INTRODUCTION

During recent years, vertical seismic profiling (VSP) and lateral seismic profiling (LSP) have evolved into viable exploration tools. As shown in Figure 12.1, these methods involve the recording of seismic energy using the geophones placed inside the well borehole. Operationally, the geophones are contained in a war sonde that is lowered to the bottom of the borehole. As the sonde is lowered, check-depth VSP recordings are done at intervals of 50 m or so. These VSP recordings will be used to check recordings made at the same wireline depth level when the tool is later raised up the borehole as a check for the detection of cable kinks or wireline depth gauge malfunction. When the geophone sonde reaches the bottom of the borehole, the wireline truck raises the sonde to the first depth location beginning production VSP recordings. The sonde has a locking arm that forces the geophone assembly against the wall of the open borehole or casing. During each reading, the sonde is lowered to the bottom of the borehole. As the tool is lowered, the source at the S1 is a zero-incidence location with respect to the source at the S2 is a non-zero incidence location as the source does not lie directly over the geophone. The source location is updated with reference to the upgoing and downgoing waves travel vertically down to the reflector and back to the receiver geophone in the borehole. The source at S1 is a non-zero-offset location as the source does not lie directly over the geophone. The source at S2 is a zero-offset location. Part (B) is usually represented in the literature as a deviated borehole intersecting horizontal layers. This estimates a zero-offset location. Part (B) is usually represented in the literature as a deviated borehole intersecting horizontal layers. This estimates a zero-offset location. Part (B) is usually represented in the literature as a deviated borehole intersecting horizontal layers. This estimates a zero-offset location. Part (B) is usually represented in the literature as a deviated borehole intersecting horizontal layers. This estimates a zero-offset location. Part (B) is usually represented in the literature as a deviated borehole intersecting horizontal layers. This estimates a zero-offset location. Part (B) is usually represented in the literature as a deviated borehole intersecting horizontal layers. This estimates a zero-offset location. Part (B) is usually represented in the literature as a deviated borehole intersecting horizontal layers. This estimates a zero-offset location. Part (B) is usually represented in the literature as a deviated borehole intersecting horizontal layers. This estimates a zero-offset location.
near-zero angle between vertical, sonde and source) in the borehole. However, unlike the check-shot survey where only the first breaks are recorded, in the VSP the geophones in the borehole record both up and downward travelling waves (Fig. 12.3) for several seconds after the first arriving energy reaches that downward geophone location. Unlike a surface seismic survey where the geophones are placed on the ground surface and receive only upgoing waves, the VSP geophones receive upgoing waves from reflections originating below, above and parallel to the geophones (that are transmitted directly or reflected down to the geophones (Fig. 12.3). Any downgoing wavewaves after the first break (the primary downgoing wave) can be either P to SV mode converted primary downgoing waves, SV downgoing primary waves (generated at or near the source) or reflected P or SV downgoing wave multiples (Fig. 12.3). The primary P to SV mode converted downgoing waves arrive later in time and at a deeper geophone location than the primary non-converted P wave due to the lower SWave velocity and altered angle of transmission at the point of conversion.

Upping and downgoing waves are sketched in the ray-path diagram in Figure 12.4a. As illustrated, downgoing multiples arrive later than the downgoing primary waves. The corresponding traveltimes are shown in Figure 12.4b. Note that the upgoing and downgoing waves trend in opposite directions on the depth/traveltime plot.

As the geophone is lowered into the borehole:
1) the traveltime of the upgoing waves decrease since the downward travelling geophone is travelling towards the geological reflector (Fig. 12.4a);
2) upgoing reflections from a particular horizon will cease to be recorded when the geophone is deeper than that horizon (Fig. 12.4d);
3) the upgoing primary reflected waves will merge with the primary downgoing wave on the VSP depth/traveltime plot where the geophone intercepts the reflecting horizon (Fig. 12.4d);
4) the traveltime of the downgoing primary wave will increase beyond the primary downgoing waves (Fig. 12.4c) and
5) the traveltime of the downgoing surface-generated multiples and interbed multiples will increase. The surface generated multiples will appear on the data from the shallowest recorded geophone level to the deepest level and will be a delayed image of the downgoing primary. The interbed downgoing multiple will be recorded only where the geophone is beneath the TOP

Figure 12.4. Examples of the upgoing and downgoing raypaths for both primary and multiple reflections are shown in part A. The upgoing rays are illustrated on the left side of the diagram whereas the downgoing rays are illustrated on the right side. The geometry for the zero-offset sources are displayed with exaggerated source offset for clarity. The surface generated downgoing multiples will be recorded at all subsurface geophone locations whereas the interbed downgoing multiple generated between layers A and B will only be recorded when the geophone is below layer A. Upgoing reflections from layer A will be recorded only at geophone locations above layer A. The up and downgoing primaries will merge when the geophones are located at the generating interface. A traveltimes curve plot for the zero-offset case parallel the downgoing primary. The upgoing primary (B) generates a reflected downgoing multiple at interface A, which in turn can generate an interbed upgoing multiple at reflector B.
layer that generates the downgoing reflection of the multiple. Above that layer, the interbed downgoing multiple is not recorded (Fig. 12.4) as a downgoing wave.

Compressional (P), shear vertical (SV) and the shear horizontal (SH) ray-paths are depicted in Figure 12.3. Depending upon the emergent angles that the various modes have with the X, Y and Z axes of the geophone package (Fig. 12.5), these wavefields will be vectorially partitioned between the three downhole geophone axes. The result is that the Z-axis geophone will not record P wave energy only but will record a combination of P and SV energy. Similarly the X- and Y-axis geophones will record some P-wave energy. Figure 12.5 illustrates the amount of partitioning onto the various axes can vary significantly depending on the source-receiver geometry in the deviated borehole example.

The three geophones in the triaxial sonde are oriented vertically and horizontally with the two horizontal geophones aligned orthogonal to each other. Usually, there will be three geophones aligned in series in each direction for a total of nine geophones per tool. As the sonde with the triaxial package is lowered down the borehole (Fig. 12.3), the VSP tool containing the geophone package will rotate and the X and Y channels will change orientation due to the twisting motion of the wireline cable and the deviation of the borehole. In the processing sequence, various numerical pseudo-rotations are needed to redistribute the P, SV and SH energy back onto separate channels. These numerical rotations or redistributions of the recordings from the three geophone axes onto new orientation axes are called the polarization or hodogram analysis and a recent development called time-variant model-based polarization. These two methods will be discussed in the far-offset LSP case history.

The VSP example for the Lanaway/Garrington area is a zero-offset dataset. In Figure 12.2 the approximate location of the well is shown. The primary geological target is the updip edge of a gas prone Leduc Fm reef. This Leduc Fm reef is approximately 200 m high with an updip eastern edge containing a 50 m pay zone. The eastern and western limits of the gas pool are the reef foreslope and the gas-water interface, respectively.

The main pre-drilling seismic interpretation markers are displayed on the surface seismic line shown in Figure 12.6. A time-structural anomaly at the Leduc level near the well location is interpreted as localized Leduc structure. This time-structural anomaly is associated with both a character and isochron change. Specifically, near the well location the Leduc event broadens into two peaks, the upper of which was interpreted as the top of a localized structure on the otherwise relatively flat reef. The Leduc to Cretaceous, Leduc to Wabamun and the Leduc to Cambrian isochrons were also interpreted as indicative of a thicker buildup.

Drilling, on the basis of the interpretation of the surface seismic data, was expected to show the overlying breccia to be as thin as 10 m thick. The three geophones in the triaxial sonde package will receive contributions of P, SV and SH waves on all geophone axes. The Z component even for the "zero-offset" source location at Sz will not contain P waves only. To separate the various wavefield contributions, the geophone package will be numerically rotated using hodogram polarization analysis (Fig. 12.24). This is the "theoretical" geometry used in the analysis of the upgoing rays for the deviated borehole. Note however that the upgoing rays travel very different directions when the subsurface layers are not horizontal as in Figure 12.1.

**ZERO OFFSET CASE HISTORY**

**REGIONAL GEOLOGY AND GEOPHYSICS**

The VSP example for the Lanaway/Garrington area is a zero-offset dataset. In Figure 12.2 the approximate location of the well is shown. The primary geological target is the updip edge of a gas prone Leduc Fm reef. This Leduc Fm reef is approximately 200 m high with an updip eastern edge containing a 50 m pay zone. The eastern and western limits of the gas pool are the reef foreslope and the gas-water interface, respectively.

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the surface without any bulk shift being added or subtracted from the raw recorded time (field recorded time) is used to describe the time placement of the data. To align the data along the first break suggesting that the zero-offset traveltimes for each trace is subtracted from that trace and the aligned data is bulk shifted to some 30 to 40 m. The gas/water contact differed from the neighboring wells to the north so that the well location was classified as a separate pool.

The VSP was run in order to resolve the discrepancy between the interpreted surface seismic data and the well data. Specifically, the interpretation of the VSP was expected to determine:

1) the nature of the character anomaly on the seismic data; and
2) the isochron/isopach relationship of the anomaly.

SEPARATION OF UPGOING AND DOWNGOING WAVES
In the following text, the terms FRT, +TT time and –TT time will be used repeatedly (Table 12.1). When the data are recorded in panels 3, 4, 5 and 6 in Figure 12.8. In order to separate the upgoing and downgoing waves in –TT time (the TT refers to the first break traveltime for that trace). To align the upgoing waves of a zero-offset VSP (before deconvolution) and those traces respective first break time is added to that trace. The data in this time configuration is said to be in +TT time.

To evaluate data quality during interpretation, the effects that various processing operations have on the raw through separated upgoing P wave data, must be systematically analyzed. It is the upgoing waves, placed into pseudo-two-way time (+TT), that are directly tied to the surface seismic at the wellbore location (Fig. 12.7). Unfortunately the upgoing waves are always of significantly lower amplitude than the downgoing waves. If these weaker upgoing waves are distorted during processing then this operation should be followed back to where the data were interpreted to be distorted and reprocessed from that point on.

The IPP in Figure 12.8 consists of seven panels which depict the raw data through to the wavefield separated data. The first and second panels show the raw and gained data in field recorded time (FRT). These two plots allow for an evaluation of the relative signal strength of the upgoing and downgoing waves. The difference between the amplitudes of the upgoing and downgoing waves where they constructively and destructively interfere in the area of the first break (Fig. 12.8, panel 1). If the downgoing wave contamination is too severe then the various processing steps that analyze the data in the first break zone such as field separation will be suspect. The primary events have been interpreted on the entire set of panels. In Figure 12.8, shallow and deep reflections and multiples are also interpreted.

The wavefield separation quality control panels are displayed as panels 3, 4, 5 and 6 in Figure 12.8. In order to separate the upgoing and downgoing waves, the downgoing waves are aligned horizontally and enhanced by median filtering in panel 4. Panel 4 is then subtracted from the combined wavefield panel in +TT time of panel 3 to separate the downgoing waves. To show the effect of the separation, the deconvolved upgoing waves are shown in two-way traveltime (+TT) without and with an application of a median filter in panels 4 and 5, respectively. The sequence of panels 3 to 6 show that the wavefield separation operation has not significantly altered the signal information contained in the separated upgoing waves.

The initial interpretation of the upcoming events is performed using the median filtered separated upgoing waves in +TT time (Fig. 12.8, panel 7). This interpretation is incorporated into the previous panels in Figure 12.8. The zero-offset VSP interpretation is premised on the basis that only primary VSP events intersect the first break curve (see upgoing reflecting from a boundary merge, with the downgoing primary when the geophone is at that interface). As the depth of the seismic markers is known from drilling, the trave for that particular depth can be determined and then followed to the first break. At that first break point, the corresponding primary upgoing event will be observed.

The wavefield (up going and down going) waves separation in Figure 12.8 was performed with the use of median filtering. There are other methods of wavefield separation such as Karhunen-Loeve method, the wave equation based methods, the frequency-wavenumber method and the Tau-F method. A comparison of all of the methods with respect to interpretation is a topic for future research.

DOWNGOING WAVES
The downgoing waves contain the surface generated and interbed multiples and are recorded on both the surface and a downgoing VSP. The separated downgoing wavefield can be deconvolved to a single primary pulse using an inverse filter operation. The filter is designed from a set of deconvolved wave panels and all relevant multiples can be represented and therefore collapsed. That same deconvolution filter operation can be applied to the separated upgoing waves in order to remove all existing multiples. The logic for designing the inverse filter operation is based on the upgoing waves and the fact that the base of the downgoing waves for the zero-offset VSP data (called "apiups" or "up over down" deconvolution) is illustrated in Figure 12.8.

The IPP that enables the interpreter to determine the effect of the application of the inverse filter (aperture deconvolution) on their data is shown in Figures 12.10. Panel 1 (Fig. 12.10) shows the deconvolved upgoing waves (+TT) and panel 2 shows the effect of applying the medium filter in the separated upgoing waves of Panel 1. Panel 3 (Fig. 12.10) shows the downgoing waves in –TT time and the deconvolved downgoing waves in –TT time. In panel 5, the comparison of panel 4 and 5 enables estimation of the effect that deconvolution has on the dataset. One of the results of applying a downgoing wave designed inverse filter to the upgoing waves is to change the polarity of the operator. Panel 5 (Fig. 12.10) shows the polarity change in panel 4. This polarity change is compensated for in the next two panels. The deconvolved upgoing data in panel 6 (+TT) is median filtered and shown in panel 7.

The interpreted multiples are evident on an examination on panel 4 (Fig. 12.8). The multiple reflection generating at 120 ft lies at a depth of approximately 2900 m. The multiple in Figure 12.9 is tentative and may be interpreted as a deeper reflecting or a reverberating multiple with the operator at 2900 m. The Leduc Pick at 2900 m.

INSIDE AND OUTSIDE CORRIDOR STACKS
Two types of IPP displays have been designed to enhance the recognition of multiples and the possible influence on interpretation of the surface generated and interbed multiples (Figs. 12.11, 12.12, 12.13) on the dataset. These are called the Inside and Outside
Figure 12.8. The interpretive processing panels that shows the wavefield separation operation in detail. The multiples and primary reflected waves can be traced from the raw data to the upgoing separated data.
Figure 12.10. The interpretive processing panel that shows the effect on up/down deconvolution on the upgoing wave datasets. The separated
downgoing waves display the downgoing primary and the downgoing multiples. The downgoing multiples are collapsed to the first break wavelet
by deconvolution. The same operator is applied to the upgoing waves. The median filtered deconvolved and nondeconvolved upgoing waves in
(+TT) time can be directly compared in order to estimate the reliability of the deconvolution operation for the zero-offset case.
The interpretation differences in these corridor stacks can be due to:
1. The presence of multiples on the nondeconvolved inside stacks;
2. The depiction of multiples on the outside nondeconvolved corridor stacks because the multiply reflected upgoing events do not intersect the first break curves;
3. The processing problems involved in the usage of these panels: (a) the application of an inappropriate multiple deconvolution operator which could cause phase shifts and ringing; (b) the corridor stacks were derived must be analyzed.

Correlator panels consist of the non-muted input upgoing wave data, the muted corridor and the resultant corridor stack. Comparison of the input and the resultant corridor stack will give an indication whether the deconvolution was successful, then the two stacks will be an indication of the reliability of the inside and outside stacks of the deconvolved data will be primary events. The inside corridor stack will contain both primary reflections in that zone. This was point (3) in the discussion on the problems of the corridor stacks. The observation of most importance for the interpreter is that the Niobe and Leduc events do not seem to be influenced by the interbed multiple interference.

The interpretational differences in these corridor stacks can be compared. Whether or not the zones suffer from multiple interference can then be determined. This can be further investigated on surface seismic data using closely spaced common offset patches.

The corridor stack panels consist of the non-muted input upgoing wave data, the muted corridor data and the resultant corridor stack. Comparison of the input and resultant corridor stack will give an indication whether the deconvolution was successful, then the two stacks will be an indication of the reliability of the inside and outside stacks of the deconvolved data in Figures 12.12 and 12.13 show that the interpreted corridor stacks were essentially flat lying events. One assumption in the usage of the corridor stacks is that the data image horizontal reflections in the local area of the borehole. This can be confirmed by the observation that the VSP would be sampling at the most only 100 m from the bottom of the borehole with the stack receiver (by using a 200 m offset) and that the data appears flat.

The panels are analyzed by examining the corridor of data that will be horizontally summed. The multiples can be contaminated by median filter artifacts created by the applied median filter; removing the first breaks the interpreter should confirm that the horizontal sum from the muted corridor data represents the input data. The two outside corridor stacks, nondeconvolved and deconvolved, differ sufficiently to permit the event for approximately 200 m and then match each other from the Pekisko event down to the base. This difference is between the first break and the deconvolved data, and the deconvolution is therefore used for the purpose of this example to remove the Mannville/Basal Quartz interbed multiple; and the interbed multiple is of such a short period that the nondeconvolved outside corridor stack was unable to completely represent only primary reflections in that zone. This was point (5) in the discussion on the problems of the corridor stacks. The observation of most importance for the interpreter is that the Niobe and Leduc events do not seem to be influenced by the interpreted multiple interference.

Comparison of the inside corridor stack of the deconvolved data and the outside corridor stacks of the deconvolved data show that the updown deconvolution has successfully removed the Mannville/Basal Quartz interbed multiple in the data. This results in the correlation. The peak for the reflector between the Mannville and the Basal Quartz has been preserved on all of the traces to positively bias the surface-generated multiples (the interpreter should investigate exactly how a wavefield separation operation).

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Other methods create transposed corridor stacks that take into account slightly dipping interfaces about the borehole and the interpretation pitfalls associated with the usage of that resultant data will be discussed in later research.

THE INTEGRATION OF OTHER INTERPRETATION DATA

The Integrated Interpretive Display (IID) is one of the first views of the data that the interpreter will see after the initial geologic and seismic information such as well log and surface seismic data. Modified versions of this display may also be seen in other environments, for example, the area. As shown previously, the IPF allows the interpreter to gain confidence in the processing steps. Both types of presentations are necessary to ensure that a complete set of displays are available to the exploration team in order to enable full exploitation of the subsurface images found in the VSP or LSP data.

The interpretation of the IID typically begins with the sonic and gamma logs displayed in depth. Other logs to indicate porosity and electrical character can also be plotted on the display. Well logs in true vertical depth can be used for slightly deviated boreholes as long as the VSP, placed directly beneath the well logs, is plotted with the same depth scale. The VSP traces should be plotted relative to the depth of the sonic log at 2616 m whereas the nearest depth trace for the VSP is at 2610 m. The sonic log and gamma-ray log response of the Wabamun Gp are shown in Figure 12.14 as a sharp decrease in the gamma-ray reading and as an increase in velocity in the sonic log at the 2616 m level. The vertical depth location can be followed down the VSP trace to the first break located around 1450 m on the 2610 m geophone depth trace. Visually interpreting between the 2610 m trace and the next deeper trace allows one to interpret the primary Wabamun seismic event.

Figure 12.14 illustrates that the main seismic markers can be integrated into the VSP using this method. The seismic markers having been tied to the geological depths are now represented in two prerovette, the common bond between the surface seismic and the VSP in TT time. The interpretation can be followed to the left to the well location on the surface seismic and onto the inside and outside corridor stacks. Away from the location of the seismic markers can be interpreted noting that the Glauconite to Basal Quartz sequence is generally below the top of the Mannville and the Basal Quartz interbed multiple shows up as the main disturbance in the data. Fortunately, the multiples can be removed by the updown deconvolution of the data.
Figure 12.12. The inside and outside corridor stacks of the non-deconvolved data for the zero-offset Lanaway/Garrington VSP. The corridor stacks are presented altogether on the same interpretive processing panel to allow for an analysis of the multiple contamination of the data. The input data in both polarities along with the displaying of the muting zones indicate the reliability of the stacks as a representation of the main seismic events and corresponding multiples in the data.
Figure 12.13. The inside and outside corridor stacks of the deconvolved data for the zero-offset Lanaway/Garrington VSP. Both of the corridor stacks should approximate the primary upgoing wave events with the minimal contamination of upgoing multiples. This panel can be used to analyze the reliability of the deconvolution operation.
Figure 12.14. The integrated interpretation display for the zero-offset Lanaway/Garrington well. The interpretation of the panel begins with the tie of the VSP depth axis with the depth axis of the sonic and gamma-ray logs. The interpreted geologic events are tied to the VSP at the first break curve of the VSP. Choosing the Wabamun Gp marker at 2616 m, one locates the depth trace of the VSP for that log depth and the primary upgoing event that intersects the first break time of that trace should be the VSP Wabamun Gp event. The surface seismic, synthetic seismogram and corridor stacks are tied to the (+TI) time of the VSP. For a comparison of the tie of the primary event (outside) corridor stack and the synthetic seismogram to the well log data, the sonic and gamma ray logs are plotted in time.
peak overlying the regional Leduc event. The VSP corridor stacks show that the trough above the regional Leduc event is the location, in time, of the structurally higher Leduc anomaly. The surface seismic did not image the feature of the reef properly at this location.

The inside and outside corridor stacks, plus the synthetic seismogram imposed between the two separate parts of seismic section (separated at the well location), allows comparison of the multiple contamination and evaluation of the synthetic seismogram to indicate the zone of interest. The corridor stacks show minimal multiple contamination around the zone of interest, the Leduc Fm. The synthetic seismogram poorly represents the Nisku to Jurassic sequence. A possible explanation for the sonic misrepresentation may be revealed in the observation that the fluid (mud) in the borehole was increased in density to prevent destabilization of the fluid column by any highly-pressured fluids from porous zones around the borehole. This causes a mud-oke in the porous Leduc Fm which may affect the sonic logs readings enough to cause the synthetic seismogram to poorly represent the true acoustic impedance.

To the right of the VSP (Fig. 12.14) is the outside corridor stack (containing predominantly primary events), the synthetic seismogram and the two well logs converted to time. This allows an evaluation of the reliability of the corridor stack and synthetic seismogram. Because the synthetic seismogram is calculated from the finely depth sampled sonic log, in some areas the synthetic will have a higher resolution than the corridor stack. Since the range of the wavelengths contained in the VSP are the same as for surface seismic, in some zones the corridor stack will tie to the seismic better. Thus, the corridor stack does not need to be stretched to fit the clastics part of the seismic section and then restretched to fit the carbonate part of the seismic section.

The interpretation of the IID has allowed the creation of an exploration picture around the well location and the investigation of the seismic signature of the top of the reef at the borehole. The interpretation performed on all of the interpretive displays lead to a reinterpretation post-VSP surface seismic section shown in Figure 12.15. Other look-alike anomalies on seismic lines in the area may also be economically productive as was this case history well.

REGIONAL GEOLOGY AND GEOPHYSICS

The Lateral, or Multi-offset, Seismic Profile (LSP) example is from the Leduc field which is located approximately in Twp 34 Rge 8 W5M (Fig. 12.2). The oil and gas production from the Leduc field is from 40 separate Cardium pools, four Viking pools, two Leduc (D-3) pools and unassigned pools. The target of the VSP well was the D-3B pool which has produced 5,695,805 MCF of gas along with 16,912 BBL of water as of September 1987. The areal extent of the D-3B pool can be estimated to be 25-30 m. In the separate D-3A pool (from the Leduc well to the northeast), 71,115,835 MCF of gas and 286,771 BBL of water have been produced from three producing wells as of September 1987.

The primary target of the VSP was the updip edge of the gas prone Leduc Fm. Three wells are shown in the geological cross-section shown in Figure 12.16. The well that was used for the VSP will be referred to as the "VSP well". The other two wells will be referred to as "well A" and "well B". Well A is in the geological section of the window directly above the Leduc Fm. Well B is located updip in the same pool encountered a thicker gas zone than the shut-in potential gas well A. As shown in the geological section the geological markers above the reef are the Elkton Member of the Turner Valley Fm (limy dolomite), Shunda Fm (limy dolomite), Feltisko Fm (limy dolomite) and Barf Fm of the Riddle Gp (limy dolomite), the Waterton Gp (anhydritic dolomite and anhydrite), the Nisku Fm (dolomite) and the Ireton Fm (dolomite). Off-reef formations include the Ireton Fm, the Wabamun Gp (anhydritic dolomite, halite), and the Davelton Fm (shaly dolomite). Underlying the Leduc reef are the Cooking Lake Fm (dolomitic limestone), and the Swan Hills Fm (dolomite) which unconformably overlies the Elk Point Gp. Interpreted on the seismic section is a near-Cambrian marker.

The surface seismic line with the pre-drilling interpretation is shown in Figure 12.17. One kilometre to the west of the VSP well location, the surface seismic line shows a drop at the Waterton Gp level and pull-up of the near-Cambrian event under the interpreted Leduc reef. The well was drilled with the expectation that the updip edge of the reef would be intersected. The Mesozoic faulting in the area complicates the interpretation of the surface seismic by causing

Figure 12.15. The reinterpretation surface seismic section incorporating the VSP interpretation. The previously interpreted reef top at the well is 12 ms above the VSP interpreted Leduc reef top. This account for the 20-30 m loss of expected reef build-up and both the VSP and reinterpret time tie the isopach values from the well logs.
Figure 12.16. The predrilling geological section for the D-3B Ricinus pool. The main markers in the section are the Elkton, Shunda, Pekisko and Banff Units of the Rundle Gp (Mississippian), the Wabamun Gp, the Nisku Fm, the Westerdale Limestone unit (sometimes called the "fast Ireton"), the Duvernay Fm, the Leduc Fm and the Swan Hills Fm. Well A was drilled on the downdip side of the reef and encountered less gas reserves than did Well B which is located updip. The predrilling prognosis for the VSP well was that the well would be updip and still be above the gas/water contact.

Figure 12.17. The predrilling surface seismic line. The upper section of the line is distorted due to faulting in the Mesozoic section. At the VSP well location, the Ireton Fm is interpreted to rise onto the reef. The Wabamun shows drape from reef to off-reef of approximately 10 ms. The near Cambrian event (trough) displays about 5-10 ms of pull-up under the interpreted reef. This amount is decreased from normal pull-up for Leduc reefs because the off-reef section around the reef does not consist entirely of low velocity shales but also is made up of the Westerdale Limestone (which is about the same velocity as the reef). The labelled main seismic events in this figure are the Nordegg Fm, Ireton Fm, Leduc Fm, Westerdale Unit, Duvernay Fm, Cooking Lake Fm (from the VSP interpretation) and a postulated near-Cambrian event.
confusing time structure anomalies in the data at the Viking Fm level down to the near-Cambrian event.

A thick off-reef Ireton, Westerdale limestone and Duvernay Fm were encountered in the VSP well. The VPCLSP survey was run in order to:

1) establish an accurate seismic tie with the geology in the area;
2) determine the effect of multiple interference on the seismic (and VSP) dataset;
3) determine whether the edge of the Leduc Fm reef can be interpreted to be in the near vicinity of the well (between 0 and 500 m).

Two offsets were used in the survey, at 200 m and 1100 m, in the direction of the interpreted Leduc Fm. The interpretation of the “zero-offset” Interpreting Processing Faults (IP) will be presented below without the lengthy technical explanations already done in the Lanaway/Darrington VSP example.

ZERO-OFFSET VSP

At a distance of 200 m away from the well, the source is still considered to be at a zero-offset location. The drilling rig was positioned on a prepared area called the wellpad which was 2-3 m above the ground and the depth spacing was 30 m from a depth of 4350 m up to 420 m. Above 420 m, the depth spacing was 60 m up to the shallowest level of 180 m. Each station was repeated during the survey from 3000 to 5000 ft (915 to 1530 m). The borehole and these station locations were repeated during the zero-offset survey (Fig. 12.18). At each geophone location, the local geophone axis will be referred to as X, Y and Z (also shown in Figure 12.5 for the deviated borehole). For each zero-offset data, only the Z axis geophone data is considered (similar to the data analysis in the Lanaway VSP example).

As an additional note, for mineral exploration situations where the object may lie to be the areal extent of a steeply dipping reflector, the zero-offset VSP data interpretation can make use of all three geophone components. For this case, the hodogram analyst for the far-offset LSP is used so rotate such zero-offset data if the two offsets were acquired during the same production run in the borehole.

Figure 12.18. The orthogonal coordinate system of the local X, Y and Z geophone along with the coordinate axis that will be used as the principal axis in hodogram analysis.

WAVEFIELD SEPARATION

The IPP which illustrates the processing from raw data stage to the wavefield separation stage is shown in Figure 12.19. The data, when aligned along the first breaks (-TT) in panel 3 show surface generated downgoing multiples (appearing as horizontal events after the first wavelets down to 400-500 ms). Comparing the gained data in FRT (field recorded traveltime, panel 2), the interpreted near-Cambrian reflector can be followed up to its representation on the trees for the shallowest wellhole location (recorded on the shallow depth geophone position around 2000 ms FRT). Looking at the gained data, the upgoing near-Cambrian event turns into a downgoing multiple and begins to travel downward. This Cambrian-to-surface downgoing multiple is displayed on the downgoing aligned data in panel 3 as the series of events around 2000 ms. This example of tracing multiples from the raw data panel onto the downgoing wave panel can be done for most of the visible multiples.

The strongest events on the separated upgoing wavefield panel after the data was placed it into a 2TT time (pseudo two-way traveltime) are the Viking Fm, Nordegg Fm, Wabamun Gp, Ireton Fm, Westerdale limestone, Duvrnay Fm and the postulated near-Cambrian event.

DECONVOLUTION

The downgoing-aligned waves (panel 3 shifted into -TT time in Fig. 12.19) showed that the data was affected by surface-generated downgoing multiple contamination. The VSP deconvolution process is illustrated in Figure 12.20. The deconvolved data can now be used in the corridor stack analysis panels in order to determine the extent of the effect of the multiples on the data.

INSIDE AND OUTSIDE CORRIDOR STACKS FOR MULTIPLE REMOVAL

The inside and outside corridor stacks of both the nondeconvolved and deconvolved zero-offset data are displayed in Figures 12.21 and 12.22, respectively. The multiples in Figure 12.21 are colored and when compared with the multiple attenuated outside corridor stack (of the nondeconvolved data) the surface and inscribed generated multiples are seen to extend throughout the entire VSP section.

The Viking, Ireton, Westerdale and Duvernay formation events, the Viking, Ireton and Duvernay reflectors are shown on the VSP upgoing wave section and the nondeconvolved upgoing near-Cambrian event is seen on the VSP upgoing wave section, the Nordegg Fm multiple originates beneath the point where the Nordegg Fm intersects the first break curve (+TT). The Wabamun Gp upgoing primary event will be unaffected at geophone locations beneath that depth level.

The deconvolved corridor stacks (Figure 12.22) show the Wabamun Gp primary is a flat lying continuous event across the section once the effect of the multiple is minimized. At this point the surface seismic can be reinterpreted at the well location.

NON-ZERO OFFSET (LATERAL SEISMIC PROFILE)

In the zero-offset example, the wavefield separation technique assumed that the upgoing wavefield was flat and linear. The underlying assumption was that the vertical geophone would record predominantly P-wave energy and that the horizontal geophones recorded solely SH and SV energy. The amount of shear wave energy recorded by the horizontal geophones in the zero-offset geophone survey was used to determine the downgoing and upgoing P-waves are partitioned onto all three geophone channels.

HODOGRAPH ANALYSIS

Figures 12.18 and 12.23 illustrates that the data from the X, Y and Z channels can be rotated into a new coordinate system which, by assumption, should contain separated wavefield components (SH on one channel, Downgoing P and Upgoing SV on another channel and Upgoing P and Downgoing SV on the third channel). The hodogram method that is used to separate the X, Y and Z data into PSV and SV components using windowed downgoing P wave first break data is called the Hodogram or Polarization Analysis (Hardage, 1983).

Assumption made in doing the hodogram analysis are:
Figure 12.19. The Interpreting Processing Panels for the zero-offset Ricinus VSP which shows the wavefield separation operation in detail. The multiples and primary reflected waves can be traced from the raw data to the upgoing separated data.
Figure 12.20. The Interpretive Processing Panel for the zero-offset Ricinus VSP which shows the effect on up/down deconvolution on the upgoing wave datasets. The separated downgoing waves display the downgoing primary and the downgoing multiples. The downgoing multiples are collapsed to the first break wavelet by deconvolution. The same operator is applied to the upgoing waves. The median filtered deconvolved and nondeconvolved upgoing waves in (+TT) time can be directly compared in order to estimate the reliability of the deconvolution operation for the zero-offset case.
Figure 12.21. The Inside and Outside Corridor stacks of the nondeconvolved data for the zero-offset Ricinus VSP. The corridor stacks are presented altogether on the same interpretive processing panel to allow for an analysis of the multiple contamination of the data. The input data in both polarities along with the displaying of the muting zones indicate the reliability of the stacks as a representation of the main seismic events and corresponding multiples in the data.
Figure 12.22. The Inside and Outside Corridor stacks of the deconvolved data for the zero-offset Ricinus VSP. Both of the corridor stacks should approximate the primary upgoing wave events with the minimal contamination of upgoing multiples. This panel can be used to analyze the reliability of the deconvolution operation.
1) P and SV downgoing and upgoing wave energy travel in the two-dimensional plane made by the borehole and the source;
2) the borehole is assumed to be vertical and in the plane of the source and the well;
3) the downgoing and upgoing waves arrive at right angles to each other at the geophone (Fig. 12.18 and 12.23);
4) the downgoing primary P-wave travels in the source-well vertical plane in an analysis window of one period (the source wavelet can be fully described by looking at one period of the primary P-wave after the first break arrival time); and
5) noise as a result of poor tool coupling and casing ring does not exist or is negligible on the data.

The initial stage of the polarization analysis is to rotate the X and Y geophone data numerically so that the resultant output channels have the P and SV downgoing energy maximized (HMAX) and the other channel has the P and SV downgoing energy minimized (HMIN). The method of numerically rotating the traces can be thought of as redistributing the amplitudes of the two input traces onto the two output traces. Taking the X and Y data at one geophone location, a hodogram is generated by plotting the respective amplitudes of the X and Y channel for each time sample over a given time window on the two traces. For the analysis of the P downgoing energy, the time window is a window around the P wave first break arrival on the two traces (Figure 12.24). The resultant data points will trace a curve called the hodogram of the particle trajectory. The angle that is traced by the hodogram is used in a two-by-two matrix for application on the two input channels in producing the two output channels. Ideally, this analysis should be done interactively at a computer terminal.

The inputs and outputs of the hodogram analysis where the X and Y channels have been transformed into the HMIN and HMAX should be done interactively by the recently developed interactive processing workstations.

The Hodogram analysis using the first break downgoing P-wave energy of the X and Y channels to rotate into the HMIN and the HMAX output channels. Windows are placed around the primary downgoing wave on the two input channels, X and Y. The respective amplitude values in the two windows are plotted onto a X, Y axis forming a hodogram. The angle that is traced by the hodogram is used in a two-by-two matrix for application on the two input channels in producing the two output channels. Ideally, this analysis should be done interactively at a computer terminal.

The hodogram analysis of the X and Y channels on the Ricinus far-offset data. The X and Y channels are plotted along with the resultant HMIN and HMAX output datasets.

The HMIN channel should contain minimal P and SV data being predominately SH energy (and out-of-the-plane reflections).
Figure 12.26. The result of the hodogram analysis for the HMAX and the Z channels on the Ricimes far-offset data. The Z and HMAX channels are plotted along with the resultant Z' and HMAX output channels are shown in Figure 12.25. The resultant HMIN channel should contain predominantly SH wave energy and P or SV energy that did not fit the assumptions of the analysis. Noisy data will be amplified and spread onto both of the resultant channels.

The HMAX channel should contain mostly downgoing P-wave and upgoing SV-wave data. The Z' channel should contain mostly downgoing SV-wave and upgoing P-wave data.

The next rotation using the P downgoing waves takes a time window around the P wave first break curve on the HMAX and Z channel and the resultant hodogram rotation angle converts the two input channels into the HMAX' and Z' channels (Figure 12.26). Once again, the polarization method has been performed on the datasets. The HMAX' channel should contain mostly downgoing P-wave and upgoing SV-wave data. The Z' channel should contain mostly downgoing SV-wave and upgoing P-wave data.

Figure 12.28. After the second downgoing wave first break polarization analysis, the downgoing P and SV wavefields are downgoing first break energy. On the Z' and HMAX' panels, the upgoing P and SV wavefields are not yet polarized. In order to accomplish this, the time-variant model-based polarization method is used. The IPP which serves as a quality control measure on the usual downgoing P wave first break hodogram analysis is shown in Figure 12.27. On the panel, the degree of success of the downgoing P and SV wavefield polarization can be determined by comparing the downgoing waves on the X, Y and Z channels versus on the Z' and HMAX data.

The downgoing waves, both P and SV, are separated from the Z' and HMAX data using one of the wavefield separation techniques.
Figure 12.27. The IPP that is a quality control measure for the downgoing P-wave first break based hodogram analysis. The panel consists of the X, Y, Z, HMIN, HMAX, Z, and HMAX data.
Figure 12.29. After the second downgoing wave first break polarization analysis, the upgoing P and SV wavefields are separated from the downgoing P and SV wavefields on the Z' and HMAX' panels. The process of up and downgoing wavefield separation applied to the Z' and HMAX' panels results in four new panels, namely Z'up, Z'down, HMAX'up, and HMAX'down. It is important at this point to keep track of the inputs and outputs to the datasets because of the many algorithms that are being used on the data. The interpreter cannot simply have faith at this point. The separated downgoing P and SV wavefields from the input Z' and HMAX' channels are shown in Figure 12.28. The mixed upgoing P and SV wavefields (polarized on the downgoing first breaks) in the Z' and HMAX' input panels are shown in Figure 12.29.

Figure 12.30. The upgoing P and SV isolated waves appearing on both Z'up and HMAX'up panels (generated by the processing sequence of hodogram analysis on the Z' and HMAX' data, upgoing wavefield separation on the Z' and HMAX' data and then de-rotating the Z'up and HMAX'up back to the Zup and HMAXup datasets) are not separated in different panels because the hodogram analysis was accomplished using the downgoing wave first break region. At this point, the hodogram-based rotations are reversed in action on the upgoing wavefield panels of the Z' and HMAX' panels. The polarization angle for each trace on the two panels is "backed-out". The result is the Zup and HMAXup data.
The combined cross, 4060 panels before attenuation of those waves took place. The resultant downgoing waves had to be polarized first in the Z' and HMAX' new Z and HMAX panels (Fig. 12.30) will be called the Zup and the upgoing waves (Zup and HMAX up). Note that the P and SV and HMAX"up output. The Z"up output is then used for the derived from the time-variant model-based analysis to form the Z" up theory-based (Beydoun, 1985) ray-tracing modelling package. This and the well log data.

The VSPCDP TRANSFORMATIONS

In order to reasonably image the subsurface at the zone of interest away from the borehole, the VSPCDP transform is used to convert the LSP data axis from depth and TT time to offset away from the well and "migrated" TT time". As shown in Figure 12.23, the image points of upgoing wave energy reflecting from horizontal layers of equal or different acoustic impedance form a locus curve. The VSPCDP transform takes the traces recorded at the different depths and, using an input velocity-depth function, stretches the layers of equal or different acoustic impedance and then the resultant binning (or regrouping) into the horizontal axis is now offset away from the well.

INTERPRETATION

The VSPCDP transform has imaged the data from 0 to 500 m away from the wellbore. The events from 300 to 1000 ms may be less continuous than expected. Usually, the downgoing SV energy will be of larger amplitude than the upgoing P energy and, as a result of the SV wave separation from the data, the P wave events will suffer destructive interference (or "leaks") into the Z" up data. When the SV energy is filtered out of the Z"up data, the effect of the filtering on the resultant upgoing P wave energy theoretically should be primarily polarized into the HMAX"up data, but due to violations of the assumptions by the data in the polarization analysis, some of the upgoing SV "leaks" into the Z" up data. The SV data had previously shown in the pseudo-migration, the dataset is shifted spatially to a new horizontal axis, being offset away from the well (after Dillon and Thomson, 1984).

The VSPCDP of the Z"up data in Figure 12.34 shows that:

- Figure 12.33. The VSPCDP transform locus curve. For this pseudo-migration, the dataset is shifted spatially to a new horizontal axis, being offset away from the well.
Figure 12.32. The IPP for the time-variant model-based rotations showing the separated upgoing P and SV mixed wavefield panels after the second downgoing P-wave first break based hodogram rotations, the same two panels after the backing out of the second hodogram rotations and the resultant $Z_{up}$ and $HMAX_{up}$ after the time-variant rotations are applied. The $Z_{up}$ panel is median filtered and placed into offset away from the well and two-way traveltime coordinates (Fig. 12.34) using the VSPCDP transformation to enable a final interpretation.
Figure 12.34. The Interpretive Processing Panel for the $Z_{sp}$ and the VSPCDP in normal and reverse polarity. The IPP contains the input data and the transformed data allowing a visual check on the VSPCDP transformation. The Ireton Fm, Westerdale Limestone and Duvernay Fm are continuous and flat lying indicating that the edge of the reef has not been imaged for at least 450 m in the direction of the LSP offset.
Figure 12.35. The ZVSPCDP result merged with the seismic data. The VSPCDP shows that the reef edge is further than 450 m to the west. The areal limits of the VSPCDP can be used to constrain the extent of reliable migrated LSP data if other migration schemes are used on the same datasets.

Figure 12.36. The updated geological cross-section incorporating the VSP well log results and the interpreted LSP results. The updip edge of the reef terminates at least 450 m away from the VSP/LSP well.
1) the Ireton Fm, Westerdale Limestone and Duvernay Fm events are continuous and do not resemble Ireton Fm to reef platform isochron thickening; 
2) in the opposite polarity plots, the Westerdale Limestone is continuous and does not truncate as would be expected if the reef edge had been encountered; 
3) there is no apparent drape features towards the reef exhibited on the Viking and Nordegg formations or Wabamun Gp; and 
4) there is no apparent pull-up displayed by the near-Cambrian event (between the Wabamun Gp and the near-Cambrian event) across the LSP section. 

The VSPCDP LSP results can be merged into the seismic data as is shown in Figure 12.35. The interpretation of the LSP shows that the reef edge is beyond the 450 m distance in the interpreted reef direction. The reinterpreted surface seismic data along with the post-drilling LSP interpretation aided the redesign of the geological cross-section of well A, B and the VSP well shown in Figure 12.36. 

CONCLUSIONS 

This chapter has presented the logic and displays used to maximise the amount of information that can be derived from a VSP or LSP. The interpretation was shown to be intimately linked to the evaluation of the various processing steps. 

The Lanaway/Garrington VSP enabled the surface seismic interpreter to better understand both the isochrons and amplitude anomaly on the surface seismic. The Ricinus VSP enabled a redefined higher resolution interpretation of the surface seismic at the well location plus an evaluation of the effect of multiples on the Wabamun seismic marker. The LSP interpretation showed that the off-reef seismic markers extended to a distance up to 450 m away from the borehole. 

VSP and LSP surveys when performed with specific exploration objectives in mind can produce high resolution results that will further minimise the risk of drilling non-profitable oil and gas wells.

REFERENCES 