also appears that the corridor stacks are useful in designing predictive deconvolution parameters for deconvolving multiples from both surface and VSP reflection data.

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