Chapter 11

3-D SEISMIC

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INTRODUCTION

If 2D seismic lines were acquired close enough together to exhibit spatial integrity in all directions, the equivalency of a 3D survey could be created (except for statics). Throughout most of the Western Canadian Basin, this limit of spatial integrity is 25 to 50 m. It is obvious that it would be very expensive and environmentally damaging to shoot such closely spaced conventional 2D acoustic lines. With the recently-developed, large channel and multiline recording systems this spatial integrity can be achieved using surface lines separated by 8 or more times the distance of the required subsurface seismic line spacing. 3D seismic has become cost effective and feasible.

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Prior to 1984 approximately 30 3D surveys had been shot in Canada. These were expensive and cumbersome to acquire. In 1984 multilane instruments were introduced and more than 20 surveys were recorded. 3D method proof success in delineating small stratigraphic targets and pinnacle reefs, and the number of 3D surveys in Canada in 1988 exceeded that of the rest of the world. Land surveys in Canada have tended to be small, compared to much larger (100's km2) marine surveys recorded elsewhere. The relatively small size of the Canadian surveys reflects the smaller physical size of the anomalies.

The interpretation advantages of 3D data are most important for stratigraphic targets and pinnacle reefs, and the number of 3D surveys more than tripled in 1985. Despite the exploration downturn in 1986, the number doubled again and has increased annually. The most significant advantage of 3D seismic data is in the power of the 3D migration. To demonstrate this, a time window over the zone of interest on an east-west line has been selected from the center of the Taber 3D survey (Line 43, Fig.11.1). A significant difference is apparent between the migrated 2D and 3D sections. The main reason for the differences between the 2D and 3D migrated displays is that the seismic line is not perpendicular to the meandering river channel and cannot be correctly migrated on the 2D survey. Such an event can be accurately migrated on the 3D data set. As evidenced by the example, all reservoirs are morphologically complex. It is, therefore difficult to select a line orientation which is perpendicular to the feature. 3D migration is the tool to insure spatial integrity.

The 3D survey technique gives a more accurate representation of the size and areal extent of features because of the denser spacing. This generally is at least a 20:1 ratio of lines per mile.

In Fig. 11.2 approximately every 20th line (400 m) is displayed. Such improvement in image detail is often just as dramatic for stratigraphic targets, as indicated here, as for structural ones. To further illustrate this point, a time slice is shown from the data volume flattened on the Blainecone. The time slice at 654 ms (Fig. 11.4) is approximately the middle of the Glauconite sandstones. This is an amplitude and polarity time slice and the sands tend to be the red shaded areas 'A' and 'B'. Note that a channel 'C' cuts through the sands from about one-third the way down on the left side into the center and that another channel 'D' is evident from the upper right corner to the center of the figure. Channel 'C' is only 2-3 traces (40-60 m) wide but with the areal view of the 3D it becomes visible.

ACKNOWLEDGEMENTS

The author would like to thank Western Geophysical and Mobil Oil Canada for the information and interpretation of the Taber 3-D, and Western Geophysical for the use of the Joffree 3-D.
interpret these displays for 3D surveys. The following displays used in this example are from a 3D survey shot in the Joffre Area over the discovery well 15-22-39-26. The survey covered an area 2.4 by 4.02 km with a cell size of 30 by 30 m to give 81 lines in a North-South direction and 135 lines in an East-West direction. It was shot with Vibroseis and with an average fold of 1500%. Typical displays which can be selected are portions of desired sections in the inline, crossline and time slice directions (Fig. 11.6A-C). Alternately, a loop or zigzag line can be developed through the data (Fig. 11.7A-B). Aside from the benefits of speed and convenience, workstations offer analytical tools that would not be available with traditional methods. For example, given a few guided points, most workstations can automatically track horizons ensuring that each interpreted pick is consistently on the same point of the seismic reflection. The workstation then presents the digitized results immediately on the screen for review and rapid manual editing. Not only is the type of the interpreted pick recorded but also the corresponding amplitude attribute (Fig. 11.8A-C).

Figure 11.5. A workstation consists of two high resolution graphic screens, a terminal to communicate with the mainframe, a joystick for cursor positioning and also a hardware zoom feature, a digitizing pen for cursor control, and a camera with both polaroid and 35 mm capability which can create color slides or prints from either screen.

Figure 11.4. A time slice at 654 ms from a volume flattened on the Blairmore. Note that even 2 or 3 trace wide features such as the channel labeled “C” shows up readily.

Figure 11.3. (Right) A window of data cut from lines 40-49, 20 metres apart. Note how rapidly the geology changes across the 180 metres.

Figure 11.2. A window of data cut from every 20th line and placed one above the other so that the traces represent parallel subsurface positions every 400 metres. Note the change in geology from line to line.

WORKSTATIONS

Traditional methods of interpretation require geophysicists to examine each paper section, individually, and highlight horizons and faults with coloured pencils. Then the interpreted values are posted onto a pre-specified map scale where the results are hand contoured. It has become apparent that traditional methods are not fast enough and that they do not extract all of the information in the large volumes of data associated with 3D seismic. Complementary advances in computer hardware and software have provided the tools whereby the geophysicist can manipulate large data volumes. These activities center around the concept of a geophysical workstation which several geophysicists can share.

A typical workstation (Fig. 11.5) allows the interpreter to display seismic data on high resolution color graphics screen and directly
On the horizons are picked they can be displayed in many fashion. Past interpretations have usually resulted in contour maps. With the aid of color the highs and lows of the horizon can be quickly recognized. Isopachs from all interpreted horizons, may be calculated and played.

Workstations also present a host of utility options. Interpreters can request that well log and synthetic traces be superimposed on seismic displays and may interactively flatten selected horizons. As the interpretation proceeds, results can be directed to various hardcopy devices such as a plotter or camera. Connection with secondary packages such as modelling, mapping, vertical seismic profiles and amplitude versus offset analysis and other in-house database programs, increases the use and flexibility of workstations.

The advent of geophysical workstations has changed the day-to-day activities of geophysicists. Most workstations require only a few hours of instruction before the interpreter becomes familiar with the system. Geophysicists can now interpret data at least one order of magnitude faster than by hand. This increases the productivity of interpreters as well as allowing more time for comprehensive interpretations.
There is a well-documented, trend in computer hardware and software development permit time, performance and capabilities to go up while the price goes down. In the context of workstations this means desktop PC based systems capable of more geophysical operations will soon be available. In the near future, workstations will also have seismic data processing capabilities. Interpreters may then interactively correct for misfires, change filters and gain parameters or device entire processing sequences.

### 3D SURVEY DESIGN

The first step in acquiring a 3D program is to undertake a survey design. Economic restrictions and exploration goals have to be balanced.

It is not possible to present a single solution to a design problem. Each design must be tailored to a particular exploration goal to obtain the most suitable solution.

The main considerations are:

1. Survey Area;
2. Resolution Required;
3. Environmental Considerations;
4. Receiver Spreads and Shooting Sequences;
5. Instrumentation;

The overall surface size for a 3D seismic survey, must take into account the subsurface area of interest, regional and anomaly dips, proximity of the anomalies to the survey boundaries, and the area over which full multiplicity is required.

A migration aperture must be included around the edges of the survey to capture the energy that is diffracted outwards by anomalies or dips so it can be moved to the correct points on the time section by the migration algorithm. The migration distance required from the anomaly to the edge of the survey can be calculated by two simple formulae as stated below and illustrated (Fig. 11.9).

Several estimates of parameters should be inserted into each equation. The largest value derived from each should then be used as the migration distance in a particular direction. Some typical values for Alberta are given in Fig. 11.10.

**FORMULA 1**

\[
X_{\text{mig.}} = Z \sin \theta = \text{dip picked from unmigrated data} \\
X_{\text{mig.}} = Z \tan \theta = \text{dip picked from migrated data} \\
Z = \text{depth} = \text{Vrms}T \\
X_{\text{mig.}} = \text{required distance}
\]

**FORMULA 2**

\[
X_{\text{mig.}} = \text{Vrms} \left( (T_m + \frac{2}{2} - T_m^2) \right)^{1/2} \\
\theta = \text{dip picked from unmigrated data} \\
\theta = \text{dip picked from migrated data} \\
Z = \text{depth} = \text{Vrms}T \\
F_m = \text{min. frequency of interest} \\
F_m = \text{max. frequency of event} \\
X_s = \text{cell spacing} \\
X_s = \text{cell spacing}
\]

The size of the feature being imaged dictates the area over which full multiplicity is required. Generally it takes between 4 and 8 cells (traces) to build up to full multiplicity from the edges of the survey. A migration aperture must also be considered but normally the full fold aperture can also be included in this distance although if the data has poor signal to noise ratio the migration aperture should be full fold.

### Resolution Required

The resolution achieved on a 3D survey is dependent on the cell size, multiplicity, overburden thickness, surface noise and charge size.

The cell size is the 2-dimensional CDP interval over which data traces will be summed in the stacking process. Several concepts must be addressed in determining the best cell size for a survey. The maximum cell size for a given frequency and dip must be calculated to avoid spatial aliasing in the migration step. (Fig. 11.11 a-c) The formula for the maximum spatial sampling interval is:

\[
X_s = \text{Vrms} \times \text{Fmax Sin} \\
X_s = \text{cell spacing}
\]
Existing Cut Lines

Regional Dips

Anomaly

Location

W.R.T.

Boundaries

Anomaly Dips

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expansion problems, the resolution demanded, and "reasonable cost." Some of these factors are interdependent with more than one other factor, eg. number of shots, multiplicity, cell size, line spacing.

The relationships between these factors are obvious. It is important to consider these factors in the design of a 3D survey, with appropriate weighting on the different factors.

Many of the basic factors involved with designing a 3D survey such as hole depth and charge size, are also common to 2D surveys. However, there is much more to consider to ensure the geophysical and economic integrity of 2D and 3D survey.

3D CASE HISTORY

The Taber area of Southern Alberta is characterized by rapid lateral facies changes within the Glauconitic Sandstone of the Upper Mannville Group (Lower Cretaceous). The reservoirs are sandstones with porosities of about 15%, surrounded irregularly by impermeable siltstones. A generalized and widely accepted interpretation of the geology in this area (Hradsky and Griffin, 1984) is shown in Fig. 11.15. Glauconitic Sandstone reservoirs are related to the main channel of an old river valley about 50 km long, 3 km wide, and up to 40 m deep. The valley crosses the area from northwest to southeast, dipping at about 5 per m km. To improve the prospects for reservoir delineation, a 3D survey was conducted and 3D inversion interpretation of the data was performed.

To meet requirements for detailed imaging, subsurface coverage was at 20 m spacing. The survey, conducted in a series of overlapping, parallel swaths of eight receiver lines each, produced 111 stacked traces in the receiver direction and 88 in the crossline direction. This effort yielded CMP coverage (typically 12- to 16-fold) over a 2,150 x 1,740 m area.

Figure 11.16 is a base map of the 3D survey showing the locations of the older producing wells (C, D, E, and F) and dry wells (A and B). Well names are identified by letters to preserve confidentiality, while the alphabetic order represents the sequence in which the wells were drilled. Successful wells (G and H) were drilled after the 3D survey was acquired, while new producing wells (I and J) were drilled later after the inversion modeling study was completed.

Historically, a major criterion in choosing drill sites in this area has been amplitude anomalies associated with the Glauconitic event (at about 600 m). The sandstone reservoir gives rise to an approximate 30% increase in amplitude relative to that associated with the siltstone facies (see, for example, the trough at 650 m in Fig. 11.17). Despite the subtlety of the available criteria for interpretation, production has been predicted with considerable confidence, both here and at other locations.

The derived thin-layer velocity model reveals details of the reservoir stratigraphy approximately 190 m below sea level (or 980 m below ground level). The Glauconitic Sandstone reservoir, which is produced at wells D and H in the north, is truncated to a given time slice will have been influenced by positions of the user-controlled bedding geometry input to the inversion. When applied to properly conditioned seismic data, this forward modeling technique also is comparatively insensitive to random noise. This is because the 3D process searches for lateral continuity of model layers, rather than aiming for a perfect match between the synthetic seismogram and the recorded seismic traces.

The 3D inversion results show distinct lateral and vertical changes in layer velocity. For example, the Glauconitic Sandstone target zone appears as a thin (0-40 m) layer with velocities ranging from 3,200 m/s (very porous sand) to 4,000 m/s (impermeable siltstones).

Although this 3D survey is not large, each of the derived 3D volumes (velocity model and synthetic data) contained more than 9,000 traces. An interactive interpretation system was used in the analysis of the 3D inversion results. Most of the figures of 3D inversion results for the Taber 3D survey shown here, were generated on the interactive interpretation system.

Fig. 11.18-21 show isometric displays of the 3D seismic data, the resulting 3D synthetic data, and the inversion derived 3D velocity model. The patterns seen on the time slices of the field and synthetic seismic data are similar. These patterns, however, are not recognizable in the corresponding time slice of the velocity model. It should be noted that the synthetic data are obtained directly from the derived inversion model and are also consistent with the seismic data. In extending the level of detail beyond that perceived directly in the seismic data, the inversion results can change the interpretation. For example, study of the seismic data alone might lead one to interpret the narrow red traverse of negative amplitudes in the time slice at 652 m (shown in Fig. 11.19 as the deepest part, assumed thickest) part of the river valley. The derived velocity model, however, indicates that this feature may not be a channel at all; instead, it may be related to a abrupt decrease of the sandstone/siltstone ratio in the layer of interest. The apparent discrepancy between the patterns in the data and that in the model can be attributed to the band limitation of the data. Features seen on a given time slice will have been influenced by positions of the (broadband) model at nearby levels.
Although the initial model was built on the basis of the sonic log from only one of the boreholes (borehole C), the derived inversion velocity solution is consistent with the log information from all six boreholes drilled within the study area (boreholes A through F in Fig. 11.16). Fig. 11.22 shows the inversion results in an isometric view that best displays the Glauconitic Sandstone in the vicinity of well C, one used for calibration of the parameters in the inversion model. The result shown in this 3D perspective not only yields the irregular appearance seen in Fig. 11.18b; the Glauconitic Sandstone becomes a definite layer, but one with rapid variations of layer velocity attributable to variations of lithology from porous sandstones to impermeable siltstones. As the inversion model indicates, the well (A producer) penetrates the low-velocity porous sandstones of the Glauconitic Sandstone.

Fig. 11.23 shows two more producing wells that penetrate the Glauconitic Sandstone where the inversion interpretation again indicates porous sandstone. Fig. 11.24, in contrast, shows two dry holes. One of them, well A, was drilled through siltstone at a place where the inversion model shows high velocity. The second dry hole, well B, was drilled in what appears to be a narrow high-velocity zone beyond the resolution of the inversion processing.

Two additional wells were drilled within the survey area after the inversion and based on the data interpretation was made. Both of them are oil producers (wells G and H in Fig. 11.16). The inversion interpretation in the vicinity of those wells is shown in Fig. 11.25 and 26.

CONCLUSION

The 3D Seismic Imaging Approach to exploration is an oil industry standard, both in exploration and production applications.

Users of the technique must pay particular attention to initial parameter selection to ensure survey objectives are met. Some basic considerations have been addressed in this chapter: However, consultation with people experienced in survey design is recommended.

3D surveys will almost certainly be commonplace in the future to aid geologists, geophysicists and engineers in the imaging of such diverse targets as enhanced oil recovery projects, oil sands development, and coal and potash mines.