Introduction

History and Basic Ideas

The earth has always been three-dimensional and the petroleum reserves we seek to find or evaluate are contained in three-dimensional traps. The seismic method, however, in its attempt to image the subsurface has traditionally taken a two-dimensional approach. It was 1970 when Walton (1972) presented the concept of three-dimensional seismic surveys. In 1975, 3-D surveys were first performed on a normal contractual basis, and the following year Bone, Giles and Tegland (1976) presented the new technology to the world.

The essence of the 3-D method is areal data collection followed by the processing and interpretation of a closely-spaced data volume. Because a more detailed understanding of the subsurface emerges, 3-D surveys have been able to contribute significantly to the problems of field appraisal, development and production as well as to exploration. It is in these post-discovery phases that many of the successes of 3-D seismic surveys have been achieved. The scope of 3-D seismic for field development was first reported by Tegland (1977).

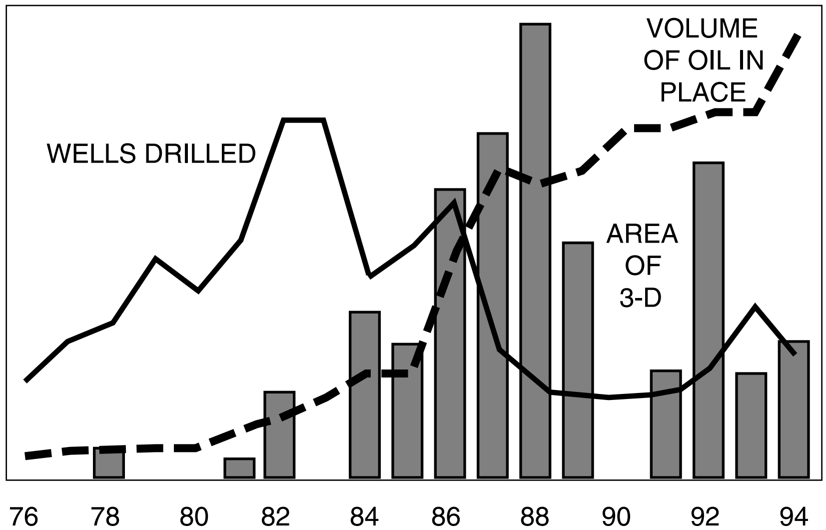
In the late 1980s and early 1990s, the use of 3-D seismic surveys for exploration increased significantly. This started in the mid-1980s with widely-spaced 3-D surveys called, for example, Exploration 3-D. Today, speculative 3-D surveys, properly sampled and covering huge areas, are available for purchase piecemeal in mature areas like the Gulf of Mexico. This, however, is not the only use for exploration. Many companies are acquiring 3-D surveys over prospects routinely, so that the vast majority of their seismic budgets are for 3-D operations. The evolution and present state-of-the-art of the 3-D seismic method have recently been chronicled in a reprint volume by Graebner, Hardage, and Schneider (2001).

In the first 20 years of 3-D survey experience (1975-95) many successes and benefits were recorded. Five particular accolades are reproduced here; others are found in the case histories of Chapter 9 and implied at many other places throughout this book. There is a major symbiosis between modern 3-D seismic data and the interactive workstation.

> *"…there seems to be unanimous agreement that 3-D surveys result in clearer and more accurate pictures of geological detail and that their costs are more than repaid by the elimination of unnecessary development holes and by the increase in recoverable reserves through the discovery of isolated reservoir pools which otherwise might be missed."*
> (Sheriff and Geldart, 1983)

> *"The leverage seems excellent for 3-D seismic to pay for itself many times over in terms of reducing the eventual number of development wells."*
> (West, 1979)

Fig. 1-1. Area covered by 3-D surveys, exploratory wells drilled and volume of oil in place for the period 1976 to 1994 in the Campos Basin offshore Brazil (from Martins et al, 1995). (Courtesy Petrobras.)



"…the 3-D data are of significantly higher quality than the 2-D data. Furthermore, the extremely dense grid of lines makes it possible to develop a more accurate and complete structural and stratigraphic interpretation…Based on this 3-D interpretation, four successful oil wells have been drilled. These are located in parts of the field that could not previously be mapped accurately on the basis of the 2-D seismic data because of their poor quality. This eastward extension has increased the estimate of reserves such that it was possible to declare the field commercial in late 1980."
(Saeland and Simpson, 1982)

"…3-D seismic surveying helped define wildcat locations, helped prove additional outpost locations, and assisted in defining untested fault blocks. Three-D seismic data helped find additional reserves and, most certainly, provided data for more effective reservoir drainage while being cost-effective…Gulf participated in 16 surveys that covered 26 blocks and has invested $15,000,000 in these data. The results show that a 3-D seismic program can be cost-effective since it can improve the success ratio of development drilling and can encourage acceleration of a development program, thereby improving the cash flow."
(Horvath, 1985)

"We acquired two offshore blocks which contained a total of seven competitor dry holes. Our exploration department drilled one more dry hole before making a discovery. At that point we conducted a 3-D survey while the platform was being prepared. When drilling commenced, guided by the 3-D data, we had 27 successful wells out of the next 28 drilled. In this erratic depositional environment, we believe that such an accomplishment would not have been possible without the 3-D seismic data."
(R. M. Wright, Chevron U.S.A. Inc., personal communication, May, 1988)

Sheriff (1992) addresses many benefits of 3-D seismic in *Reservoir Geophysics;* a few quotations from that volume follow:

3-D seismic is an extremely powerful delineation tool, and spectacularly cost-effective, particularly when well costs are high.

The success is directly attributable to the better structural interpretation made possible by the 3-D survey.

The greatest impact of 3-D surveys has been the ability to match platform size, number of well slots, and production facilities to the more accurately determined field reserves.

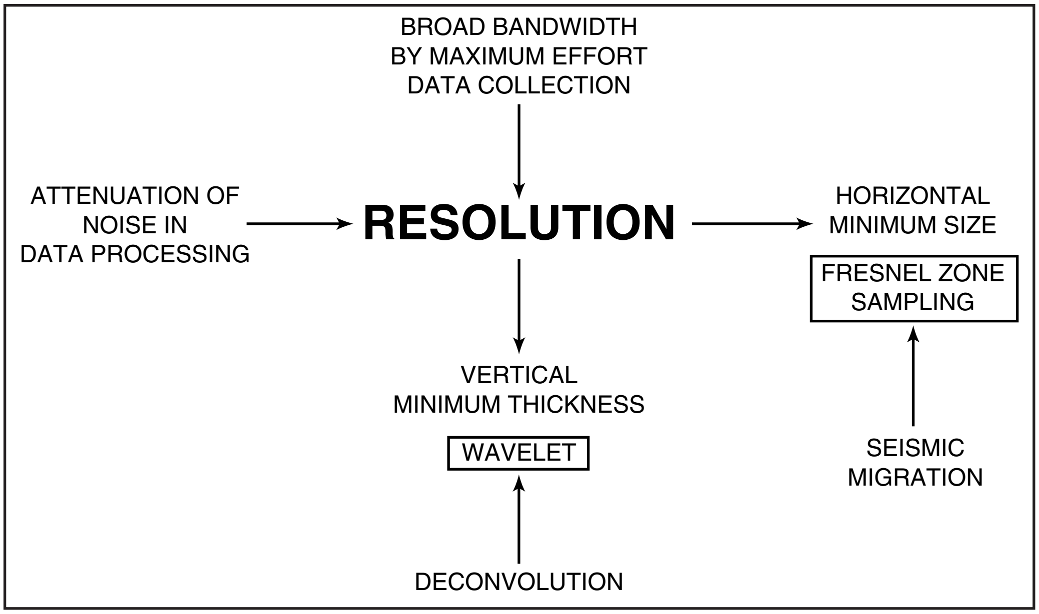


Fig. 1-2. Factors affecting horizontal and vertical seismic resolution.

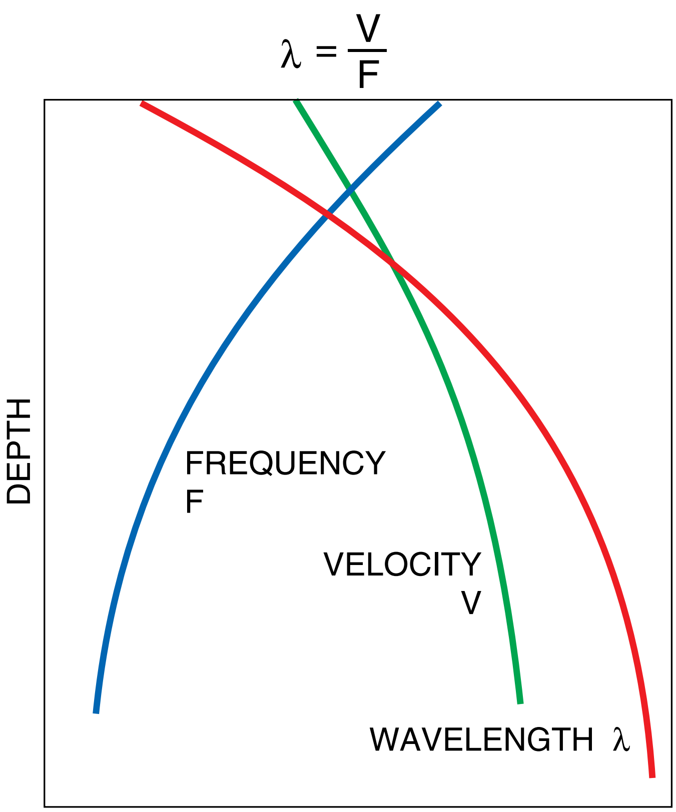


Fig. 1-3. Wavelength, the seismic measuring rod, increases significantly with depth making resolution poorer.

Martins et al (1995), working in the Campos Basin offshore Brazil, have tracked the amount of 3-D survey coverage in relation to the wells drilled and the oil reserves booked (Figure 1-1). This demonstrates very nicely that 3-D seismic is indeed replacing exploration wells!

Resolution

The fundamental objective of the 3-D seismic method is increased resolution. Resolution has both vertical and horizontal aspects and Sheriff (1985) discusses the subject qualitatively. The resolving power of seismic data is always measured in terms of the

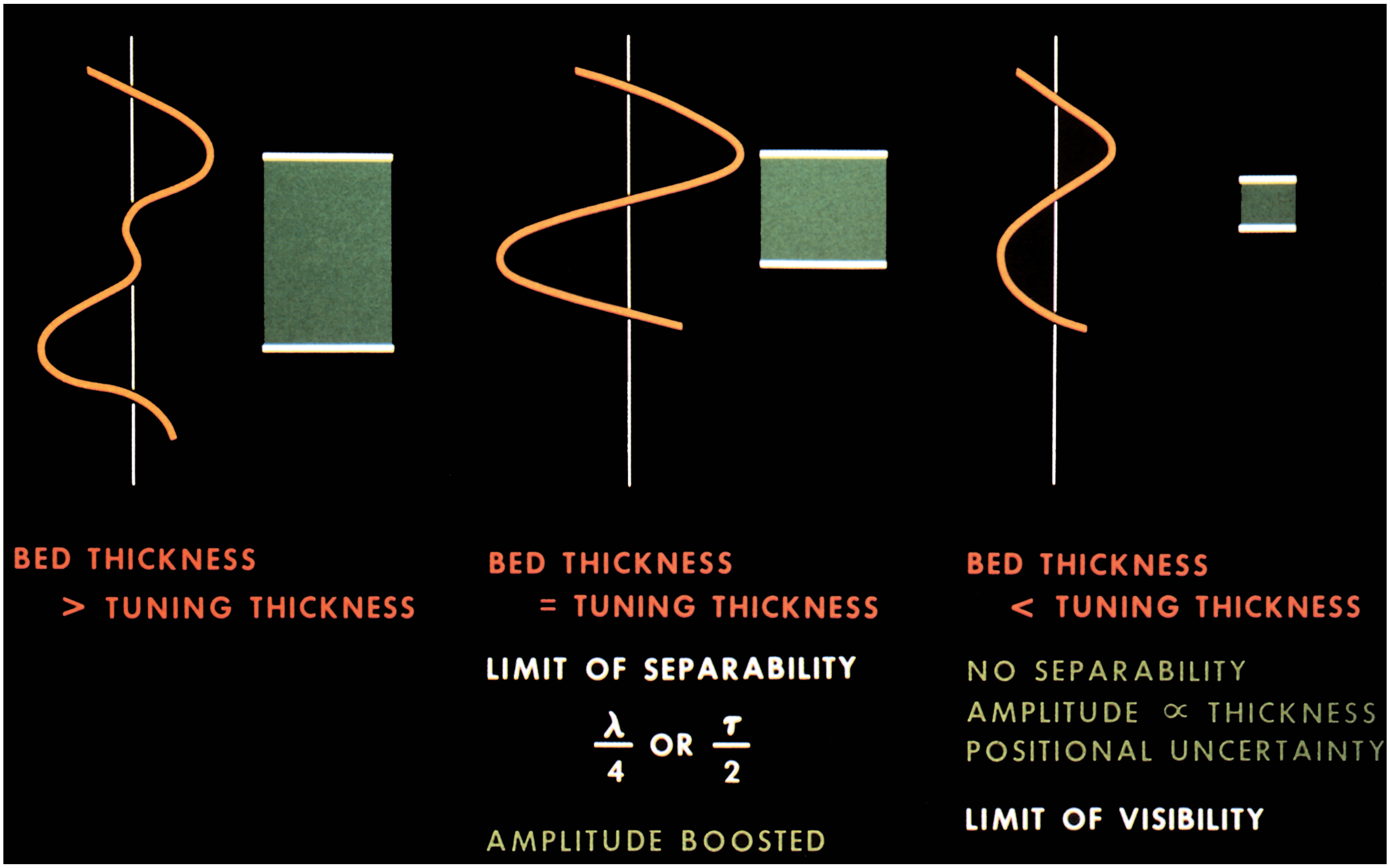


Fig. 1-4. Resolution of the reflections from the top and bottom of a bed is dependent on the interaction of closely spaced wavelets.

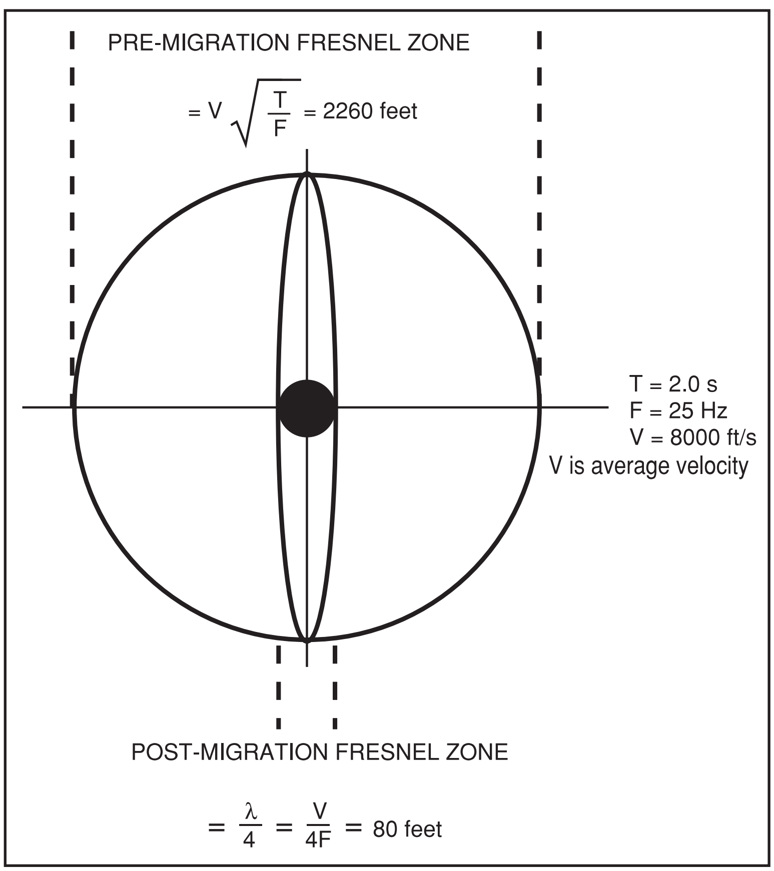


Fig. 1-5. Effect on Fresnel zone size and shape of 2-D and 3-D migration.

Table 1-1. Typical Limits of Visibility and Separability for a range of geologic situations.

Age of rocks			VERY YOUNG	YOUNG	MEDIUM	OLD	VERY OLD
Depth of target			VERY SHALLOW	SHALLOW	MEDIUM	DEEP	VERY DEEP
Formation Velocity (m/s)			1600	2000	3500	5000	6000
Predominant Frequency (Hz)			70	50	35	25	20
Wavelength (m)		λ	23	40	100	200	300
LIMIT OF SEPARABILITY		$\frac{\lambda}{4}$	6	10	25	50	75
LIMIT OF VISIBILITY — Poor S/N	e.g. Water sand poor data	$\sim\frac{\lambda}{8}$	3	5	13	25	38
LIMIT OF VISIBILITY — Moderate S/N	e.g. Water or oil sand fairly good data	$\sim\frac{\lambda}{12}$	2	3	8	17	25
LIMIT OF VISIBILITY — High S/N	e.g. Gas sand good data	$\sim\frac{\lambda}{20}$	1	2	5	10	15
LIMIT OF VISIBILITY — Outstanding S/N	e.g. Gas sand excellent data	$\sim\frac{\lambda}{30}$	<1	1	3	7	10

units are meters

seismic wavelength, which is given by the quotient of velocity and frequency (Figure 1-3). Seismic velocity increases with depth because the rocks are older and more compacted. The predominant frequency decreases with depth because the higher frequencies in the seismic signal are more quickly attenuated. The result is that the wavelength increases significantly with depth, making resolution poorer.

Figure 1-2 summarizes resolution issues. Vertical resolution has two limits, both resulting from the interaction of the wavelets from adjacent reflecting interfaces. The **limit of separability** is equal to one-quarter of a wavelength (or half a period) and is simply the bed thickness corresponding to the closest separation of two wavelets of a given bandwidth (Figure 1-4). For thinner intervals than this, the amplitude is progressively attenuated until the **limit of visibility** is reached, when the reflection signal becomes obscured by the background noise. The limit of visibility depends on the acoustic contrast of the geologic layer of interest relative to the embedding material, the random and systematic noise in the data, and the phase of the data or the shape of the seismic wavelet. Table 1-1 illustrates five geologic situations of different rock ages and target depths. Given estimated formation velocities and predominant frequencies, the wavelength and thus the limit of separability are directly calculated. Because the limit of visibility is a variable fraction of a wavelength, Table 1-1 offers four different fractions for different signal-to-noise ratios. In this way the limit of visibility has been calculated for a matrix of 20 different situations illustrating the enormous possible range in data resolution.

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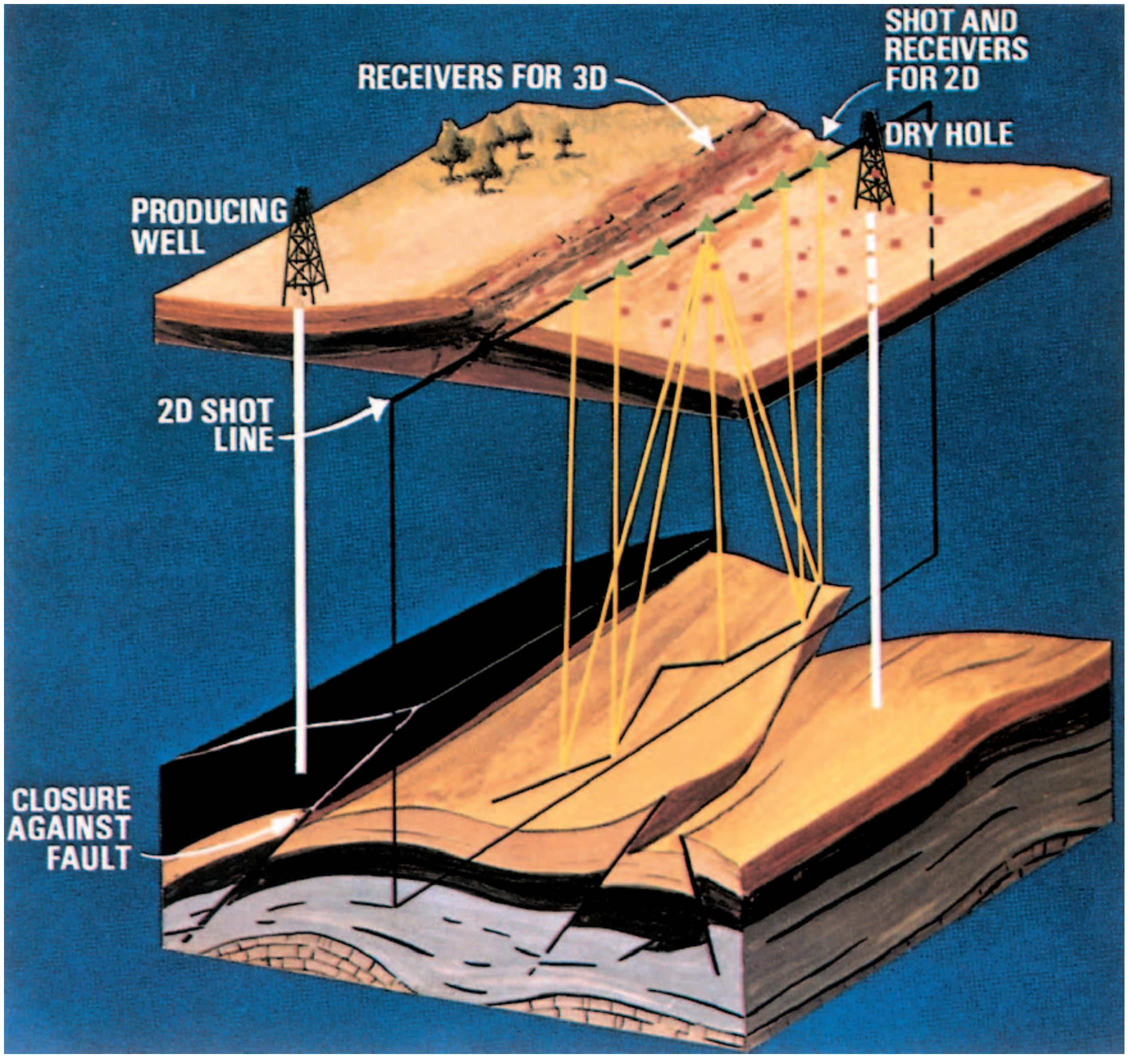

Fig. 1-6. Subsurface structure causes reflection points to lie outside the vertical plane through shots and receivers.

Migration is the principal technique for improving horizontal resolution, and in doing so performs three distinct functions. The migration process (1) repositions reflections out-of-place because of dip, (2) focuses energy spread over a Fresnel zone, and (3) collapses diffraction patterns from points and edges. Seismic wavefronts travel in three dimensions and thus it is obvious that all the above are, in general, three-dimensional issues. If we treat them in two dimensions, we can only expect part of the potential improvement. In practice, 2-D lines are often located with strike and dip of major features in mind so that the effect of the third dimension can be minimized, but rarely eliminated. Figure 1-5 shows the focussing effect of migration in two and three dimensions. The Fresnel zone will be reduced to an ellipse perpendicular to the line for 2-D migration (Lindsey, 1989) and to a small circle by 3-D migration. The diameter of one-quarter of a wavelength indicated in Figure 1-5 is for perfect migration. In practice, the residual Fresnel zone may be about twice this size.

The accuracy of 3-D migration depends on the velocity field, signal-to-noise ratio, migration aperture and the approach used. Assuming the errors resulting from these factors are small, the data will be much more interpretable both structurally and stratigraphically. Intersecting events will be separated, the confusion of diffraction patterns will be gone, and dipping events will be moved to their correct subsurface positions. The collapsing of energy from diffractions and the focusing of energy spread over Fresnel zones will make amplitudes more accurate and more directly interpretable in terms of reservoir properties. The determination of true velocity for

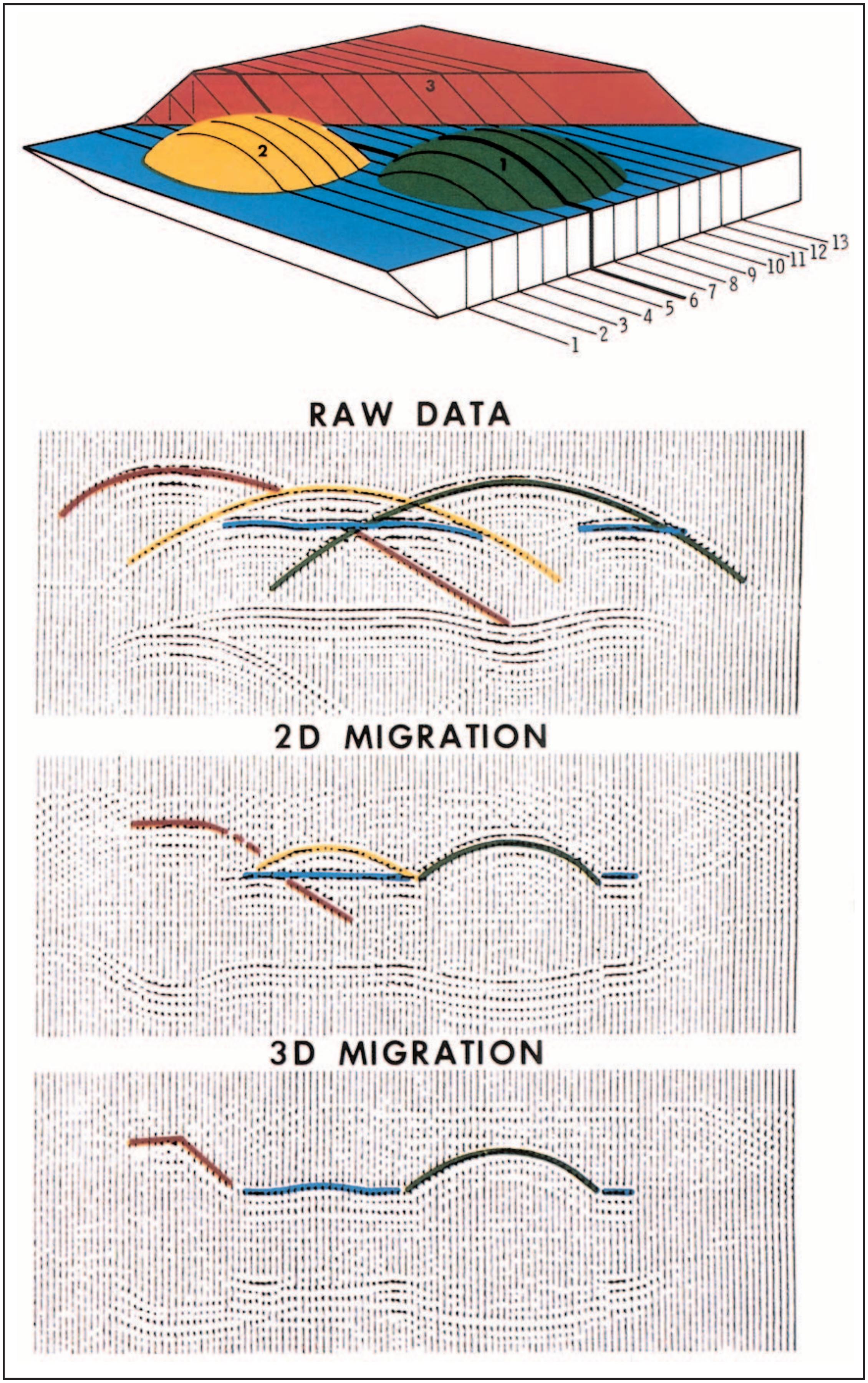

Fig. 1-7. Model of two anticlines and one fault with seismic data along Line 6 showing comparative effects of 2-D and 3-D migration (from French, 1974).

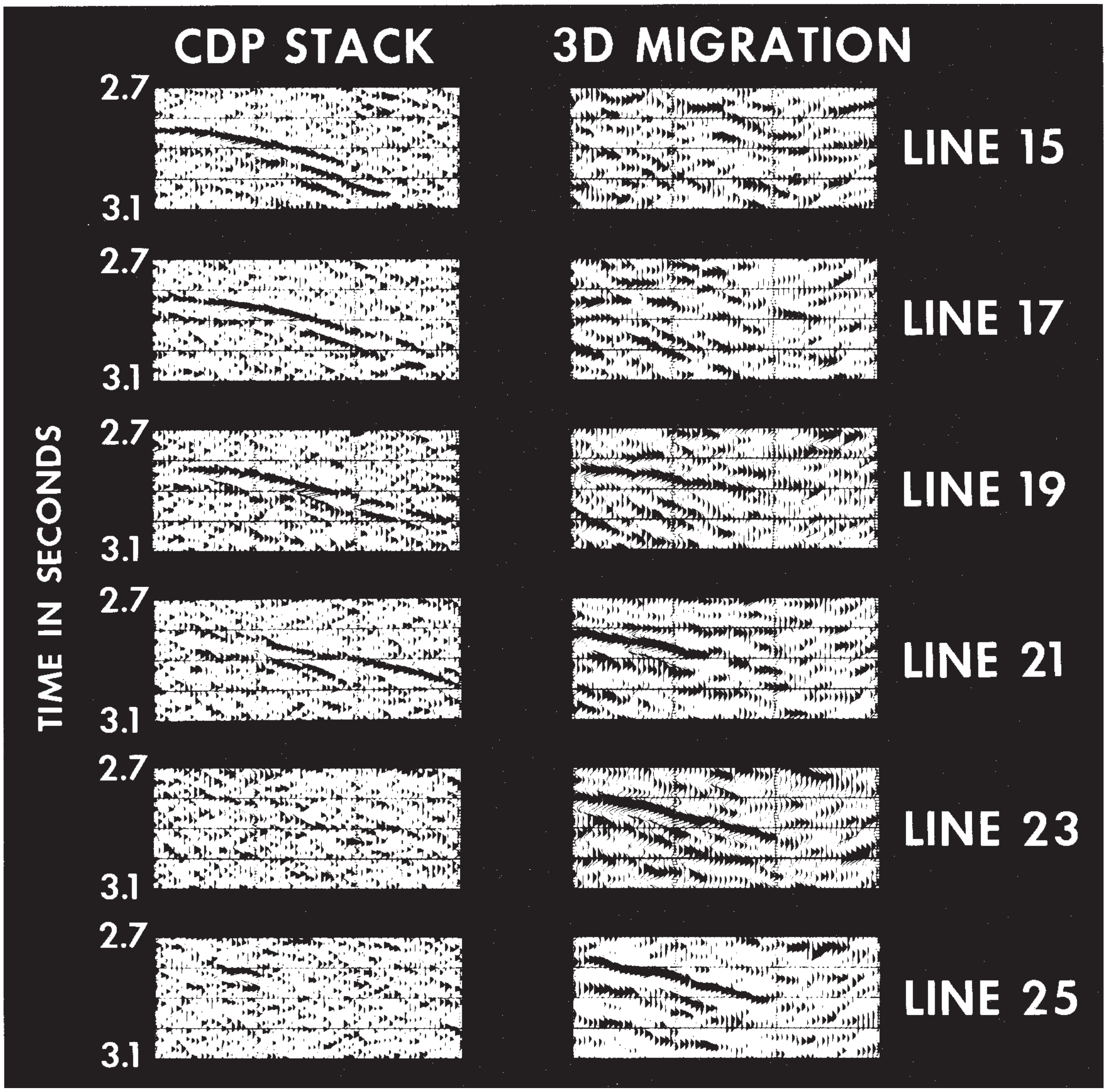

Fig. 1-8. Three-dimensional movement of a dipping reflection by 3-D migration. (Courtesy Geophysical Service Inc.)

accurate migration and depth conversion is a significant issue. It is desirable to collect data with a reasonable distribution of offsets and azimuths, so that the three-dimensional dip effects in the velocity field can be removed properly.

Examples of 3-D Data Improvement

The interpreter of a 2-D vertical section normally assumes that the data were recorded in one vertical plane below the line traversed by the shots and receivers. The extent to which this is not so depends on the complexity of the structure perpendicular to the line. Figure 1-6 demonstrates that, in the presence of moderate structural complexity, the points at depth from which normal reflections are obtained may lie along an irregular zig-zag track. Only by migrating along *and* perpendicular to the line direction is it possible to resolve where these reflection points belong in the subsurface.

French (1974) demonstrated the value of 3-D migration very clearly in model experiments. He collected seismic data over a model containing two anticlines and a fault scarp (Figure 1-7). Thirteen lines of data were collected although only the results for Line 6 are shown. The raw data have diffraction patterns for both anticlines and the fault so the section appears very confused. The situation is greatly improved with 2-D migration and anticline number 1 (shown in green) is correctly imaged, as Line 6 passed over its crest. However, anticline number 2 (shown in yellow) should not

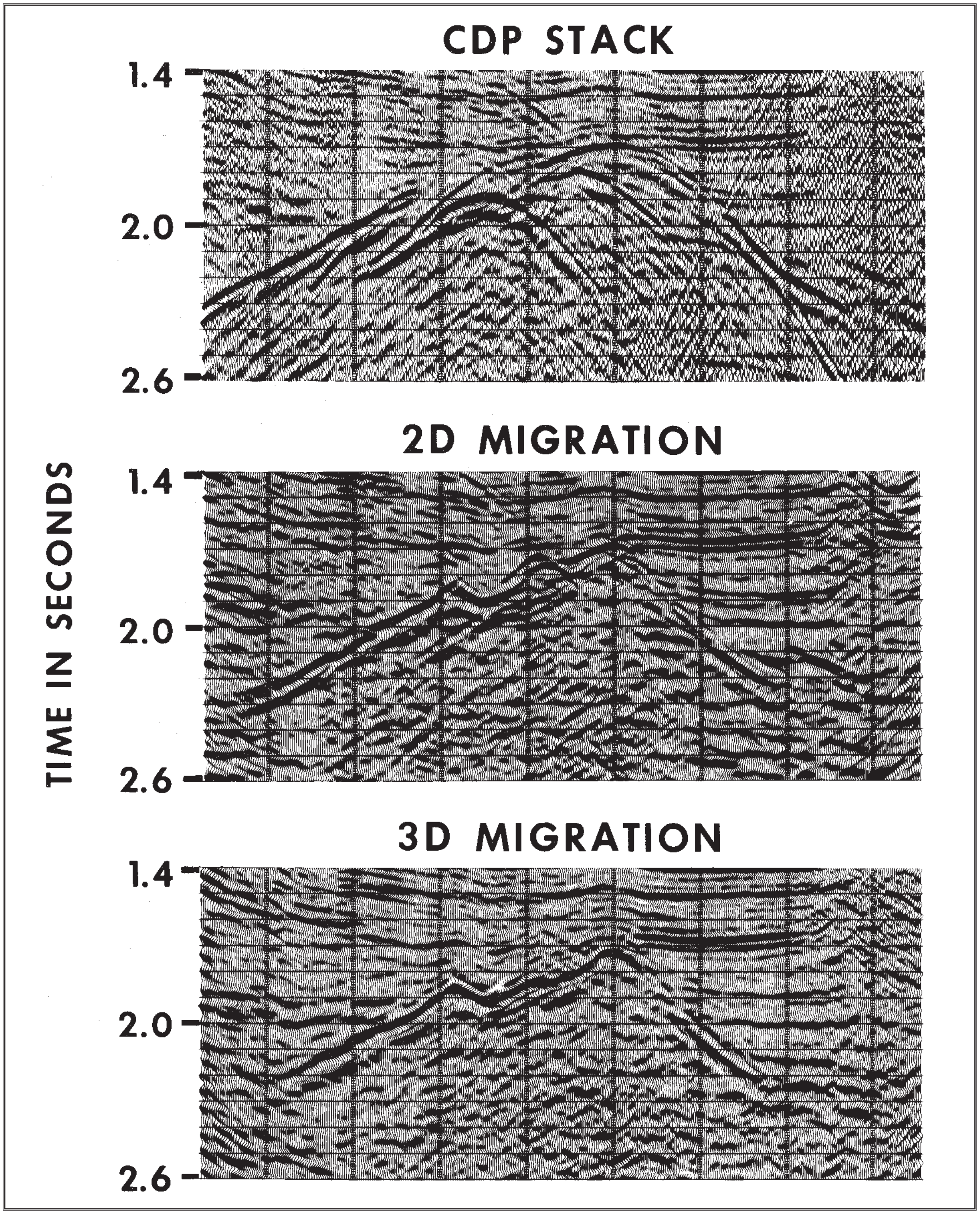

Fig. 1-9. Improved structural continuity of an unconformity reflection resulting from 2-D and 3-D migration.

occur on Line 6 and the fault scarp has the wrong slope. The 3-D migration has correctly imaged the fault scarp and moved the yellow anticline away from Line 6 to where it belongs.

Figure 1-8 demonstrates this three-dimensional event movement on real data. The same panel is presented before and after 3-D migration for six lines. Here we can observe the movement of a discrete patch of reflectivity to the left and in the direction of higher line numbers.

Figure 1-9 shows improved continuity of an unconformity reflection. The 2-D migration has collapsed most of the diffraction patterns but some confusion remains. The crossline component of the 3-D migration removes energy not in the plane of this section and clarifies the shape of the unconformity surface in significant detail.

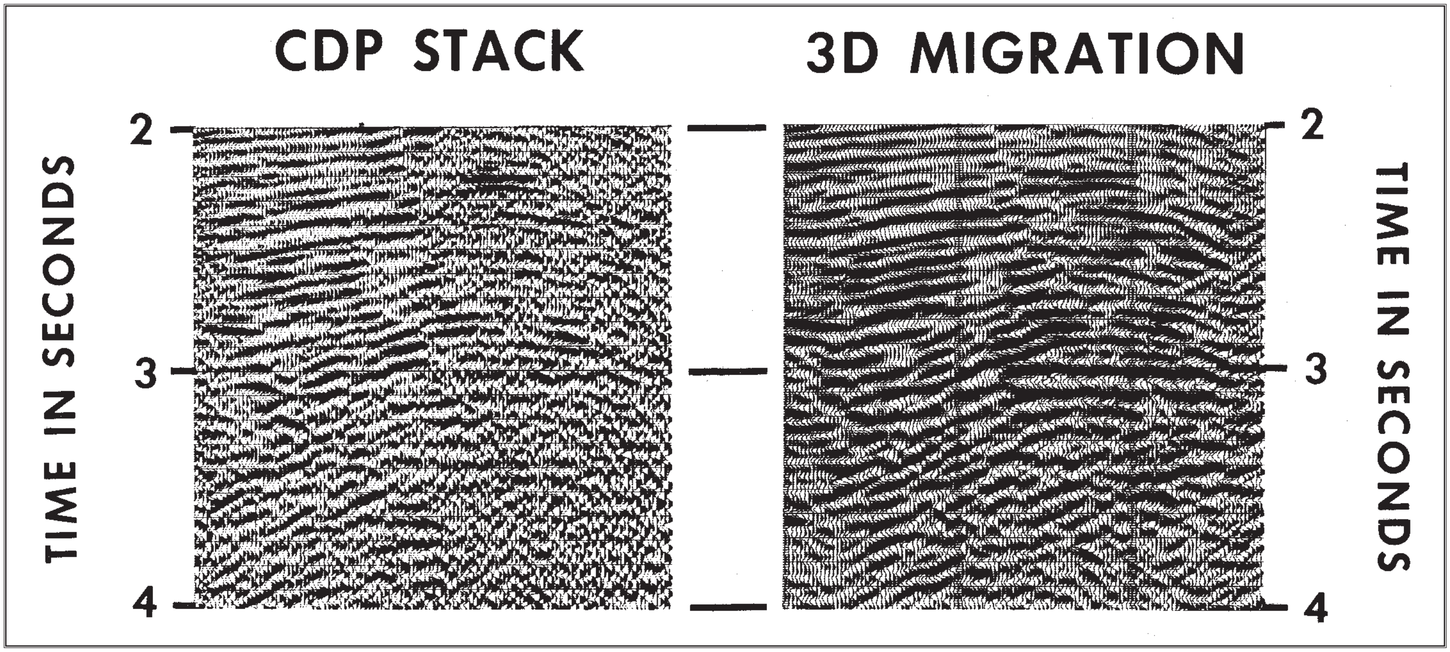

Fig. 1-10. Improved visibility of a flat spot reflection after removal of interfering events by 3-D migration.

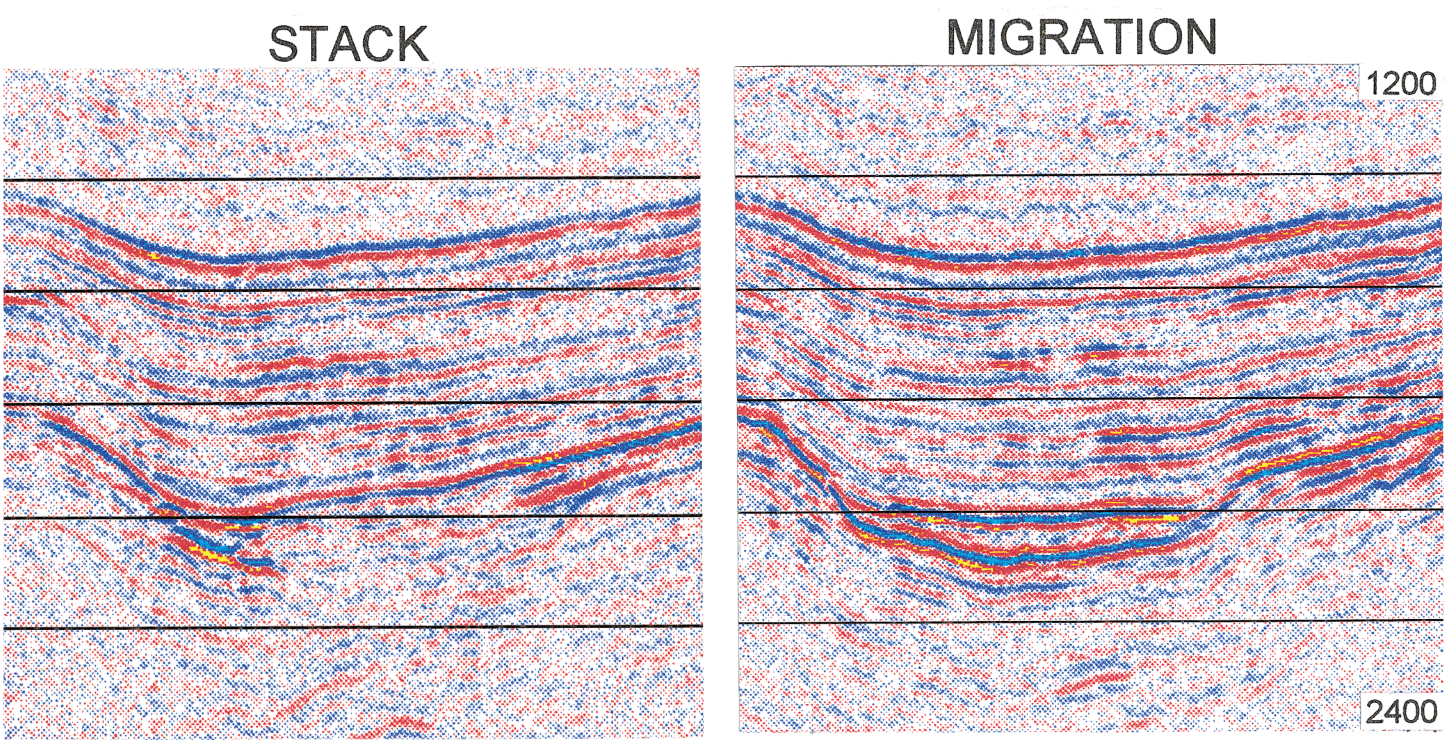

Fig. 1-11. Striking impact of 3-D migration on the attitude and continuity of reflections in South Australia. (Courtesy Santos Ltd.)

Table 1-2. Alias frequency (in hertz) as a function of subsurface spacing (in meters) and dip (in degrees) for an RMS velocity of 2500 m/s.

	SUBSURFACE SPACING				
DIP	12.5	25	50	75	100
5	574	287	143	96	72
10	288	144	72	48	36
15	193	96	48	32	24
20	146	73	37	24	18
25	118	59	30	20	15

Table 1-3. Basic formulas for the design of a 3-D survey.

Maximum subsurface spacing (2 samples per wavelength) $= \dfrac{1}{2F_{max}\ DIP_{max}}$

Desirable subsurface spacing (3 samples per wavelength) $= \dfrac{1}{3F_{max}\ DIP_{max}}$

Migration distance (or half-aperture) $= \dfrac{TV^2DIP}{4}$

Fresnel zone radius $= \dfrac{V}{2}\sqrt{\dfrac{T}{F_{min}}}$

where T is seismic two-way travel time in seconds
DIP is measured in seconds per unit distance
F is seismic frequency
V is seismic velocity

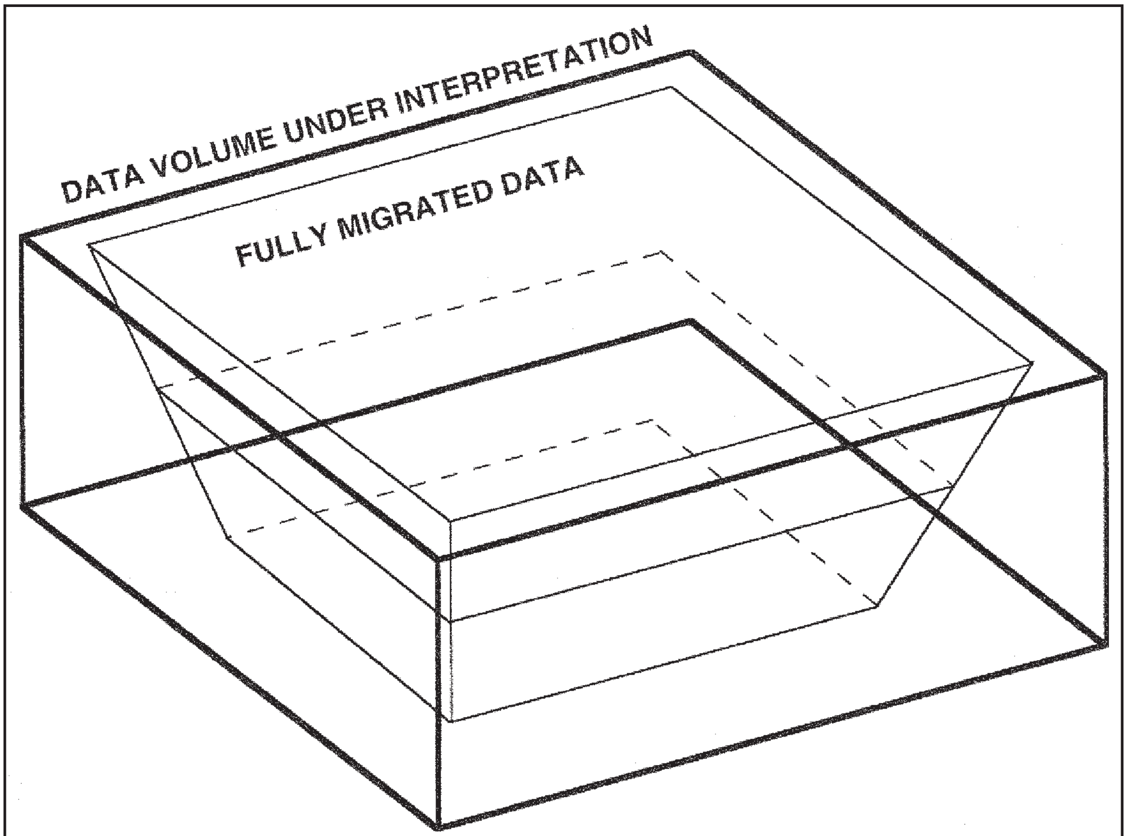

Fig. 1-12. Data around the edge of a 3-D survey are incompletely migrated because of migration distance and Fresnel zone radius. Interpreters should be extra cautious when working in this region.

Figure 1-10 shows the effect of 3-D migration in enhancing the visibility of a fluid contact reflection by removing energy not belonging in the plane of this section.

Figure 1-11 shows some major differences between the stacked and 3-D migrated versions of a line from Australia. It is easy to visualize the impact this change would have on an interpretation.

Figure 1-13 shows portions of three lines passing through and close to a salt diapir. Line 180 shows steeply-dipping reflections at the edge of the salt mass, brought into place by the 3-D migration. Line 220 shows an apparent anticline which is caused by reflections dipping up steeply toward the salt face in a plane perpendicular to that of Figure 1-13. In this prospect, 3-D migration imaged reflections underneath a salt overhang and provided valuable detail about traps located there against the salt face (Blake, Jennings, Curtis, Phillipson, 1982).

When comparing sections before and after 3-D migration to appraise its effectiveness, it is important to bear in mind the way in which reflections have moved around. In the presence of dip perpendicular to the section under scrutiny, the visible data

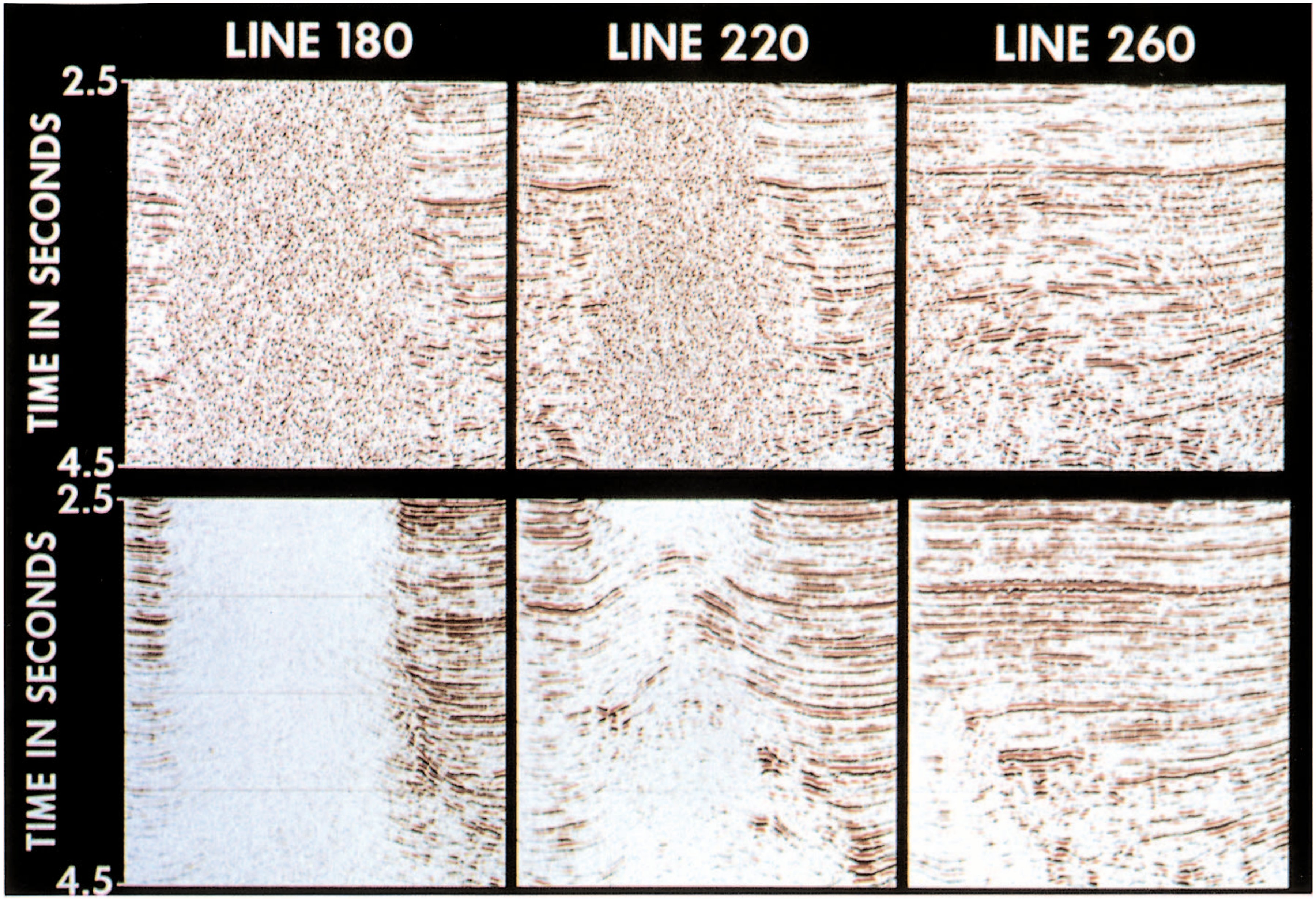

Fig. 1-13. Three vertical sections through or adjacent to a Gulf of Mexico salt dome before migration (top) and after migration (bottom), showing the repositioning of several reflections near the salt face. (Courtesy Hunt Oil Company.)

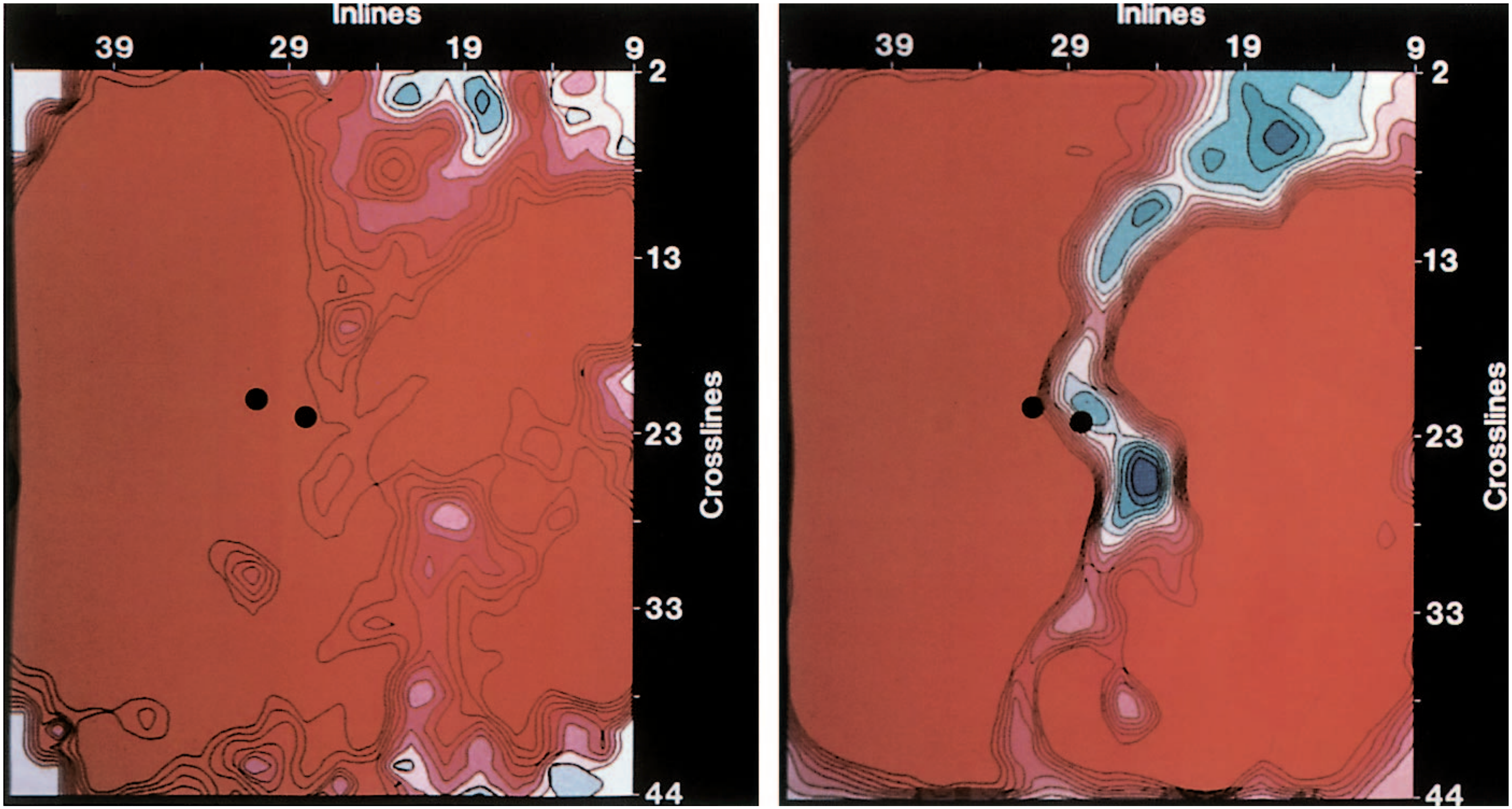

Fig. 1-14. Horizontal sections before migration (left) and after migration (right) showing the necessity of 3-D migration for the observation of shallow channels. (Courtesy Amoco Canada Petroleum Company Limited and N. E. Pullin.)

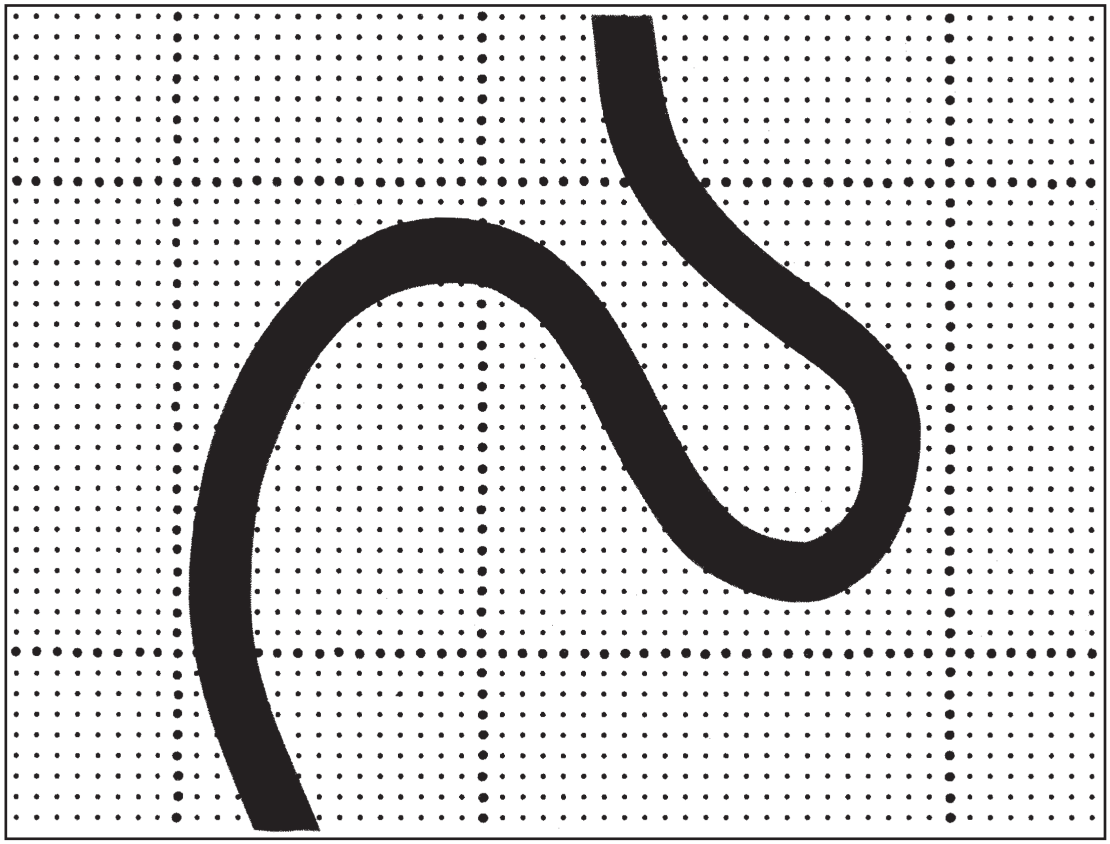

Fig. 1-15. Areal coverage of a 3-D survey compared to the coverage of a grid of five 2-D lines, and the ability of each to delineate a meandering channel.

before and after 3-D migration are different. It is unreasonable to compare detailed character and deduce what 3-D migration did. It is possible to compare a section before 3-D migration with the one from the same location after 3-D migration and find that a good quality reflection has disappeared. The migrated section is not consequently worse; the good reflection has simply moved to its correct location in the subsurface.

Figure 1-14 shows a horizontal section at a time of 224 ms from a very high resolution 3-D survey in Canada aimed at monitoring a steam injection process. The section on the left is from the 3-D volume before migration and the section on the right is from the volume after migration. The two black dots indicate wells. The striking visibility of a channel after migration results from the focusing of energy previously spread over the Fresnel zone. The fact that one well penetrates the channel and the other does not is significant: they are only 10 m apart.

Survey Design

The sampling theorem requires that, for preservation of information, a waveform must be sampled such that there are at least two samples per cycle for the highest frequency. Since the beginning of the digital era, we have been used to sampling a seismic trace in time. For example, 4 ms sampling is theoretically adequate for frequencies up to 125 Hz. In practice we normally require at least three samples per cycle for the highest frequency. With this safety margin, 4 ms sampling is adequate for frequencies up to 83 Hz.

In space, the sampling theorem translates to the requirement of at least two, and preferably three, samples per shortest wavelength in every direction. In a normal 2-D survey layout this will be satisfied by the depth point spacing along lines but not by the spacing between lines. Hence the restriction that widely-spaced 2-D lines can be processed individually on a 2-D basis but not together as a 3-D volume.

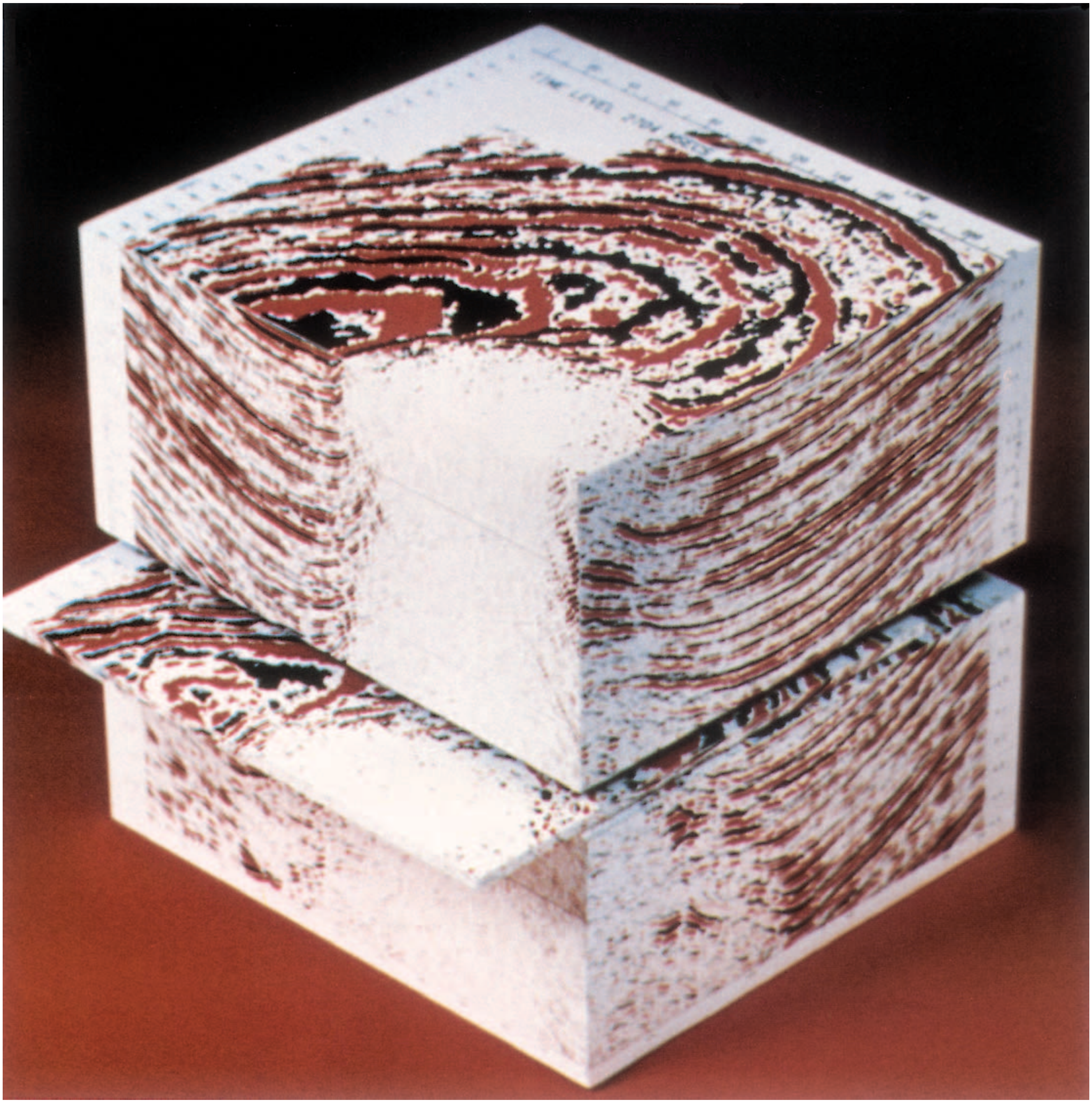

Fig. 1-16. 3-D data volume showing a Gulf of Mexico salt dome and associated rim syncline. (Courtesy Hunt Oil Company).

If the sampling theorem is not satisfied the data are aliased. In the case of a dipping event, the spatial sampling of that event must be such that its principal alignment is obvious; if not, aliases occur and spurious dips result after multichannel processing. Table 1-2 shows the frequencies at which this aliasing occurs for various dips and subsurface spacings. Clearly, a 3-D survey must be designed such that aliasing during processing does not occur. Tables like the one presented can be used to establish the necessary spacing considering the dips and velocities present. In order to impose the safety margin of three samples, rather than two, per shortest wavelength, the frequency limit is normally considered to be around two-thirds of each number tabulated. The formulas in Table 1-3 provide a general method of establishing the spacings required. The

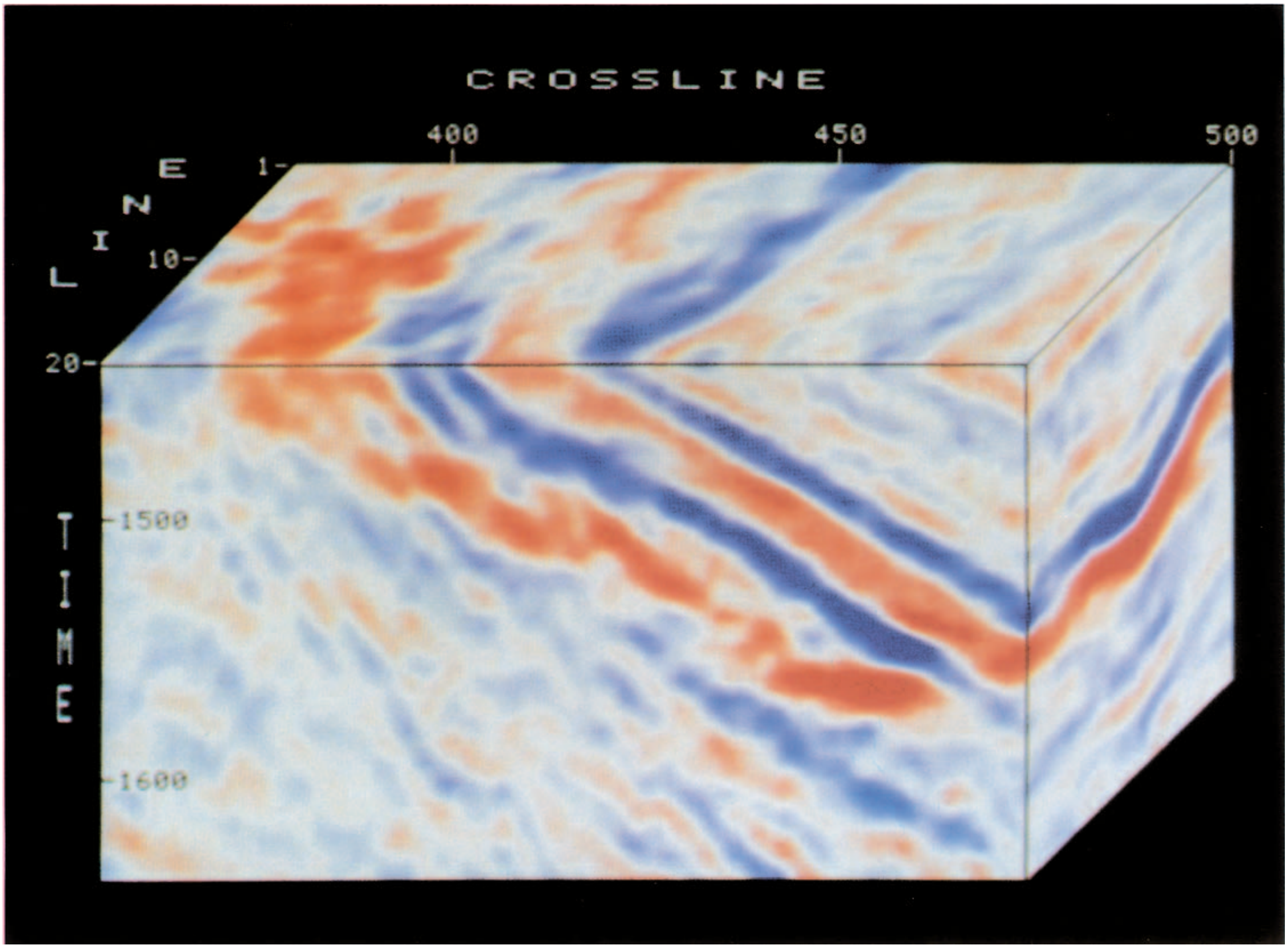

Fig. 1-17. 3-D data volume showing a bright spot from a Gulf of Mexico gas reservoir. (Courtesy Chevron U.S.A. Inc.)

first formula, based on two samples per shortest wavelength, gives the maximum spacing that can be used to image the structure. Given our ignorance of the subsurface structure at the time the 3-D survey is being designed, we should allow a significant safety margin by collecting at least three samples per shortest spatial wavelength.

Table 1-3 also shows the two formulas needed to calculate the width of the extra strip around the periphery of the prospect over which data must be collected in order to ensure proper imaging in the area of interest. The calculation of migration distance, the extra fringe width needed for structure, should use the local value of dip measured perpendicular to the prospect boundary. The Fresnel zone radius, the extra fringe width needed for stratigraphy, needs to be considered for the proper focusing of amplitudes. The two strip, or fringe, widths thus calculated should be added together in defining the total survey area.

A typical 3-D seismic interpreter does not get involved in designing surveys but nevertheless needs to appreciate these issues. Figure 1-12 demonstrates that, of the data volume under interpretation, only the central portion is fully migrated and therefore fully reliable. The fringe between the inner and outer volumes is the migration distance and the Fresnel zone radius. If the interpreter is working in this fringe zone he needs to realize that the data are unreliable and the results are subject to greater risk.

Proper design of a 3-D survey is critical to its success, and sufficiently close spacing is vital. The formulas of Table 1-3 are addressing structural design issues. In areas of

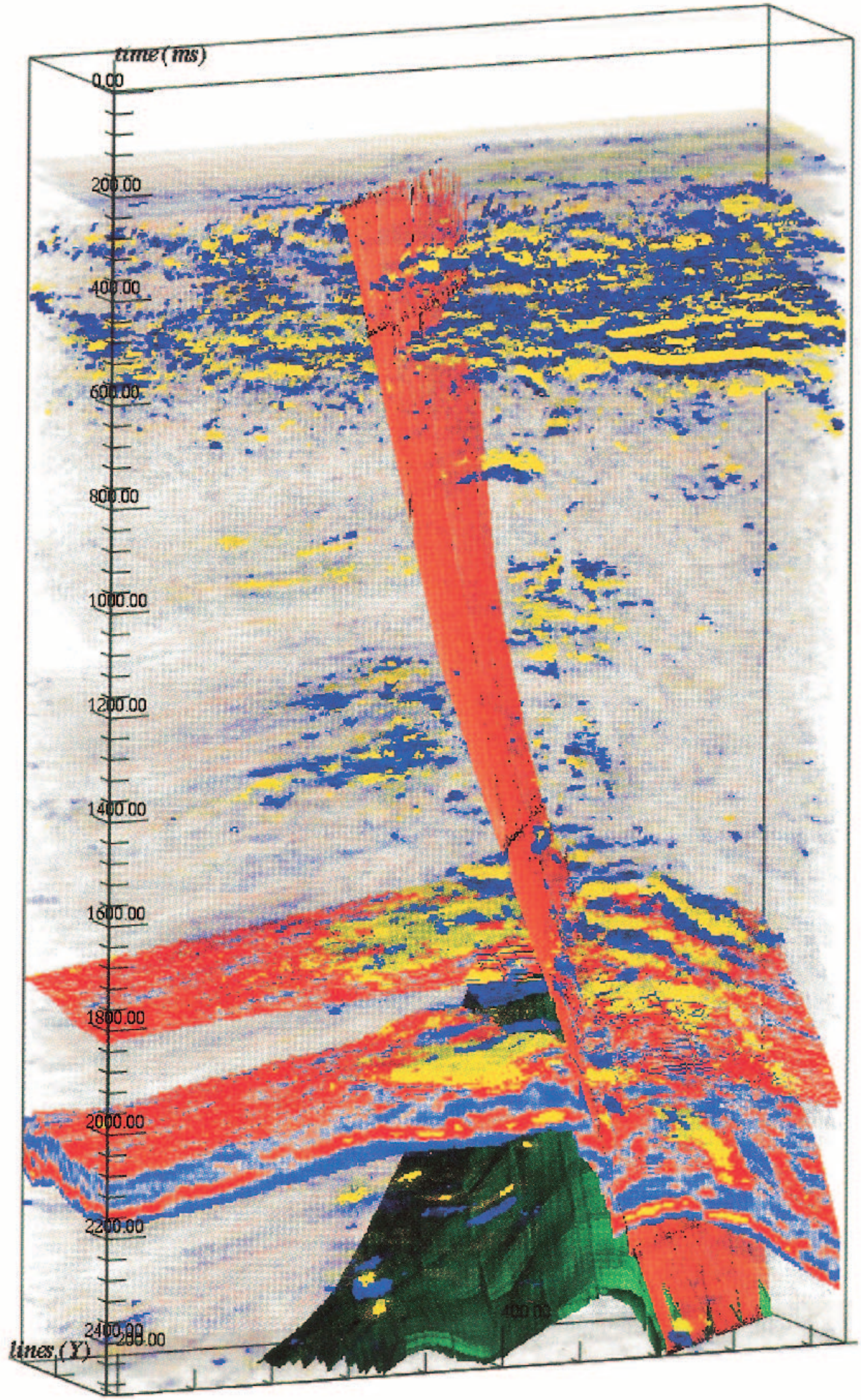

Fig. 1-18. Voxel-rendered view of data volume which, by making the voxels semi-transparent, permits the interpreter to look into the volume. (Courtesy CogniSeis Development.)

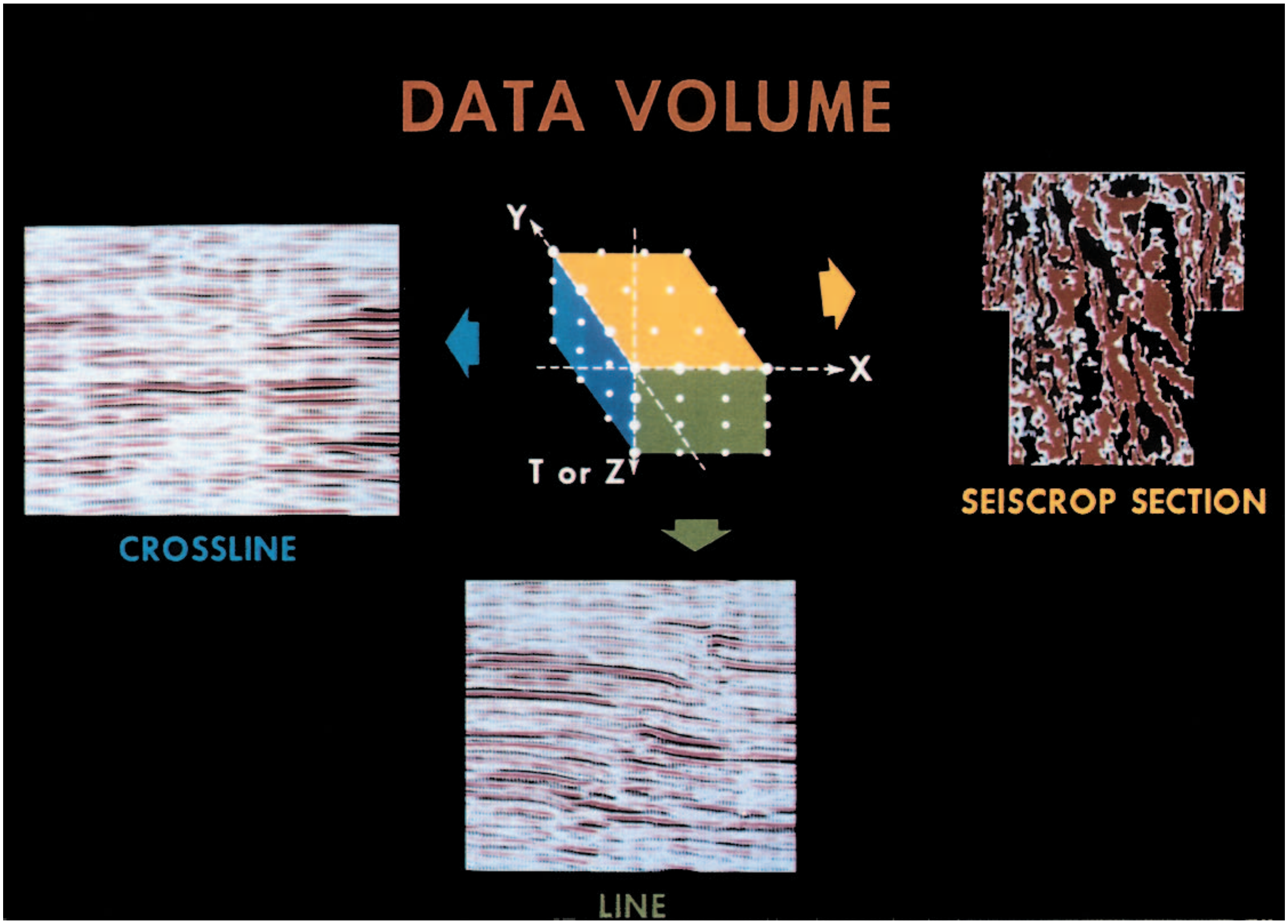

Fig. 1-19. Three sets of orthogonal slices through a data volume provide the basic equipment of the 3-D seismic interpreter.

shallow dip where the survey objectives are stratigraphic, the selected spacing must be such that there are at least two samples within the lateral extent of any expected stratigraphic feature of interest, for example the width of a channel. Figure 1-15 demonstrates a typical comparison between the subsurface sampling of a 2-D and 3-D survey. The bold dots indicate the 2-D survey depth points which satisfy the sampling theorem along each line. The 3-D survey requires a similarly close spacing in both directions over the whole area. In addition to the opportunity for three-dimensional processing which the areal coverage provides, note the sampling and thus potential definition of a meandering stream channel. Sampling for stratigraphic features like this channel requires at least two but preferably three samples within the channel width. In practice, 3-D depth point spacing ranges between 6 and 50 m.

Volume Concept

Collection of closely-spaced seismic data over an area permits three-dimensional processing of the data as a volume. The volume concept is equally important to the seismic interpreter. With 3-D data, the interpreter is working directly with a volume rather than interpolating a volumetric interpretation from a widely-spaced grid of observations. The handling of this volume and what can be extracted from it are principal subjects of this book. One property of the volume pervades everything the 3-D interpreter does: The subsurface seismic wavefield is closely sampled in every direction, so that there is no grid loop around which the interpreter must tie, and no grid cell over which he must guess at the subsurface structure and stratigraphy. This is an opportunity which an interpreter must use to full advantage. Because the sampling

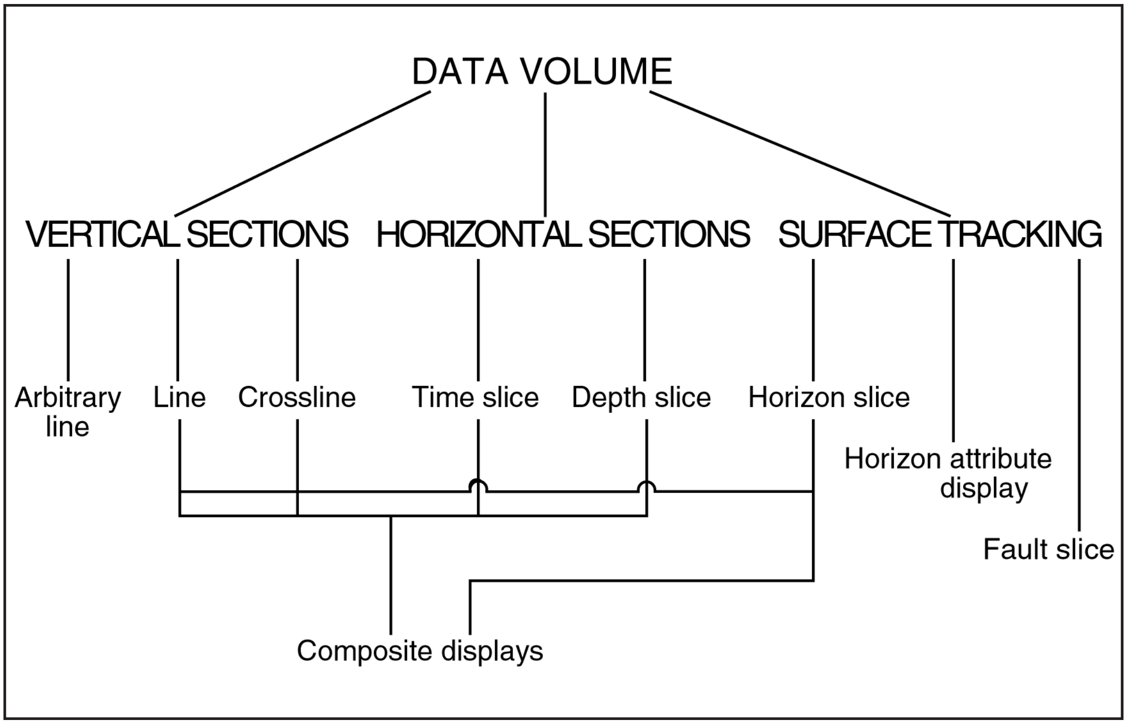

Fig. 1-20. Recognized and approved terms for display products from 3-D seismic data. All display seismic amplitude unless specified otherwise. Use of all other terms should be discouraged.

requirements for interpretation are the same as for processing, all the processed data points contain unique information and thus should be used in the interpretation. Thus, the interpreter of a 3-D volume should not decimate the data available to him but, given that he has time constraints imposed on him, he should use innovative approaches with horizontal sections, specially selected slices, and automatic spatial tracking, in order to comprehend all the information in the data. In this way the 3-D seismic interpreter will generate a more accurate and detailed map or other product than his 2-D predecessor in the same area.

Figure 1-16 shows a view of a 3-D data volume through a salt dome. It demonstrates the volume concept well and the interpreter can use a display of this kind to help in appreciation of subsurface three-dimensionality. Figure 1-17 shows another cube, in this case generated interactively, which helps in the three-dimensional appreciation of a much more detailed subsurface objective. Neither of these displays, however, permits the interpreter to look *into* the volume of data.

True 3-D display has recently become a reality on computer workstations and Figure 1-18 shows an example. The portion of the volume being displayed is composed of voxels, or volume elements, and these are rendered with differing degrees of transparency so that the interpreter can really see into the volume. In Figure 1-18 there are four interpreted surfaces as well as the semi-transparent data. As with any volumetric display the dynamic range is reduced because of the quantity of data viewed. These types of display are very useful for data visualization but they are not yet fully integrated into mainstream interpretation systems.

Slicing the Data Volume

The vast majority of 3-D interpretation is performed on slices through the data volume. There are no restrictions on the dynamic range for the display of any one slice, and therefore all the benefits of color, dual polarity, etc., can be exploited (see Chapter 2). The 3-D volume contains a regularly-spaced orthogonal array of data points defined by the acquisition geometry and maybe adjusted during processing. The three principal directions of the array define three sets of orthogonal slices or sections through the data, as shown in Figure 1-19.

The vertical section in the direction of boat movement or cable lay-out is called a **line** (sometimes an **inline**). The vertical section perpendicular to this is called a

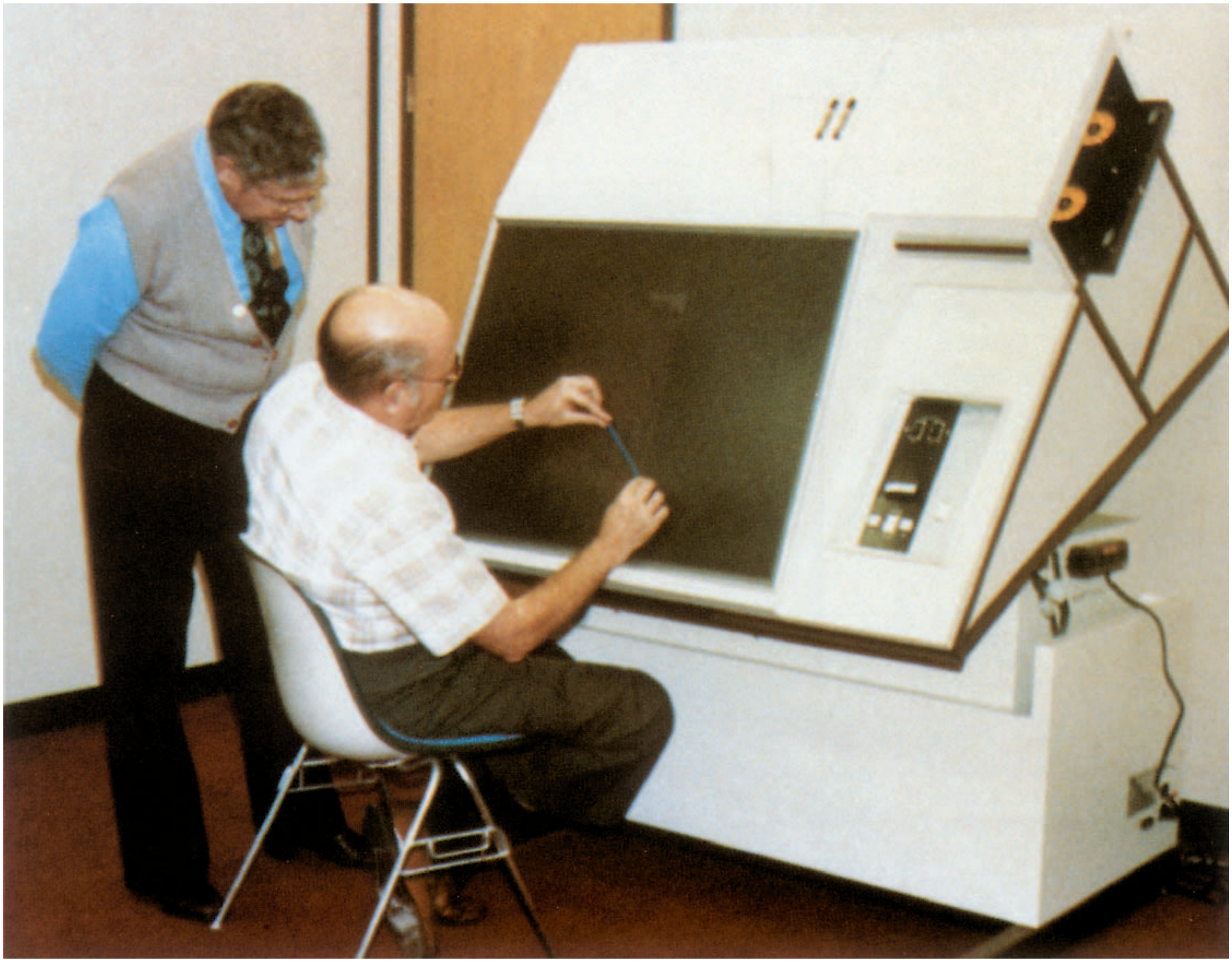

Fig. 1-21. An early optical workstation.

crossline. The horizontal slice is called a **horizontal section, time slice**, **Seiscrop* section, or depth slice**. The terminology used for slices through 3-D data volumes has become somewhat confused. One of the objectives of this chapter is to clarify terms in common use today.

Three sets of orthogonal slices through the data volume (as defined above) are regarded as the basic equipment of the 3-D interpreter. A complete interpretation will make use of some of each of them. However, many other slices through the volume are possible. A **diagonal line** may be extracted to tie two locations of interest, such as wells. A zig-zag sequence of diagonal line segments may be necessary to tie together several wells in a prospect. In the planning stages for a production platform, a diagonal line may be extracted through the platform location along the intended azimuth of a deviated well. All these are vertical sections and are referred to as **arbitrary lines**.

More complicated slices are possible for special applications. A slice along or parallel to a structurally interpreted horizon, and hence along one bedding plane, is a **horizon slice, horizon Seiscrop section,** or **amplitude map**. Slices of this kind have particular application for stratigraphic interpretation, which is explored in Chapter 4. **Fault slices** generated parallel to a fault face have various applications in structural and reservoir interpretation and will be discussed in Chapter 7. **Horizon attribute displays** are the subject of Chapter 8.

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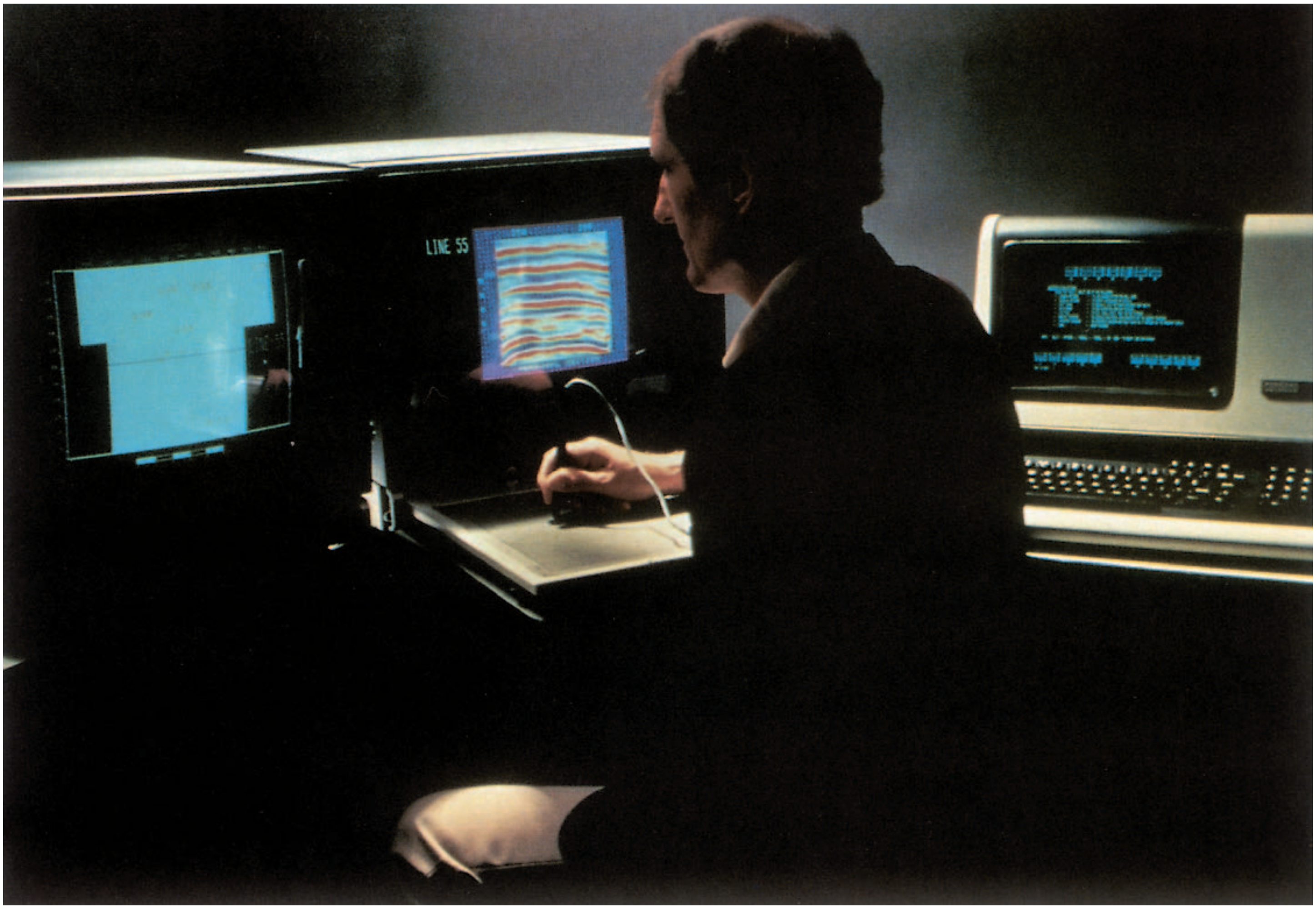


Fig. 1-22. An early interactive workstation.

Figure 1-20 shows a hierarchy of approved terms for display products from 3-D seismic data. It shows, for example, the equivalence of horizontal and vertical sections, and the equivalence of time slices with lines and crosslines. In order to aid worldwide communication, use of other terms is discouraged.

Manipulating the Slices

Because 3-D interpretation is performed with data slices and because there is a very large number of slices for a typical data volume, several innovative approaches for manipulating the data have emerged. In the early days of 3-D development a sequence of horizontal sections was displayed on film-strip and shown as a motion picture (Bone, Giles, Tegland, 1983). From this developed the Seiscrop Interpretation Table — initially a commercially-available piece of equipment incorporating a 16mm analytical movie projector. This machine was originally developed for coaches wanting to examine closely the actions of professional athletes.

The Seiscrop Interpretation Table then evolved into a custom-built device (Figure 1-21). The data, either horizontal or vertical sections, were projected from 35mm film-strip onto a large screen. The interpreter fixed a sheet of transparent paper over the screen for mapping and then adjusted the size of the data image, focus, frame advance, or movie speed by simple controls.

Today 3-D interpretation is performed interactively and there has been an explosion in workstation usage in recent years. The interpreter calls the data from disk and views them on the screen of a color monitor (Figure 1-22). The large amount of regularly-organized data in a 3-D volume gives the interactive approach enormous benefits. In fact, many interactive interpretation systems addressed 3-D data first as the easier problem, and then developed 2-D interpretation capabilities later.

Most of the interpretation discussed in this book resulted from use of an interactive workstation, and many of the data illustrations are actual screen photographs. Furthermore, the facilities of the system contributed in several significant ways to the success of many of the projects reported here. Hence it is appropriate to review the interpretive benefits of an interactive interpretation system.

(1) **Data management** — The interpreter needs little or no paper; the selected seismic data display is presented on the screen of a color monitor and the progressive results of interpretation are returned to the digital database.

(2) **Color** — Flexible color display provides the interpreter with maximum optical dynamic range adapted to the particular problem under study.

(3) **Image composition** — Data images can be composed on the screen so that the interpreter views what is needed, no more and no less, for the study of one particular issue. Slices through the data volume are designed by the user in order to customize the perspective to the problem.

(4) **Idea flow** — The rapid response of the system makes it easy to try new ideas. The interpreter can rapidly generate innovative map or section products in pursuit of a better interpretation.

(5) **Interpretation consistency** — The capability to review large quantities of data in different forms means that the resulting interpretation should be more consistent with all available evidence. This is normally considered the best measure of interpretation quality.

(6) **More information** — Traditional interpretive tasks performed interactively will save time; however, the extraction of more detailed subsurface information is more persuasive and far-reaching.

Dynamic Range and Data Loading

Interactive interpretation must commence with data loading and this is a critical first step. Should the data be loaded at 8, 16 or 32 bits? Is clipping of the highest amplitudes acceptable?

Data processing has always been performed using 32 bits to describe each amplitude value. This large word size ensures that significance is retained during all computations. The first interactive systems in the early 1980's were 32-bit machines but soon a demand for speed dictated that data be loaded using 8 bits only. The small word reduces response time and minimizes storage space for the survey data. Today interactive systems offer a choice of 8-bit, 16-bit or 32-bit dynamic range although color monitors normally display 8 bits only.

Figure 1-23 shows a typical statistical distribution of amplitudes in a data volume. There are a large number of very low amplitudes, a fairly large number of moderate amplitudes but a very small number of high amplitudes. Mainstream structural interpretation tends to work on moderate amplitude horizons. The high amplitude tails of the distribution are localized anomalies which, in tertiary clastic basins, are often the hydrocarbon bright spots. The interpreter avoids the low amplitudes as much as possible because they are the most subject to noise. Thus most interpretive time is devoted to the amplitudes lying in the stippled areas of Figure 1-23.

If interpretation is to be conducted using 8-bits only, scaling 32-bit amplitude numbers to 8-bit amplitude numbers must be done during data loading. If the maximum amplitude in the volume is set to ± 128, relative amplitudes are preserved within the precision of the 8 bits. However, this often severely limits the dynamic range available in the stippled, or heavily used, amplitude regions. Clipping of the highest amplitudes is a common reaction to this problem so that a smaller value is set to ±128. More dynamic range is then available for the mainstream structural interpretation but the highest amplitudes are destroyed and hence unavailable for stratigraphic or reservoir analysis. This can be very damaging particularly in areas like the Gulf of Mexico. Some interactive workstations load 8-bit data with a floating point scalar defined

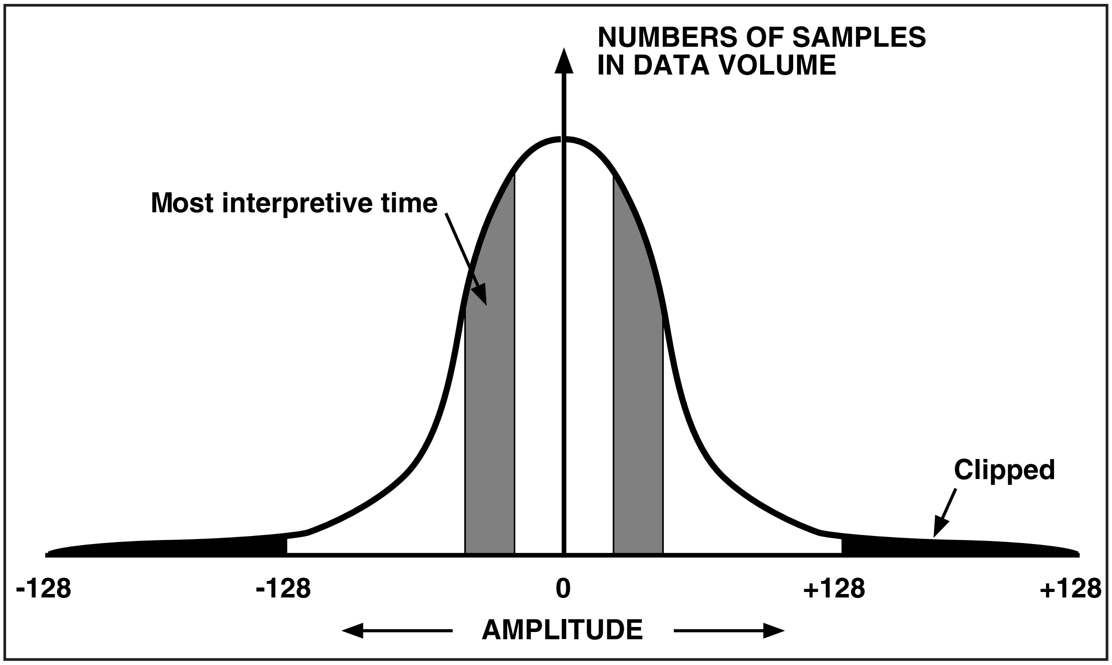
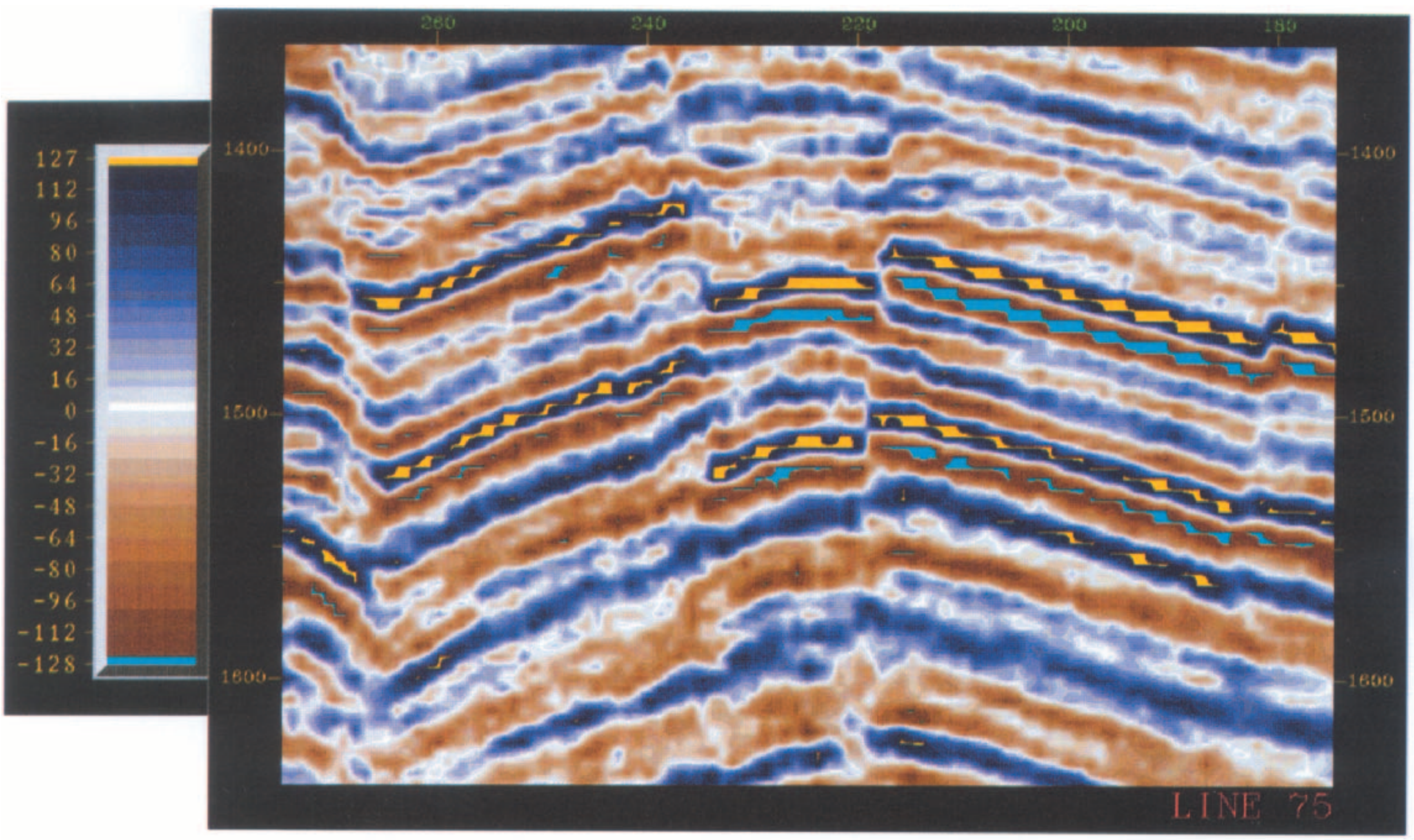


Fig. 1-23. Typical statistical distribution of amplitudes in a 3-D data volume. Plus or minus 128, the largest number which can be described by 8 bits, may be set to the largest amplitude, or alternatively to some smaller amplitude, thus causing data clipping.

Fig. 1-24. Test for and demonstration of data clipping.



individually for each trace and stored in the trace header. This lessens but does not remove the dynamic range problem discussed above.

A common and generally desirable solution today is to load the data using 16 bits for each amplitude value. In this way clipping is irrelevant and unnecessary as there is plenty of dynamic range for structural interpretation and bright spot studies.

An interesting comparison of 8-bit and 16-bit interpretation was conducted by Roberts and Hughes (1995). They concluded that there are always differences between interpretation products from 8-bit and 16-bit volumes but they are generally less than 5%. These are often tolerable but they stressed the need for *sensible clipping*. Figure 1-24 is a test for and demonstration of data clipping. Contrasting colors have been placed in the extremities of the otherwise-gradational color scheme. The large amounts of yellow and cyan demonstrate an anomalously high occupancy of those highest amplitudes, that is the data has been heavily clipped.

The author is opposed to data clipping as it places restrictions on interpretation activities. Generally the best solution is to use 16 bits and sometimes 32 bits. The total interpretation project today often involves a significant amount of post-interpretation computation. The larger number of bits helps ensure that numeric significance is maintained during these operations. Fortunately faster and cheaper hardware is now available which makes the use of 16 or 32 bits much less of a burden than it was in the past.

Synergism and Pragmatism in Interpretation

Seismic technology has, over the years, become increasingly complex. Whereas a party chief used to handle data collection, processing, and interpretation, experts are now generally restricted to each discipline. Data processing involves many highly sophisticated operations and is conducted in domains unfamiliar to the nonmathematically-minded interpreter. The ability of certain processes to transform data in adverse as well as beneficial ways is striking.

Today's seismic interpreter must understand in some detail what has been done to the data and must understand data processing well enough to ask meaningful questions of the processing staff. A summary of 3-D data collection and processing issues is included as Appendix A. Today's interpreter will also benefit greatly by using high technology aids, such as an interactive system. Critical to maximum effectiveness is an understanding of the advantages of color and how to work with horizontal sections, acoustic impedance sections, frequency sections, vertical seismic profiles, attribute displays, and the like.

Seismic interpretation today thus involves a wide range of seismic technologies. If the results of these are studied by the interpreter in concert, significant synergism can result. However, pragmatism retains its place. The interpreter must continue to take a broad view, to integrate geology and geophysics, and, to an increasing degree, engineering, and to make simplifying assumptions in order to get the job done. The progress of seismic interpretation depends on the continued coexistence of technological synergism and creative pragmatism.

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