Structural Interpretation

Direct Contouring and the Importance of the Strike Perspective

The 3-D seismic interpreter works with a volume of data. Normally this is done by studying some of each of the three orthogonal slices through the volume. This chapter explores the unique contribution of the horizontal section to structural interpretation. The interpreter of structure needs to be able to judge when to use horizontal sections and when to use vertical ones in the course of an overall interpretive project.

Figure 3-1 demonstrates the conceptual relationship between a volume of subsurface rock and a volume of seismic data. Consider the diagram first to represent subsurface rocks and the gray surface to be a bedding plane. The two visible vertical faces of the rectangular solid show the two dip components of the plane; the horizontal face shows the strike of the plane. Now consider the rectangular solid of Figure 3-1 to be the equivalent volume of seismic data. The gray plane is now a dipping reflection and its intersections with the three orthogonal faces of the solid show the two components of dip and the strike as before. Hence the attitude of a reflection on a horizontal section indicates directly the strike of the reflecting surface. This is the fundamental property of the horizontal section from which all its unique interpretive value derives.

Contours follow strike and indicate a particular level in time or depth. When an interpreter picks a reflection on a horizontal section, it is directly a contour on some horizon at the time (or depth) at which the horizontal section was sliced through the data volume.

Figure 3-2 shows three horizontal sections, four milliseconds apart. By following the semicircular black event (peak) from level to level and drawing contours at an appropriate interval, the structural contour map at the bottom of Figure 3-2 was generated. Note the similarity in shape between the sections and the map for the anticlinal structure and the strike east of the faults. In the central panel the peaks from 1352 ms are printed in black and the peaks from 1360 ms in blue/green. This clearly demonstrates the way in which the events have moved with depth.

Figures 3-3 and 3-5 provide one vertical section and several horizontal sections from which the relationship between the two perspectives can be appreciated. Line P (Figure 3-3) runs north-south through the middle of the prospect with south at the right. The time interval 2632-2656 ms shows some continuous reflections. Proceeding from south to north (right to left, Figure 3-3; bottom to top, Figure 3-5) the structure is first a broad closed anticline, then a shoulder, then a smaller anticline.

Figure 3-5 demonstrates a simple exercise in direct contouring from a suite of horizontal sections. The red event (trough) expanding in size from left to right has been progressively circumscribed in the lower part of the figure. The last frame is a raw contour map of this horizon. This first structural representation has been made quickly

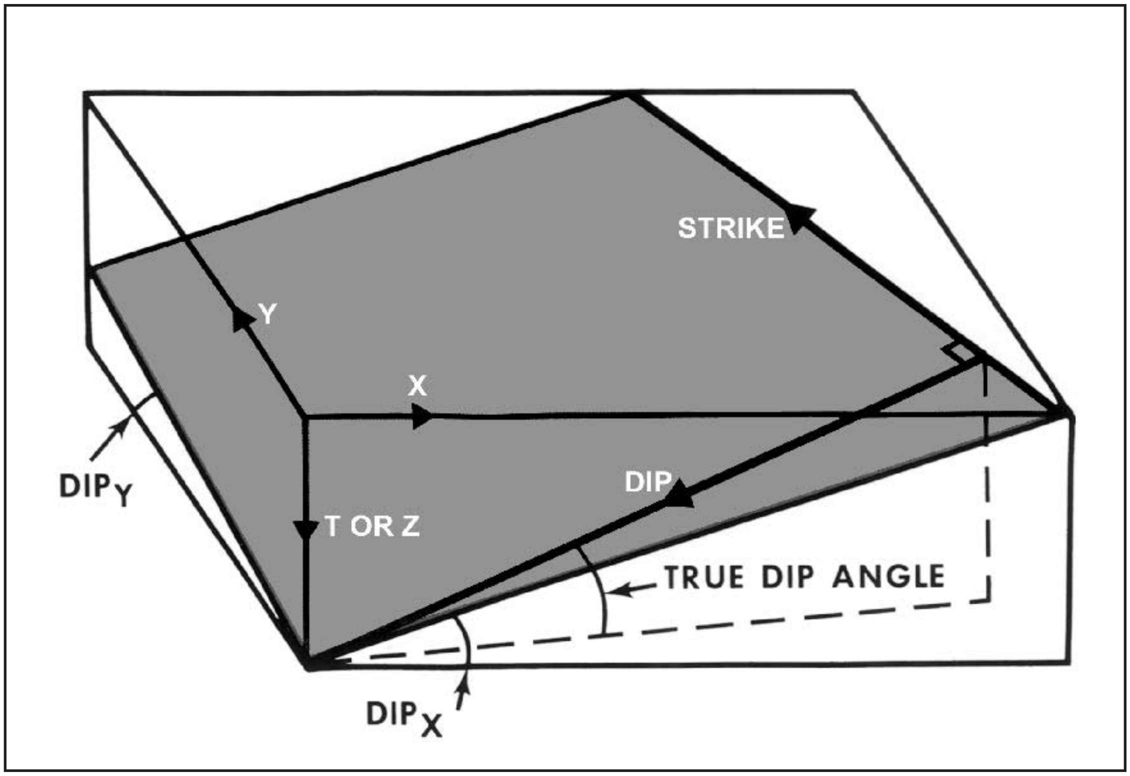

Fig. 3-1. Relation between dip and strike of a seismic reflector within a data volume.

and efficiently without the traditional intermediate tasks of timing, posting and contouring. When drawing structural contours from horizontal sections in this way, it is wise to visualize the three-dimensionality of the structure and to appreciate where on the seismic waveform the contour is being drawn (Figure 3-4). The latter problem applies particularly to the use of variable area displays as used, for example, in Figure 3-5. The contour is here drawn all the way around the red event only because the dip is down all the way around the structure; this is a consistent point on the seismic waveform, namely its upper edge (Figure 3-4).

Figure 3-6 shows 24 horizontal sections covering an area of about 5 sq mi (13 sq km). These can be used as a structural interpretation exercise. Obtain a small piece of transparent paper and register it over the rectangular area. Begin with the upper left frame and find the red event in its lower right corner. Mark this event by following its maximum amplitude and then mark its changed position from frame to frame until you reach 2160 ms. Your resultant contour map should show that the dip is generally northwest and that the strike swings about 40° toward the north over the structural range of the map. You will probably detect a fault toward the west of the area as well. If you study the arcuate events west of the fault, you will recognize a small anticline closing against the fault and a small syncline south of it. There is no way to establish the correlation across the fault.

An event on a horizontal section is generally broader than on a vertical section as dips are usually less than 45°. Figure 3-7 shows the effect of dip and frequency on the width of an event on a horizontal section. A gently dipping event is very broad and a steeply dipping event is much narrower. Increasing dip and increasing frequency both make horizontal section events narrower. The width of an event on a horizontal section is strictly half the spatial wavelength.

Because typical dips are much less than 45°, fewer horizontal sections than vertical ones are needed to study the full extent of a reflection within a given data volume. This gives horizontal sections greater efficiency than vertical sections in structural mapping. Combining this benefit with the fact that horizon tracks (picks) are directly contours, then the value of horizontal sections to structural interpretation is substantial.

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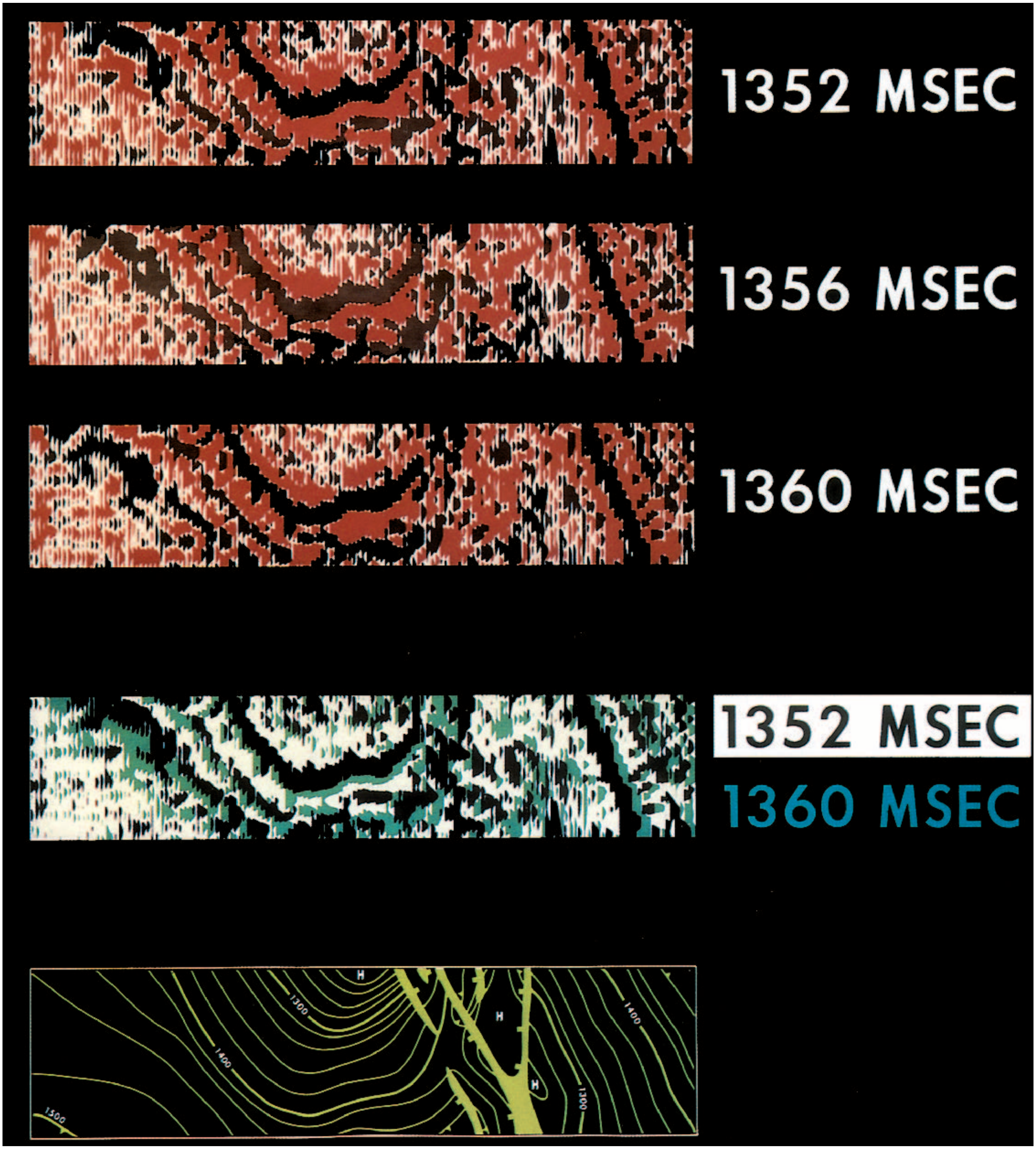


Fig. 3-2. Dual polarity horizontal sections from offshore Holland; two-level single polarity horizontal section, showing movement of events from 1352 ms to 1360 ms; interpreted contour map on horizon seen as strongest event on horizontal sections.

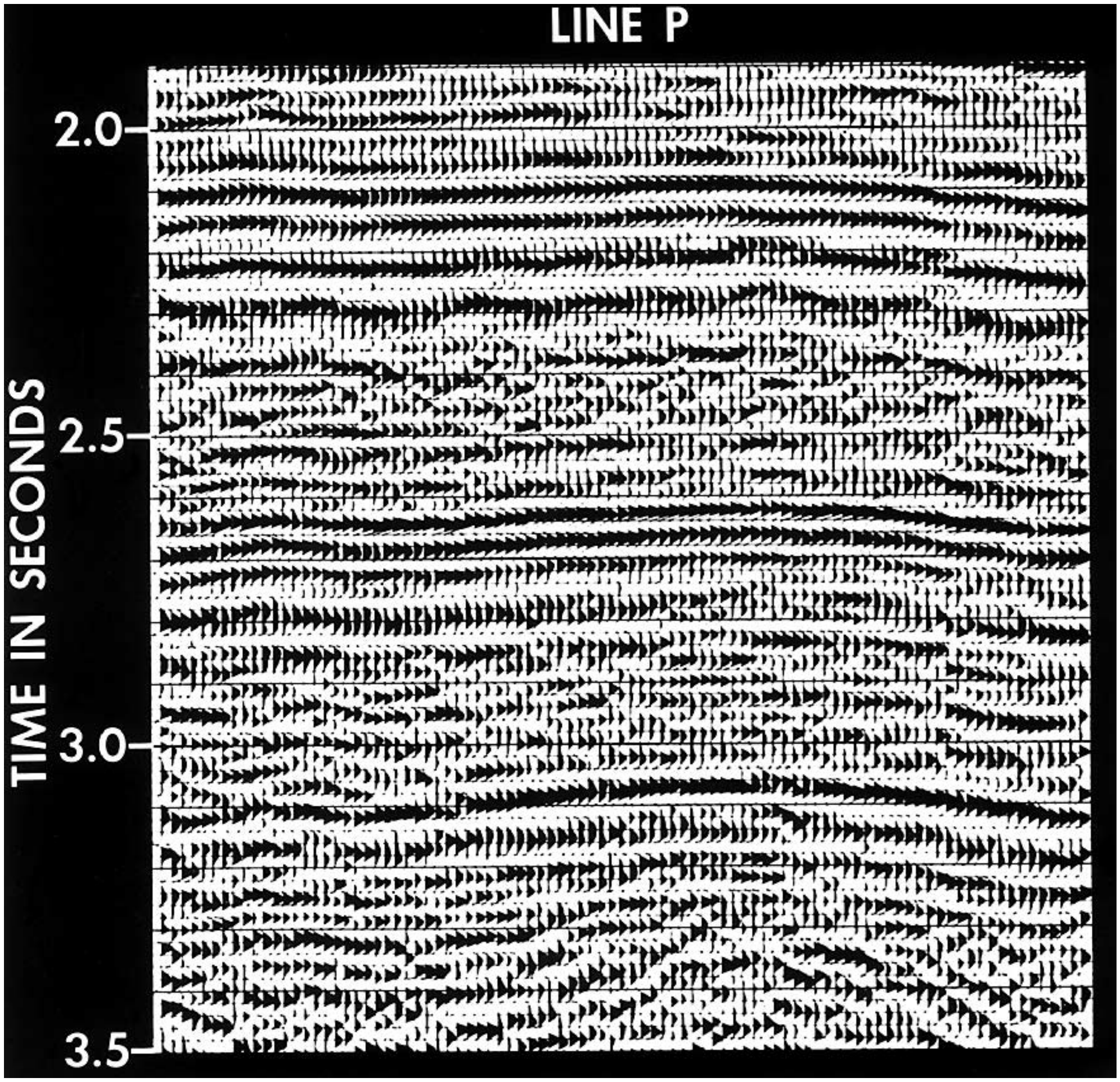


Fig. 3-3. North-south vertical section from Peru through same data volume sliced in Figure 3-4. (Courtesy Occidental Exploration and Production Company.)

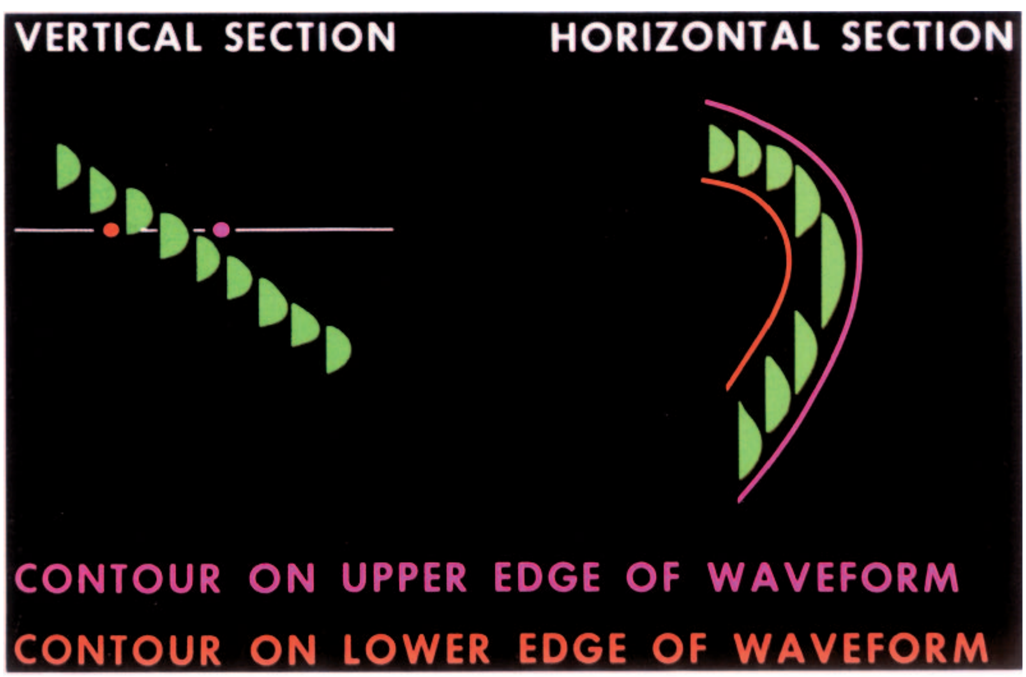


Fig. 3-4. Where on the waveform should one place the contour when working with variable area display?

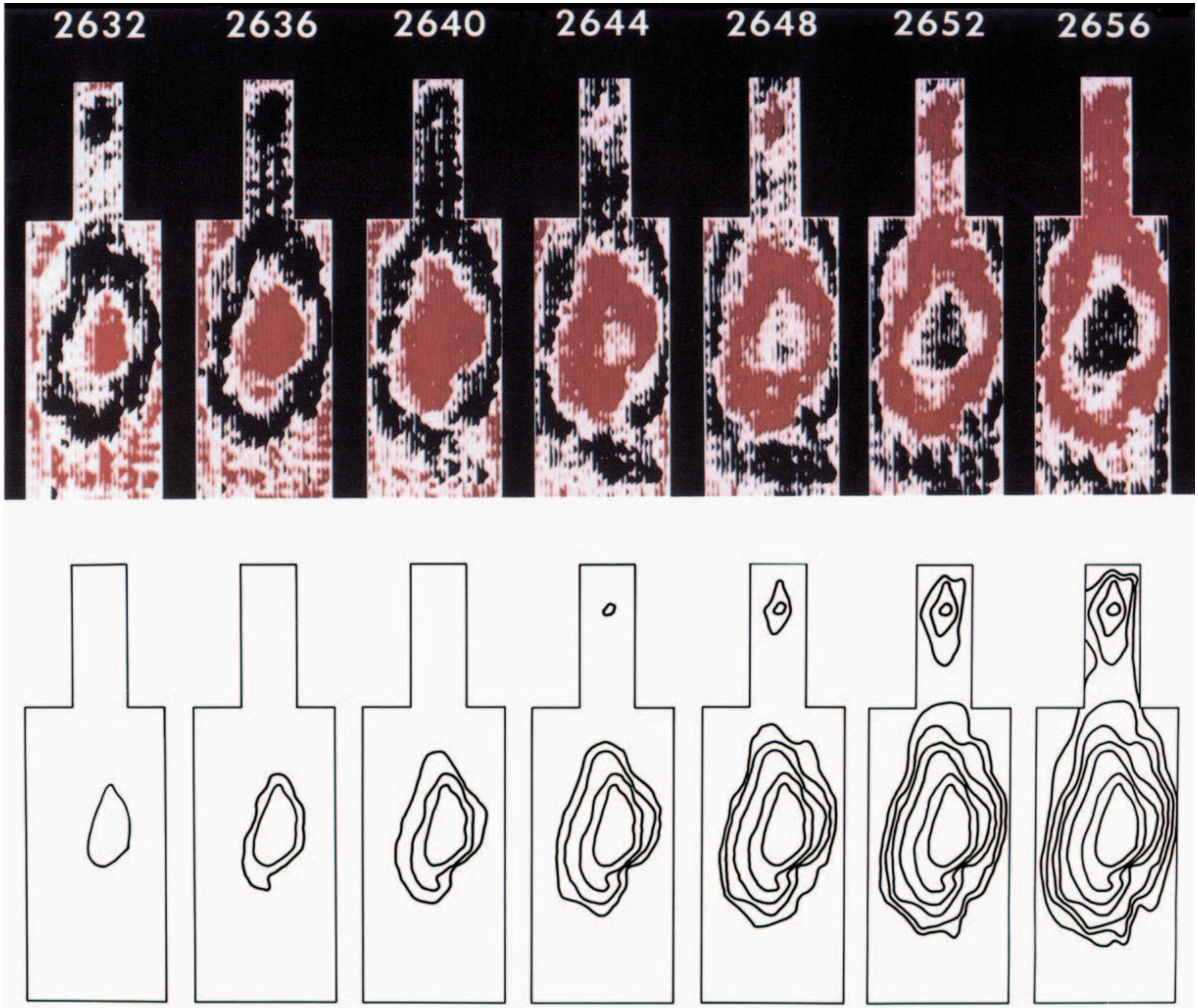


Fig. 3-5. Horizontal sections, 4 ms apart, from Peru (courtesy Occidental Exploration and Production Company) and raw interpreted contour map made by successively circumscribing the red event on each section.

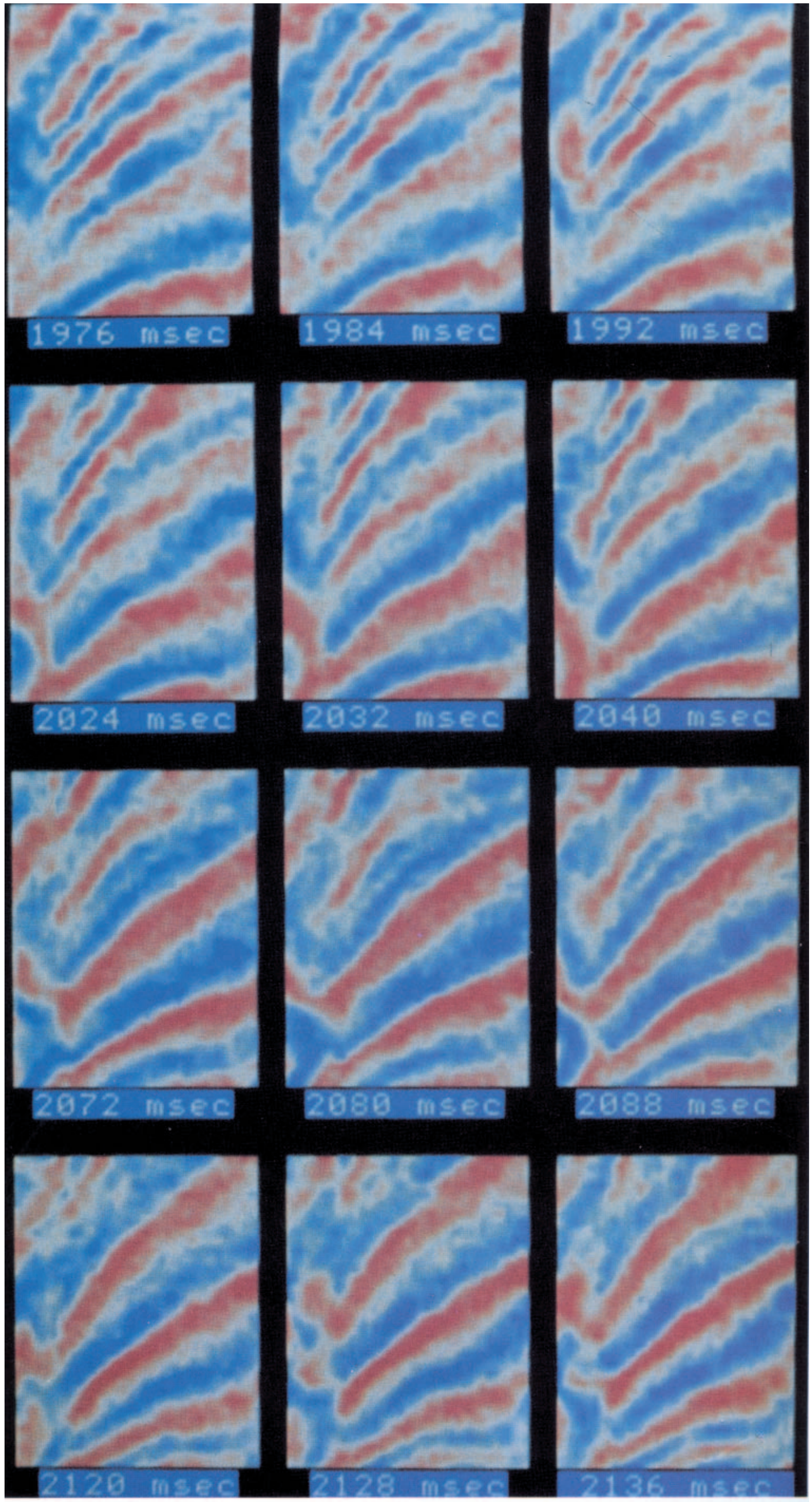


Fig. 3-6. Horizontal sections, 8 ms apart, from offshore Trinidad. (Courtesy Texaco Trinidad Inc.)

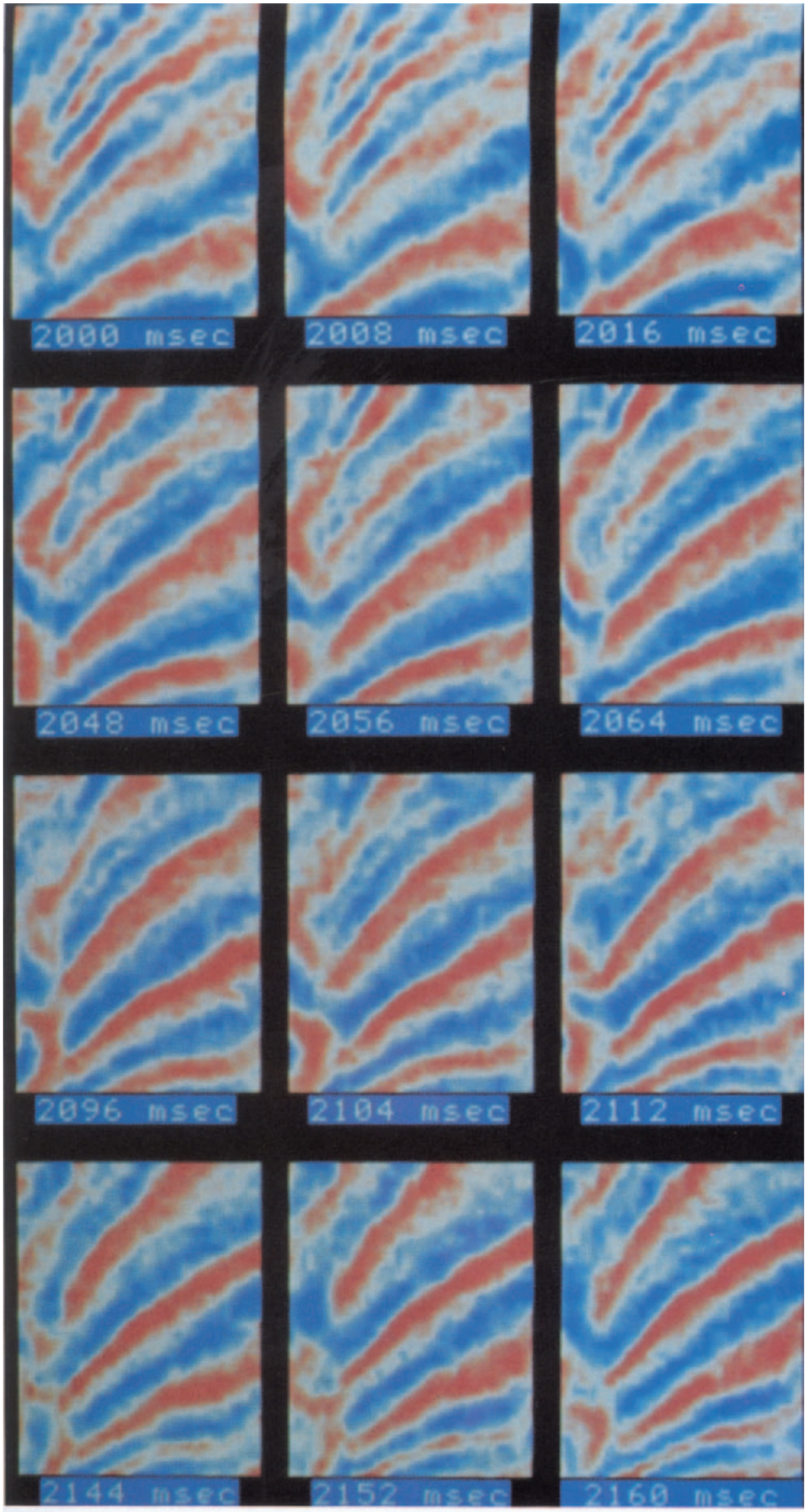
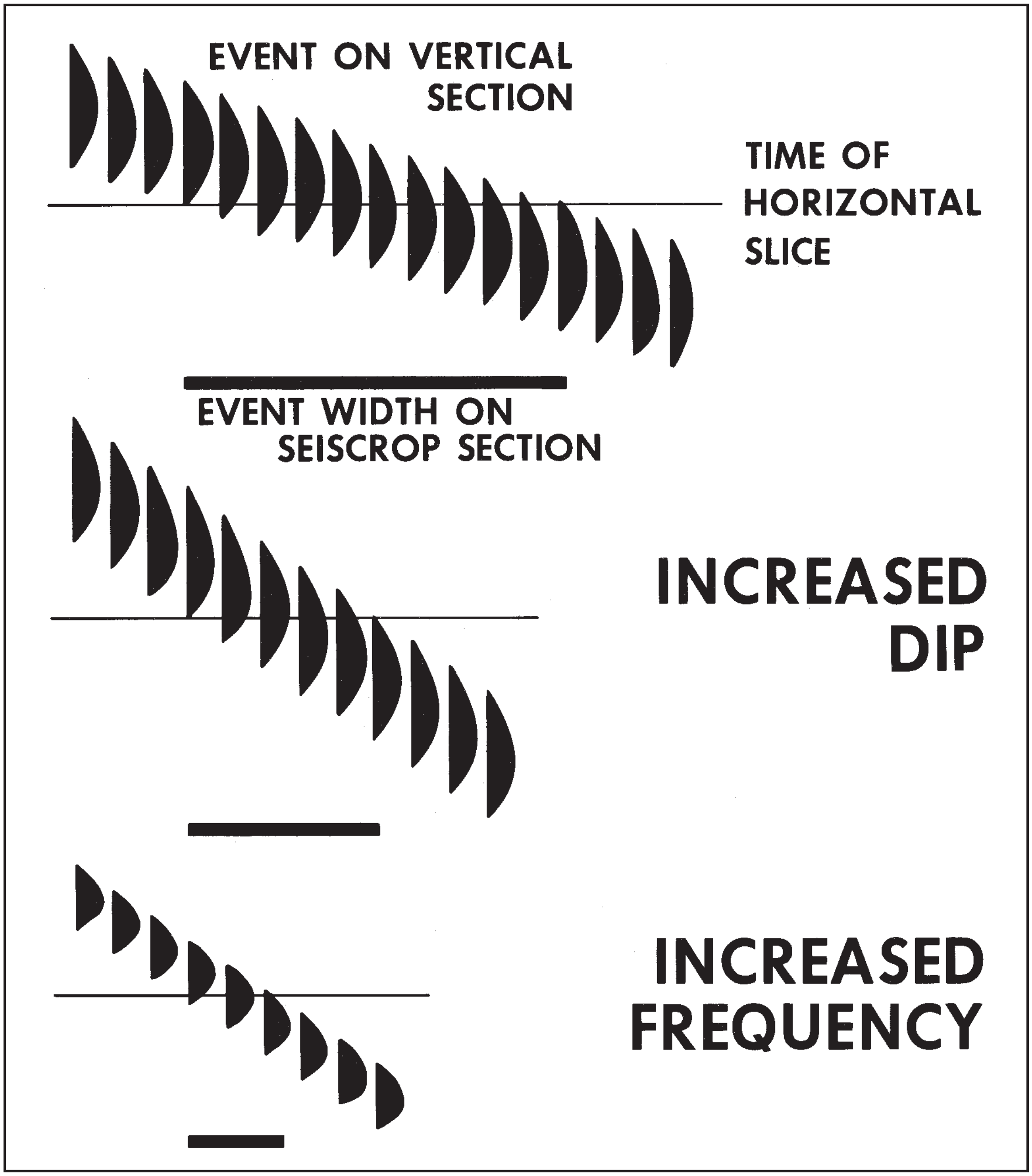

2000 msec
2008 msec
2016 msec
2048 msec
2056 msec
2064 msec
2096 msec
2104 msec
2112 msec
2144 msec
2152 msec
2160 msec

Fig. 3-7. The width of an event on a horizontal section decreases with increased dip and also with increased frequency.



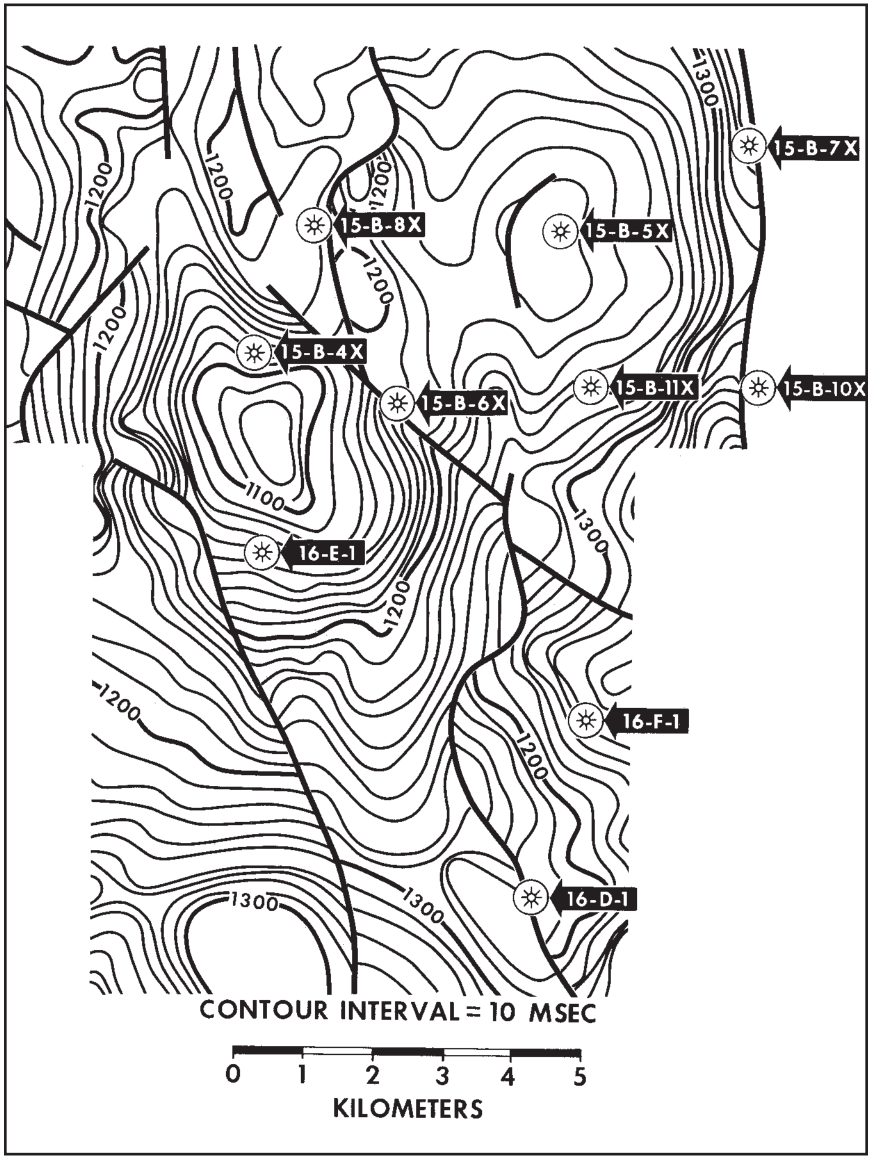


Fig. 3-8. Structural contour map derived from 2-D data from the Gulf of Thailand. (Courtesy Texas Pacific Oil Company Inc.)

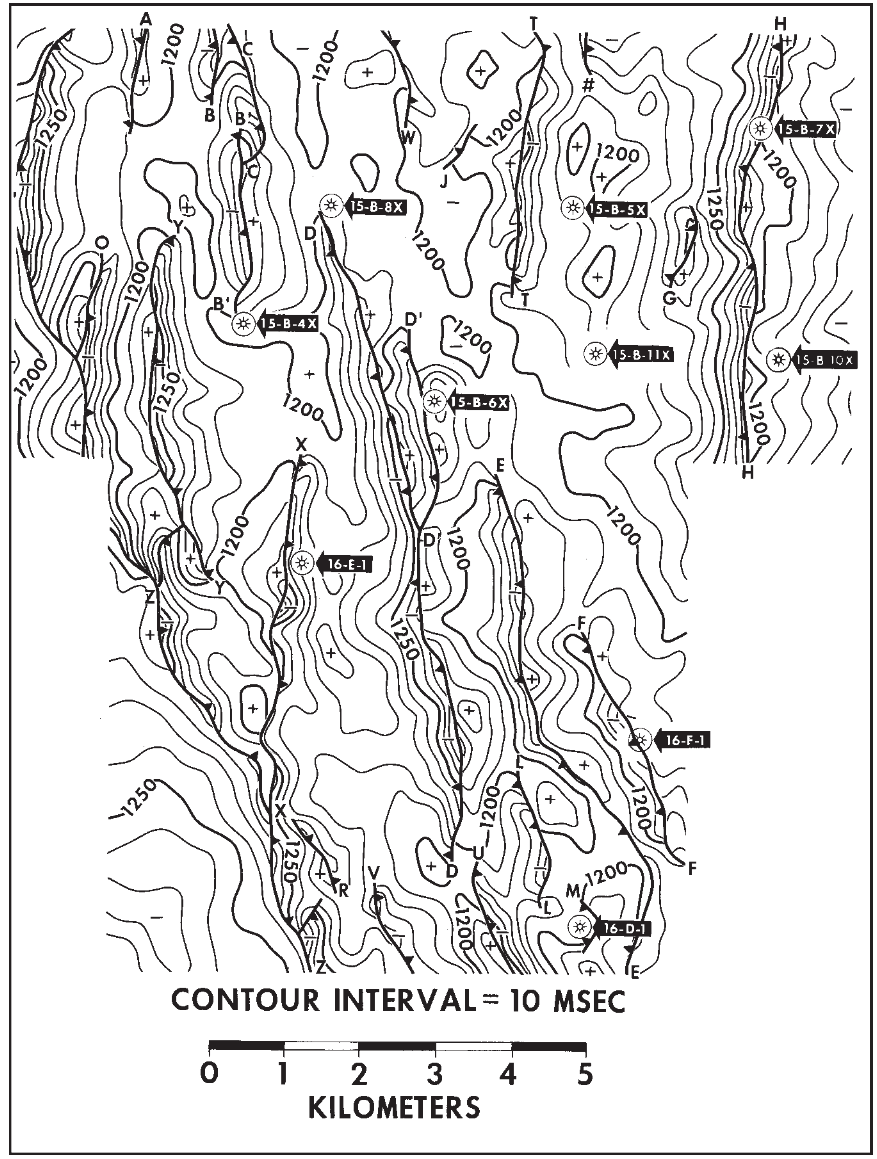


Fig. 3-9. Structural contour map derived from 3-D data from the Gulf of Thailand for the same horizon mapped in Figure 3-8. (Courtesy Texas Pacific Oil Company Inc.)

Fig. 3-10. Structural contour map derived from 2-D data from offshore Chile. (Courtesy ENAP).

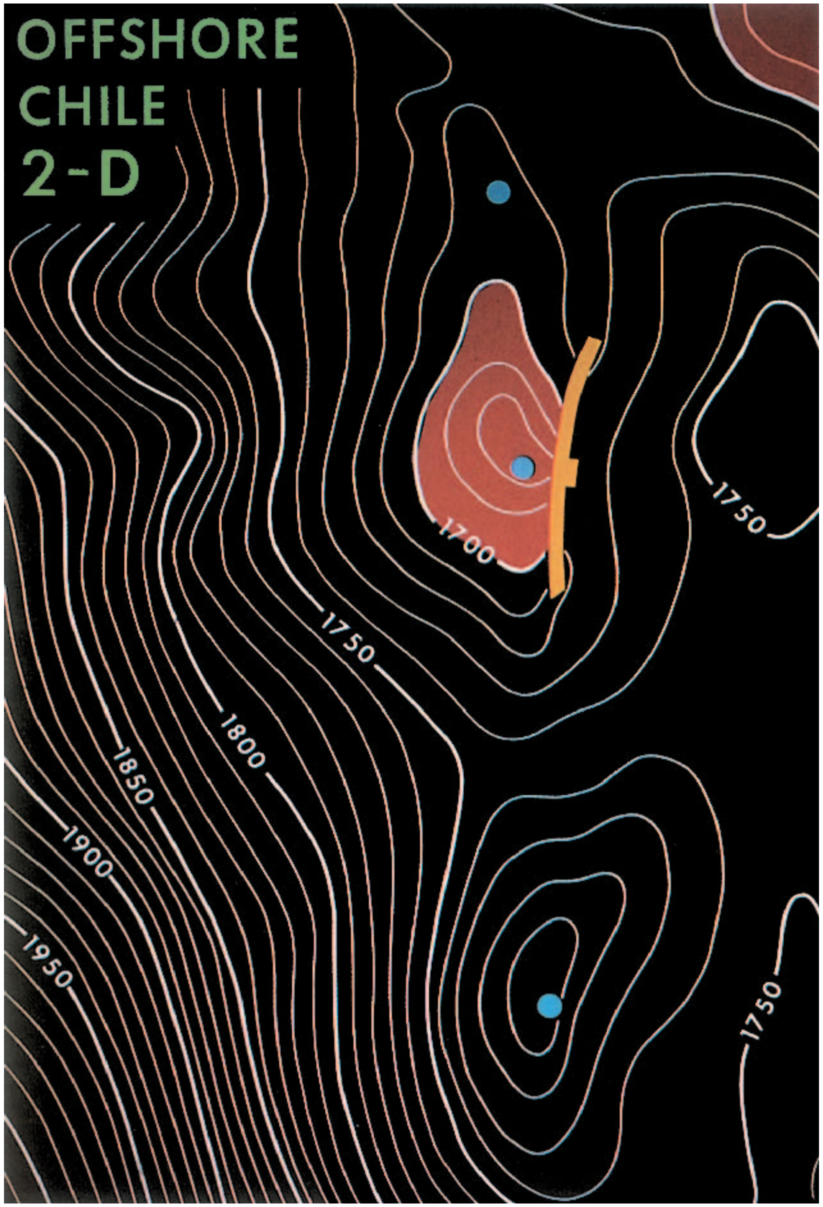
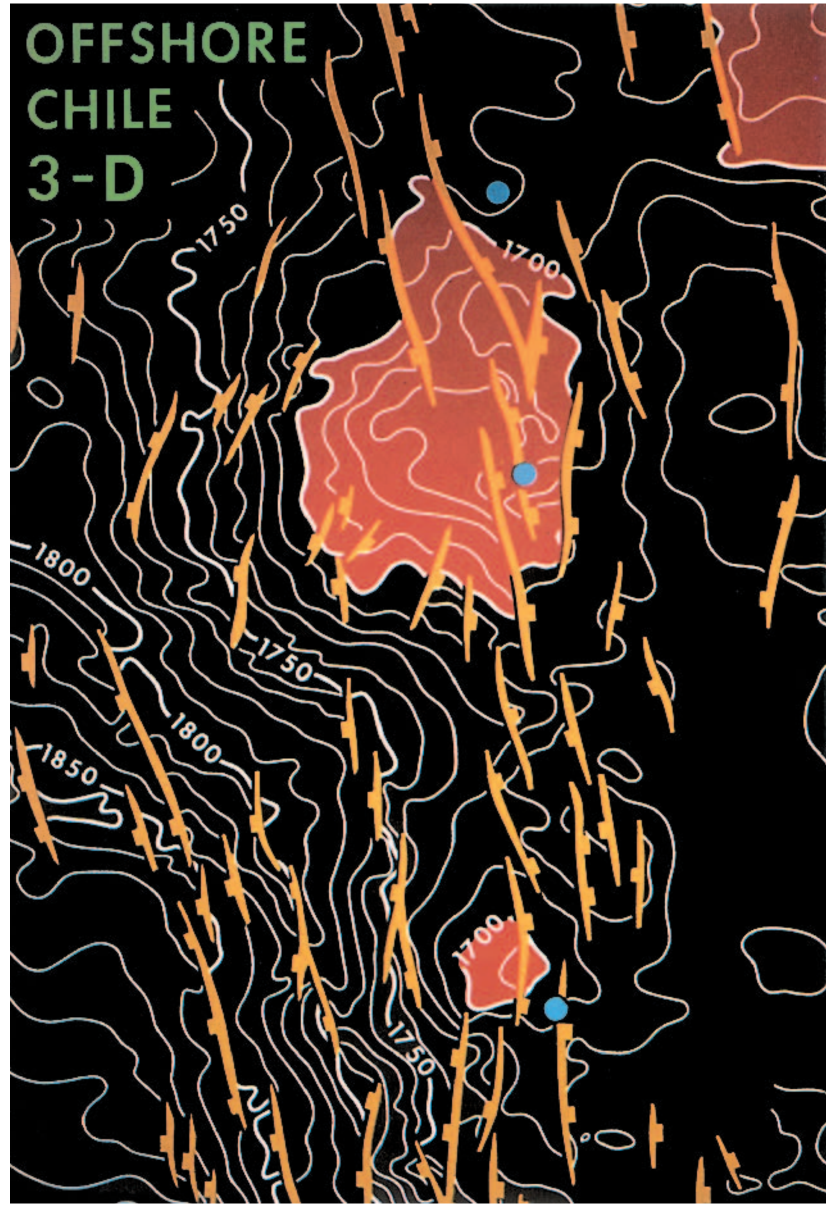


Fig. 3-11. Structural contour map derived from 3-D data from offshore Chile for the same horizon mapped in Figure 3-10. (Courtesy ENAP).



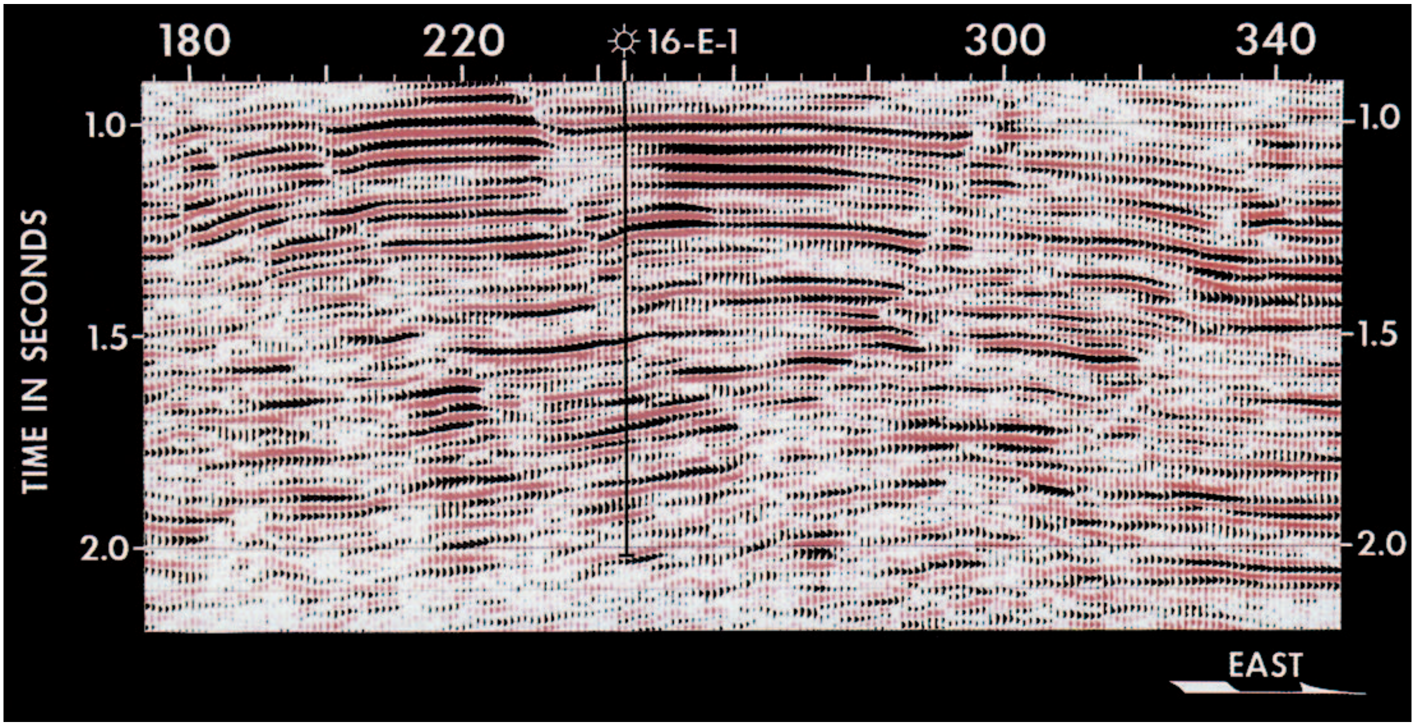


Fig. 3-12. Line 55 from Gulf of Thailand 3-D data. (Courtesy Texas Pacific Oil Company Inc.)

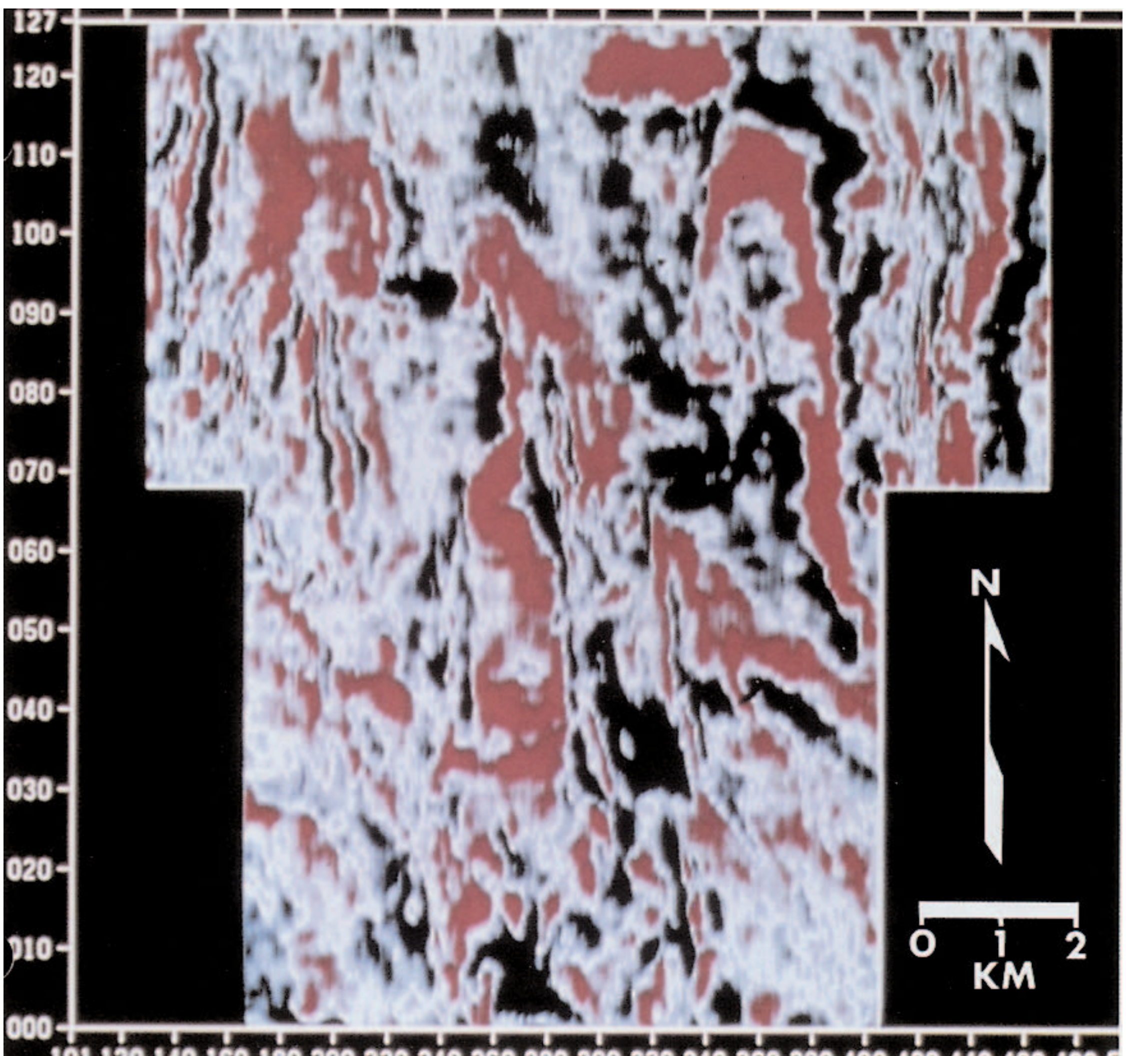
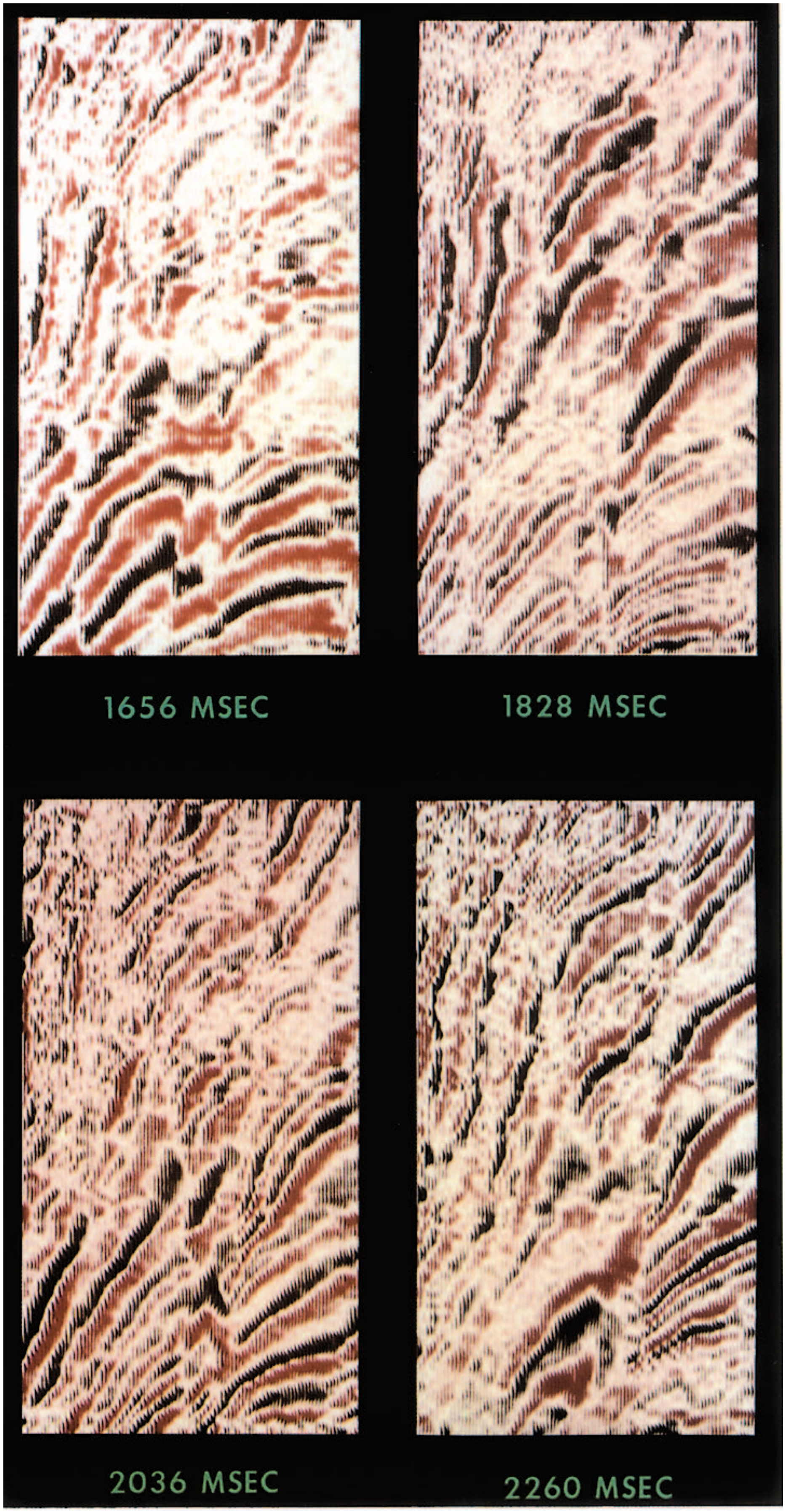


Fig. 3-13. Horizontal section at 1388 ms from Gulf of Thailand. (Courtesy Texas Pacific Oil Company.)

Fig. 3-14. Horizontal sections from offshore Trinidad. Event terminations indicate faulting. (Courtesy Texaco Trinidad Inc.)



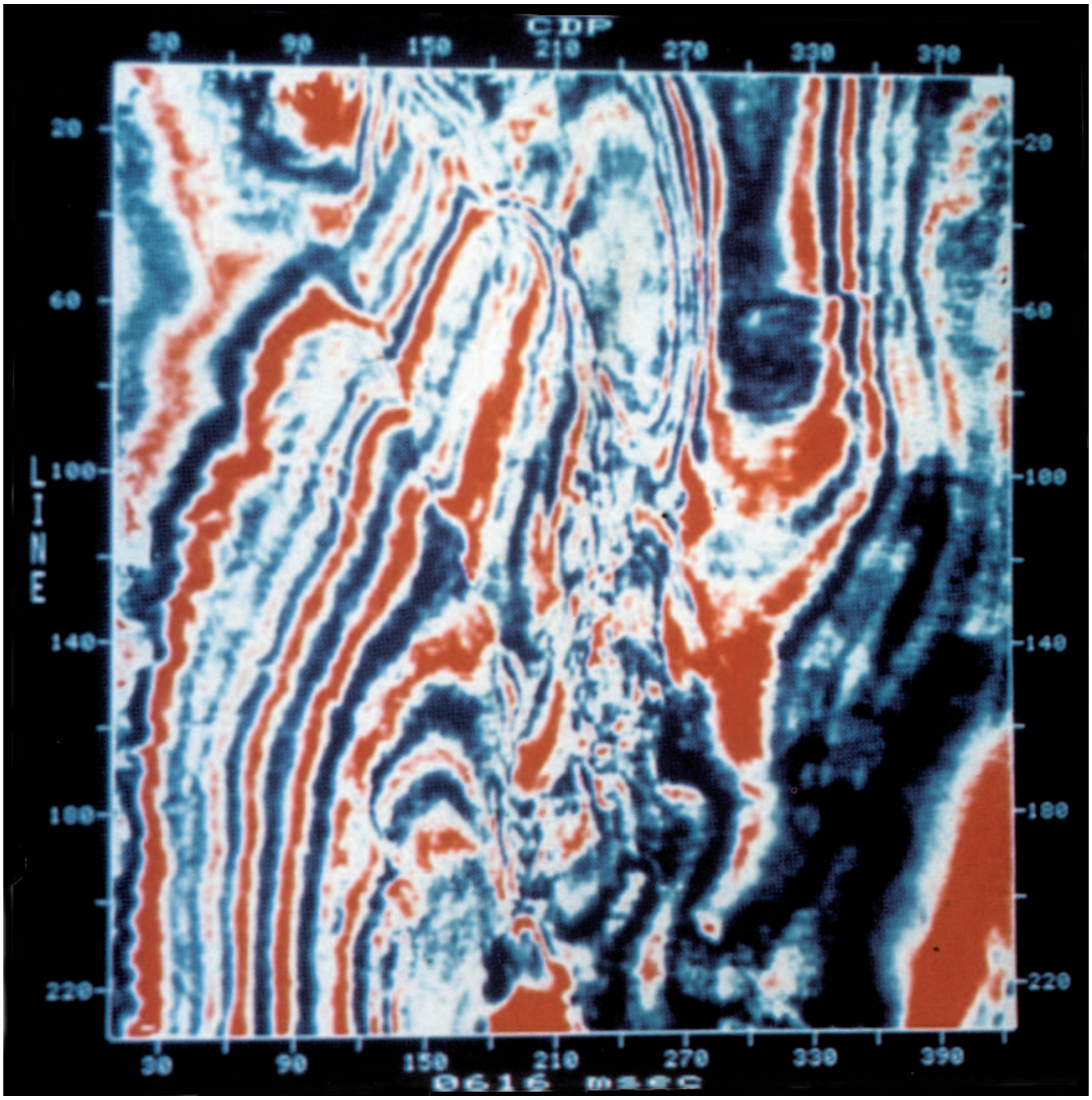


Fig. 3-15. Horizontal section from onshore Europe. Event terminations indicate faulting.

Fault Recognition and Mapping

When an interpreter works with 3-D data after having previously mapped from 2-D data over the same prospect, the most striking difference between maps is commonly the increased fault detail in the 3-D map. Figures 3-8 and 3-9 provide a typical comparison and also demonstrate increased detail in the shape of the structural contours. Comparison of Figures 3-10 and 3-11 also shows a considerable increase in the number of faults and in the structural detail. The three well locations indicated in blue appear structurally quite different on the 2-D and 3-D maps.

We expect to detect faults from alignments of event terminations. Figure 3-12 shows a vertical section from the 3-D data which provided the map of Figure 3-9. The event terminations clearly show several faults. The horizontal section of Figure 3-13 is from the same data volume and, in contrast, does not show clear event terminations. Figure 3-14 shows four horizontal sections from a different prospect but one in a similar tertiary clastic environment. Here event terminations clearly indicate the positions of three major faults on each of the four sections.

Why are event terminations visible at the faults in Figure 3-14 but not in Figure 3-13? The answer lies simply in the relationship between structural strike and fault strike. Any horizontal section alignment indicates the strike of the feature. If there is a significant angle between structural strike and fault strike, the events will terminate.

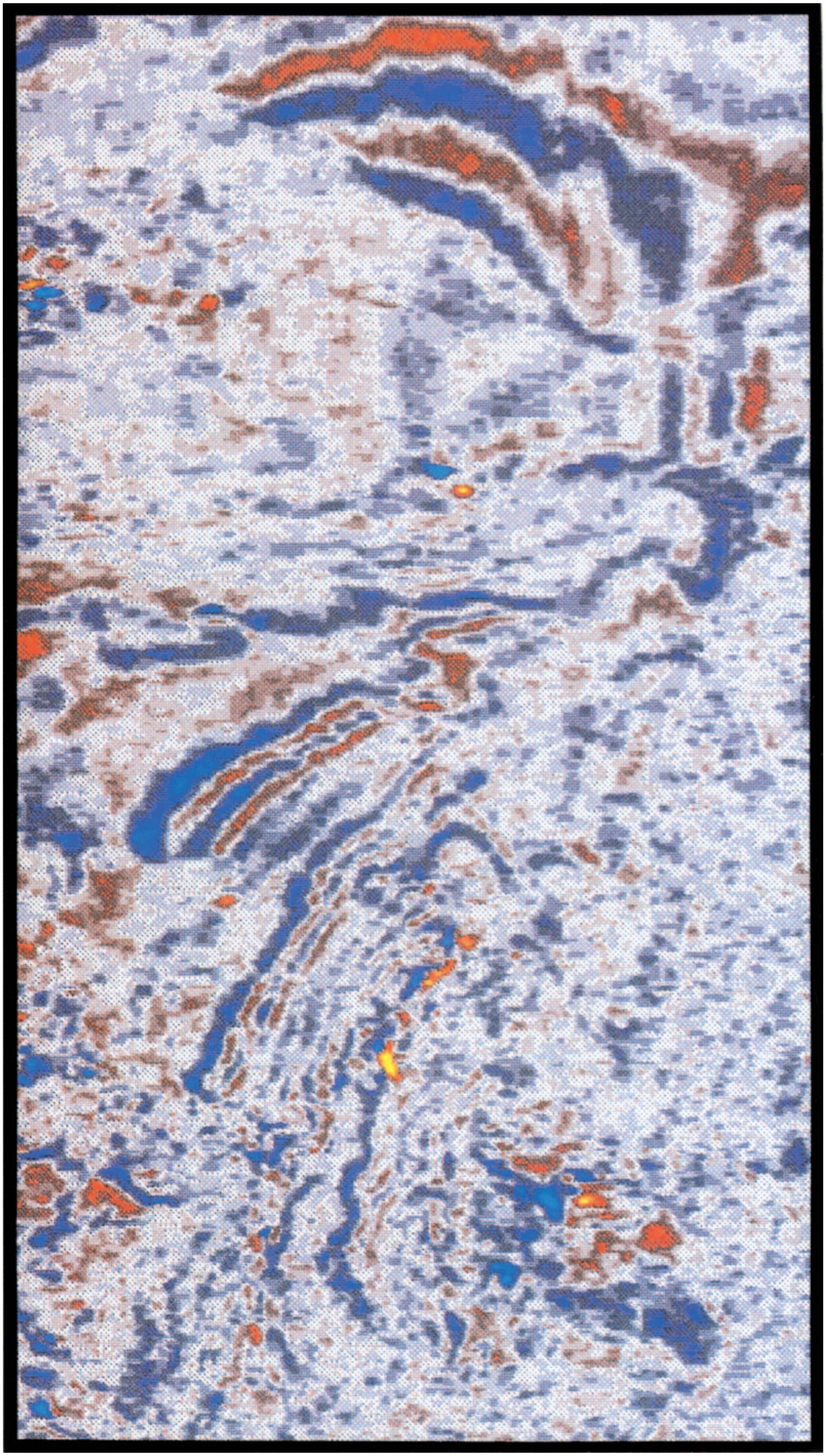


Fig. 3-16. Horizontal section at 1500 ms from Gulf of Mexico showing many clearly visible faults. At least 10 are identifiable. (Courtesy Conoco Inc. and Texaco U.S.A. Inc.)

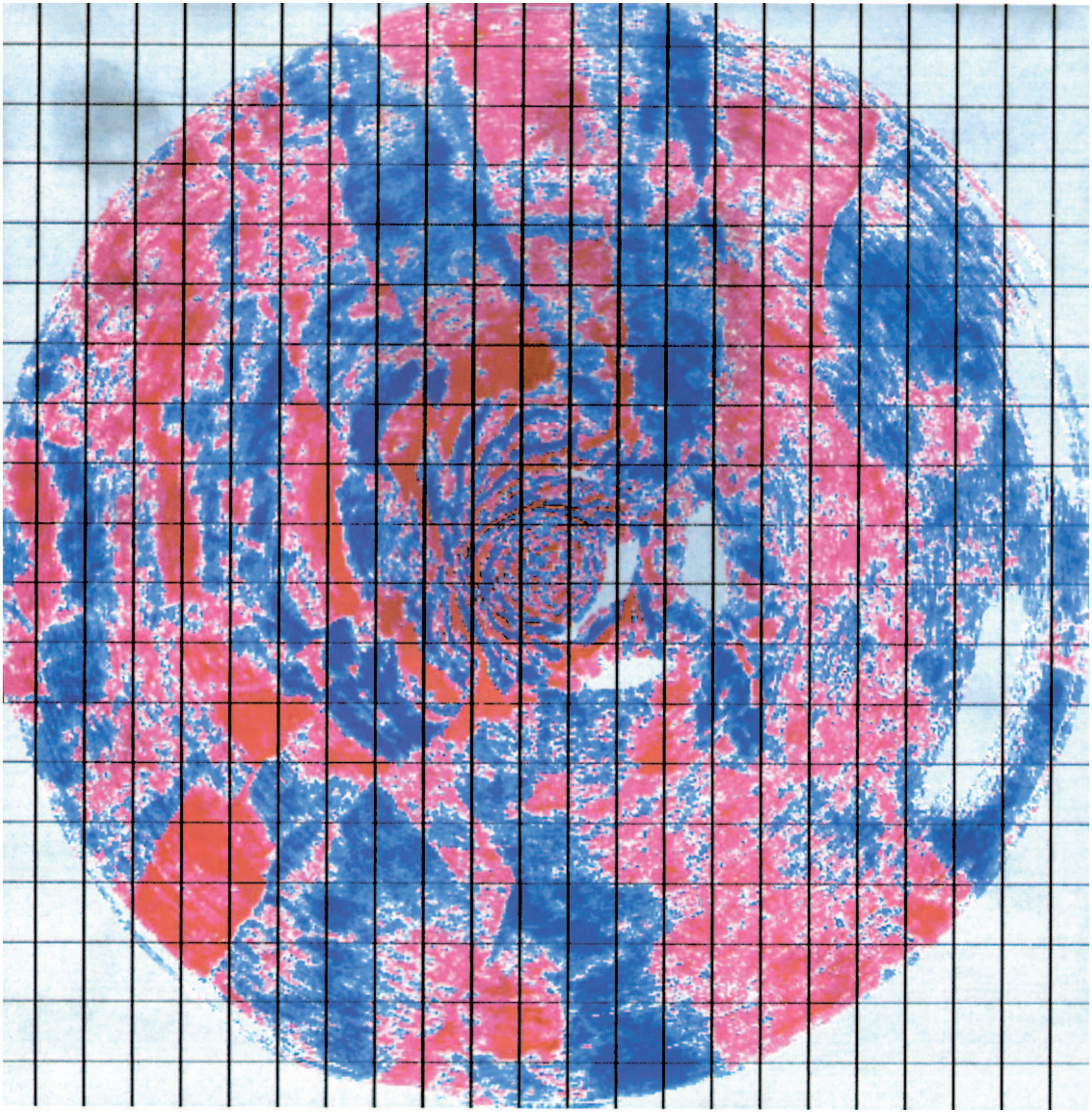


Fig. 3-17. Horizontal section at 1000 ms from Gulf of Mexico Concentric Circle Shoot showing many radial faults surrounding a salt dome. (Courtesy Tensor Geophysical Service Corporation.)

If structural strike and fault strike are parallel, or almost so, the events will not terminate but will parallel the faults. Comparison of Figures 3-13 and 3-9 demonstrates that situation. The difficulty of seeing faults on a time slice when they parallel structural strike is overcome by using the attribute coherence (see Chapter 8).

Because an alignment of event terminations on a horizontal section indicates the strike of a fault, the picking of a fault on a horizontal section provides a contour on the fault plane. Thus picking a fault on a succession of suitably spaced horizontal sections constitutes an easy approach to fault plane mapping. The faults evident in Figure 3-14 have been mapped in this way.

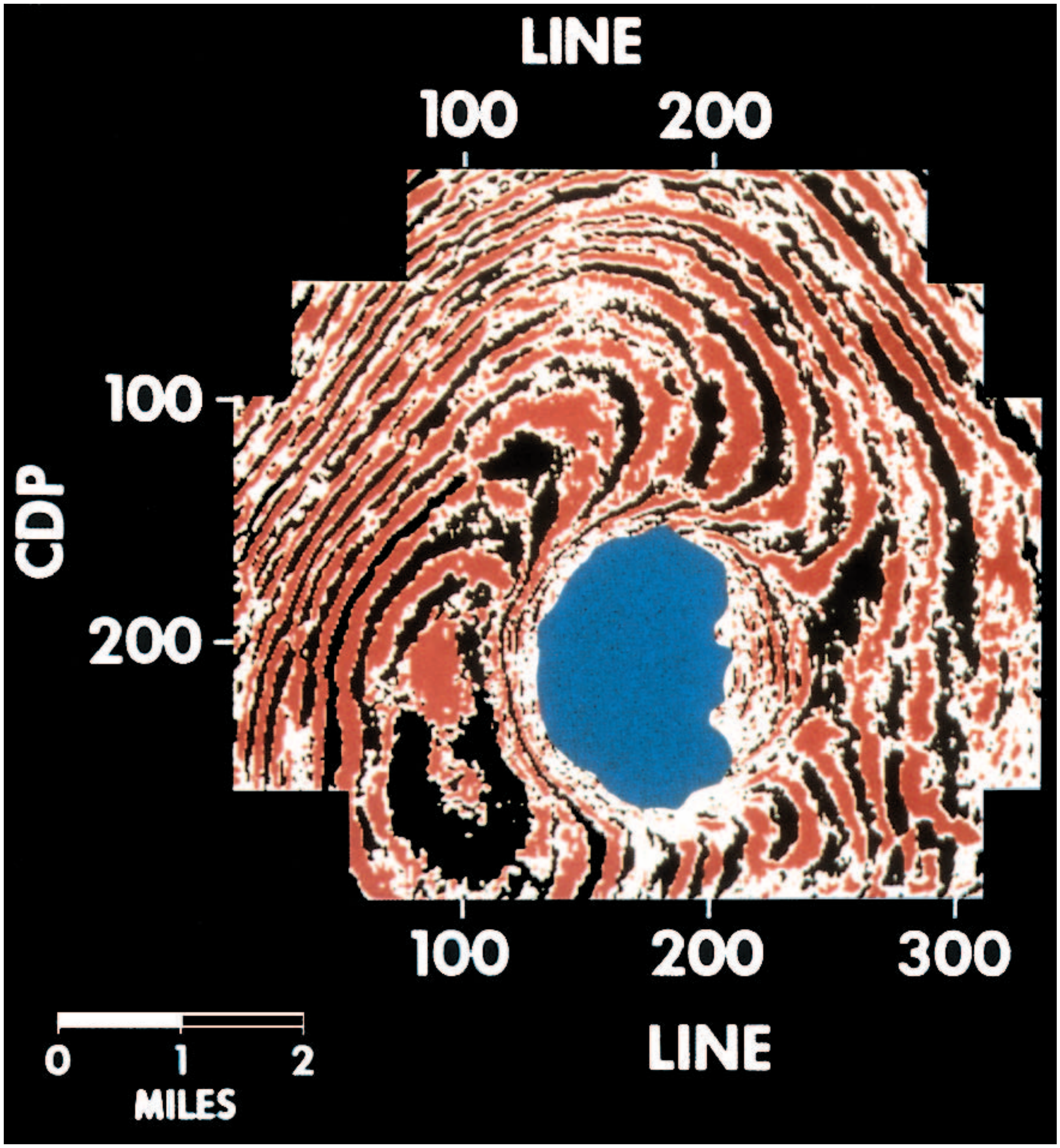


Fig. 3-18. Horizontal section at 3252 ms from Eugene Island area of Gulf of Mexico showing interpreted shape of salt plug. (Courtesy Hunt Oil Company.)

In the lower right corner of the horizontal section at 2260 ms (Figure 3-14) two fault blocks show events of quite different widths. This is the effect of dip which was explained by Figure 3-7. We also see a similar effect of dip in Figure 3-13 where the faults are mostly traced by narrow sinuous events striking approximately north-south.

Figure 3-15 shows a variety of structural features: prominent faults, more subtle faults, culminations, and various character changes. It is very important that horizontal sections play their proper role in fault interpretation. In the early stages of structural interpretation of a prospect, the major faults will be identified on some widely-spaced vertical sections. The way in which these faults join up into a fault framework should then be established from horizontal sections. This is part of the overall recommended procedure of Figure 3-32. Lineations of event terminations will normally link the faults already recognized vertically. Figures 3-16 and 3-17 show clearly visible faulting that evidently could be used in this way.

Today's interactive workstations help in the coordinated use of vertical and horizontal sections by providing the capability of cross-posting. When a fault is picked on a vertical section, its intersection will appear on an intersecting horizontal section.

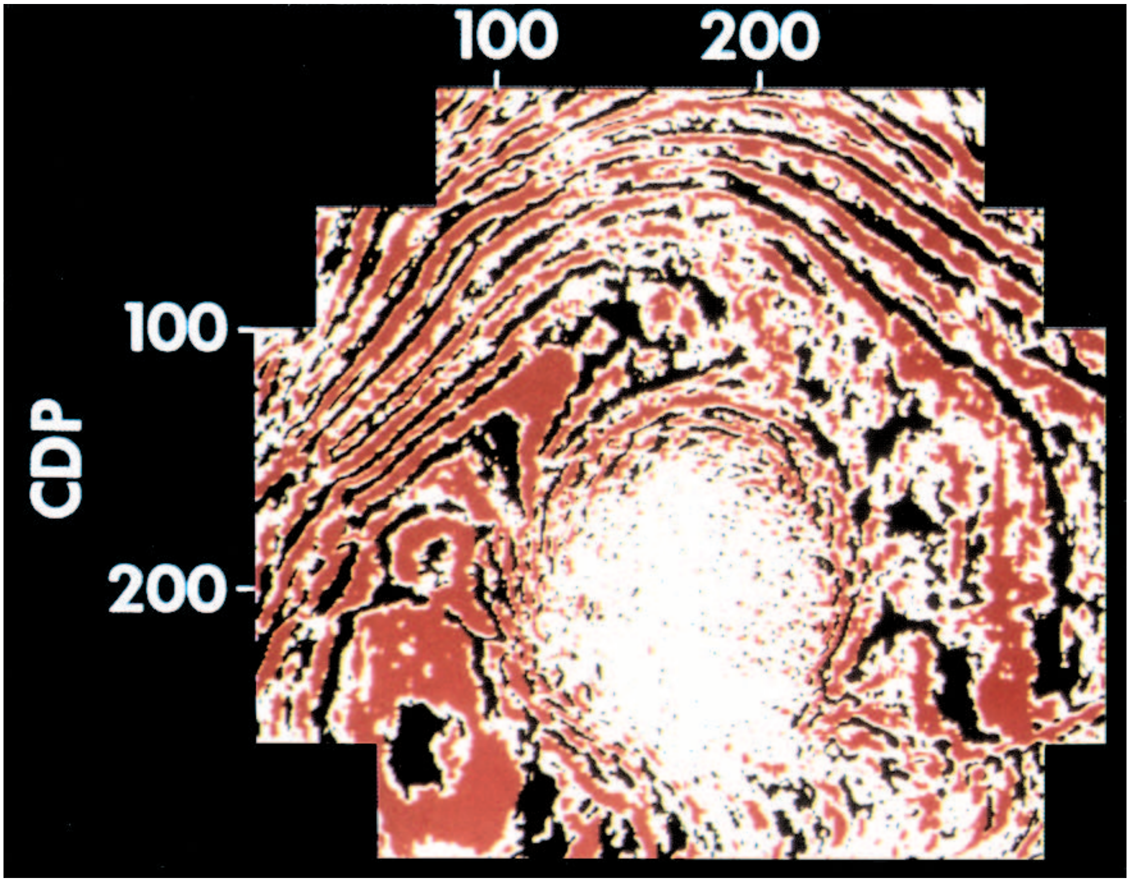


Fig. 3-19. Horizontal section at 3760 ms from Eugene Island area of Gulf of Mexico. (Courtesy Hunt Oil Company.)

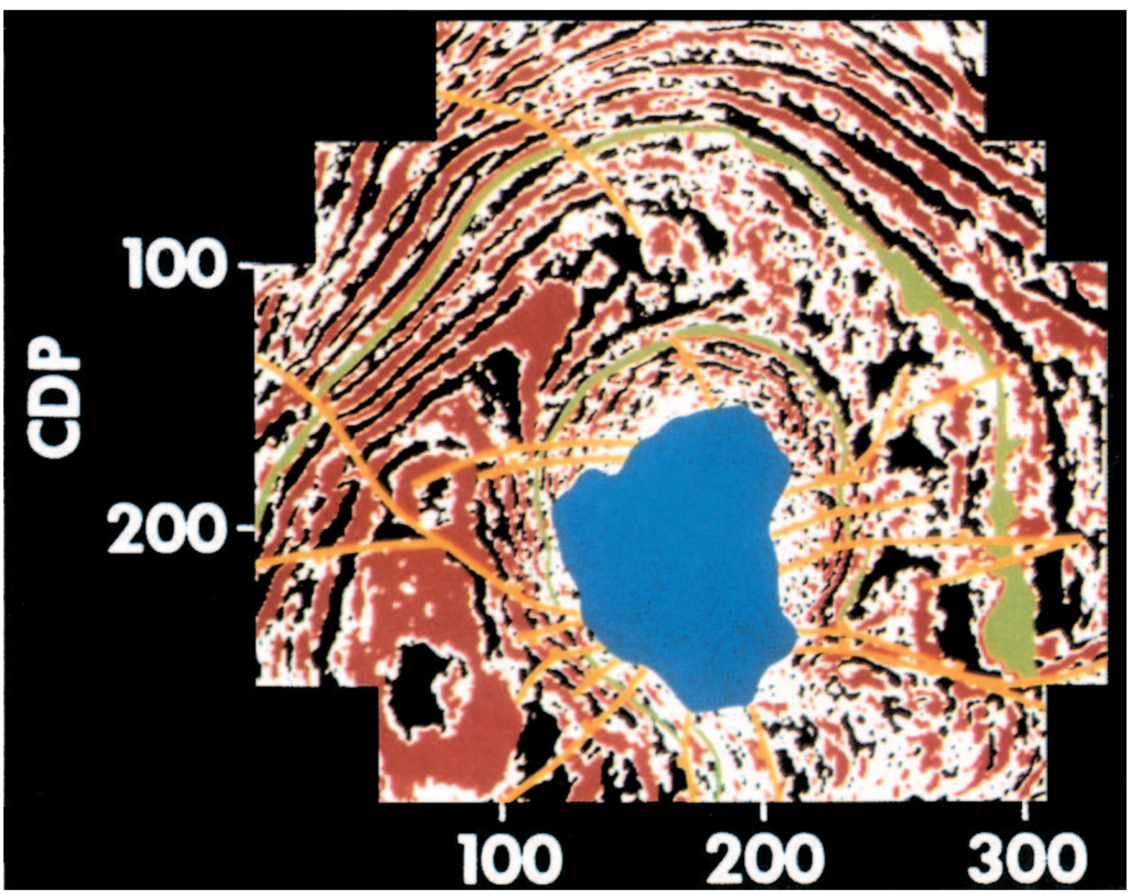
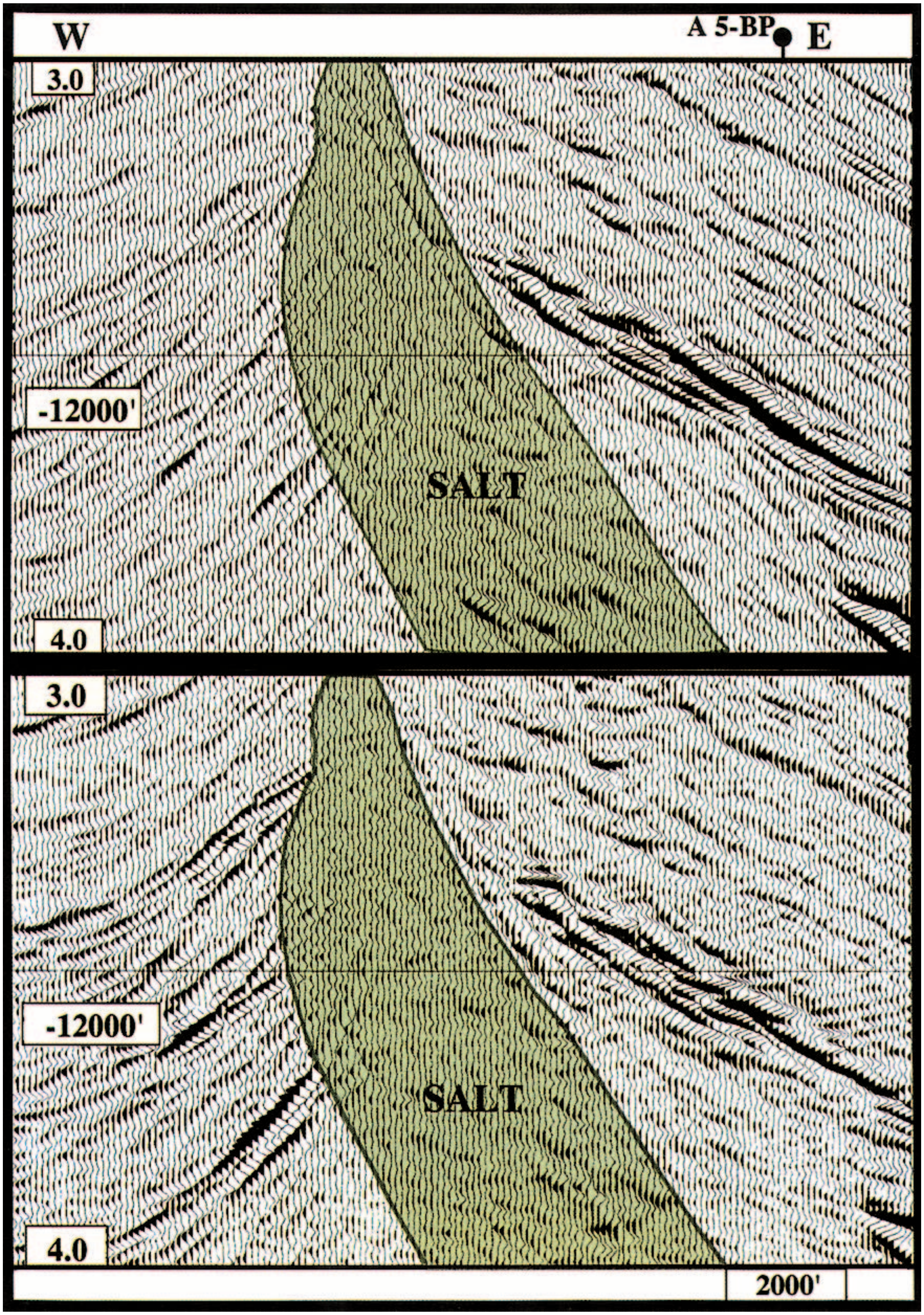


Fig. 3-20. Same horizontal section as Figure 3-19 with interpretation of faults and the green horizon. (Courtesy Hunt Oil Company.)

Fig. 3-21. Line 556 from the E-W survey at Bullwinkle (upper section). This line is extracted along the inline direction of this survey, hence the shooting direction is dip to the salt/sediment contact. Line 556 from the N-S survey at Bullwinkle (lower section). This line is extracted from the crossline direction of this survey. The shooting direction is perpendicular to the plane of the section and therefore strike to the salt/sediment contact. Note the improved sediment image along the western side of the overhung salt. This is attributed to less salt-related ray path distortion. (Courtesy Shell Oil Company.)



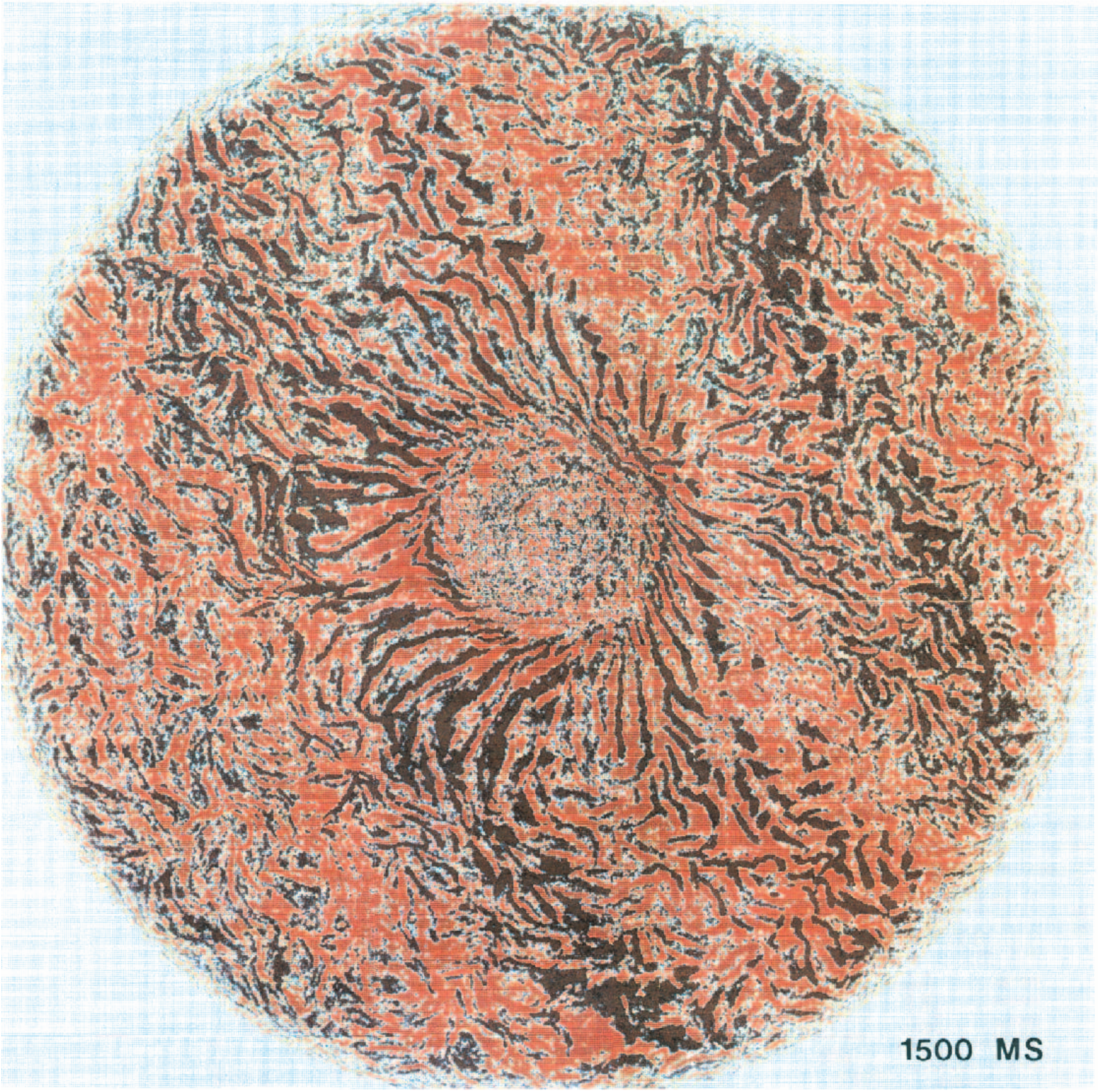


Fig. 3-22. Time slice 1500 ms from a circular 3-D survey in the North Sea. The shattered appearance results from the shattering of a thin limestone. (Courtesy Mobil North Sea Limited.)

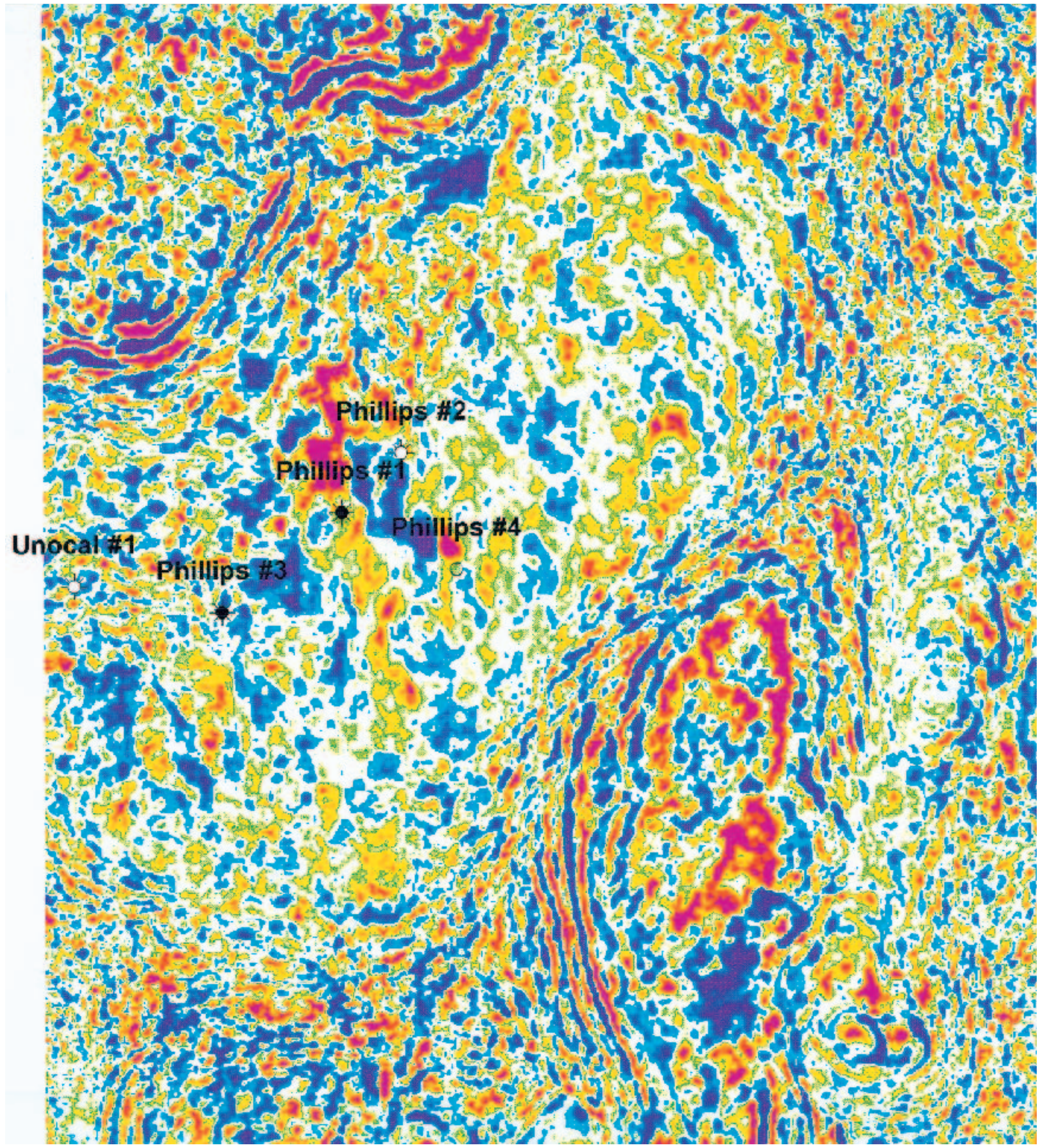


Fig. 3-23. Depth slice 4530 meters from 3-D pre-stack depth migrated data volume covering the Gulf of Mexico Mahogany prospect. (Courtesy Diamond Geophysical Service Corporation.)

When faults have been picked on several vertical and horizontal sections, the faults can be displayed as surfaces to check their geological validity.

Interpretation in the Vicinity of Salt

The horizontal section of Figure 3-18 shows a rim syncline surrounding a salt diapir. The narrow events around the salt indicate the steep dips near the intrusion. Figures 3-19 and 3-20 show a deeper horizontal section from the same volume without and with interpretation. The horizon of interest, marked in green on Figure 3-20, is intersected twice, once on either side of the rim syncline. The faulting at this level, marked in yellow, is complex but can be seen fairly well on this one horizontal section. From pre-existing 2-D data in the area only one of these faults had been identified (Blake, Jennings, Curtis, Phillipson, 1982).

Interpretation of seismic reflection terminations against salt is a very important matter because many hydrocarbon traps are found in this structural position. Numerous data collection and processing developments have been aimed at this problem

(French, 1990). For example, full one-pass 3-D migration is considered preferable to the more traditional two-pass approach.

Case History 11 in Chapter 9 discusses the importance of precise definition of the salt/sediment interface and shows success in doing so. Figure 3-21 also addresses this issue and demonstrates that, by collecting the data in a direction strike to the salt/sediment interface, the definition of reflections terminating at the salt is significantly improved.

Figure 3-22 shows time slice 1500 ms from a circular 3-D survey in the North Sea. In the center a salt diapir is visible. Collecting data in circles around a circular salt body means that the collection direction is consistently strike to the salt/sediment interface. The myriad of short arcuate features on Figure 3-22 show the effects of shattering of a thin limestone layer encased in shale.

Depth migration and pre-stack depth migration in 3-D have recently become economically feasible and have been used extensively for imaging under salt (Appendix A). It is the abrupt large velocity contrasts that make this more elaborate migration necessary. After such processing the whole data volume is in depth and thus horizontal sections become **depth slices**. Figure 3-23 shows a depth slice under the Mahogany salt sill in the Gulf of Mexico and the successful wells.

Composite Displays

The interpreter of 3-D data is not restricted to single slice displays. Because the work is done with a data volume, composite displays can be helpful in appreciating three-dimensionality and also in concentrating attention on the precise pieces of data that provide insight into the problem at hand.

Figure 3-24 is a composite of horizontal and vertical sections spliced together along their line of intersection. The vertical section shows that the circular structure is a syncline. The horizontal section pinpoints the position of its lowest point. The fault on the left of this structure can be followed across the horizontal section. Figure 3-25 provides a different view of the structure. The same horizontal section is here spliced to the portion of the vertical section above in the volume.

It is possible to make cube displays showing, simultaneously, three orthogonal slices through the volume (Figures 1-14 and 1-15, and 3-26). These can certainly aid in the appreciation of three-dimensionality but have limited application in the mainstream of the interpretation process, because two of the faces of any cube displayed on a monitor or piece of paper will always be distorted. An adaptation of the cube display concept is presented in Figure 3-27 and is known as the **chair**; it is really just the cube with a vertical section added above the horizontal section at the back. On Figure 3-27 the three-dimensional shape of a growth fault can be followed easily.

Figure 3-28 is a different kind of chair display. It is less dramatic than the chair of Figure 3-27 but probably more useful because none of the sections are distorted. The fault on the left can be followed clearly across the horizontal section indicating that the fault visible on line 75 (top, Figure 3-28) is the same as seen on line 110 (bottom, Figure 3-28). The other faults have a distinctly different azimuth and also traverse a shorter distance.

Figures 3-29 and 3-30 illustrate the study of a trio of normal faults. In Figure 3-29 one horizon has been tracked indicating the interpreted correlation across the faults. At the bottom of this figure a portion of the data from each of the four fault blocks is enlarged and again carries the interpreted track. Each block has been adjusted vertically to bring the track segments into continuity so that the correlation between these blocks of data can be assessed easily. Note how this display accentuates the apparent growth on the center fault of the three. In Figure 3-30 the composite horizontal and vertical section display permits the study of the horizontal extension of each of these three faults. A display customized to a problem usually helps significantly in the solution of that problem.

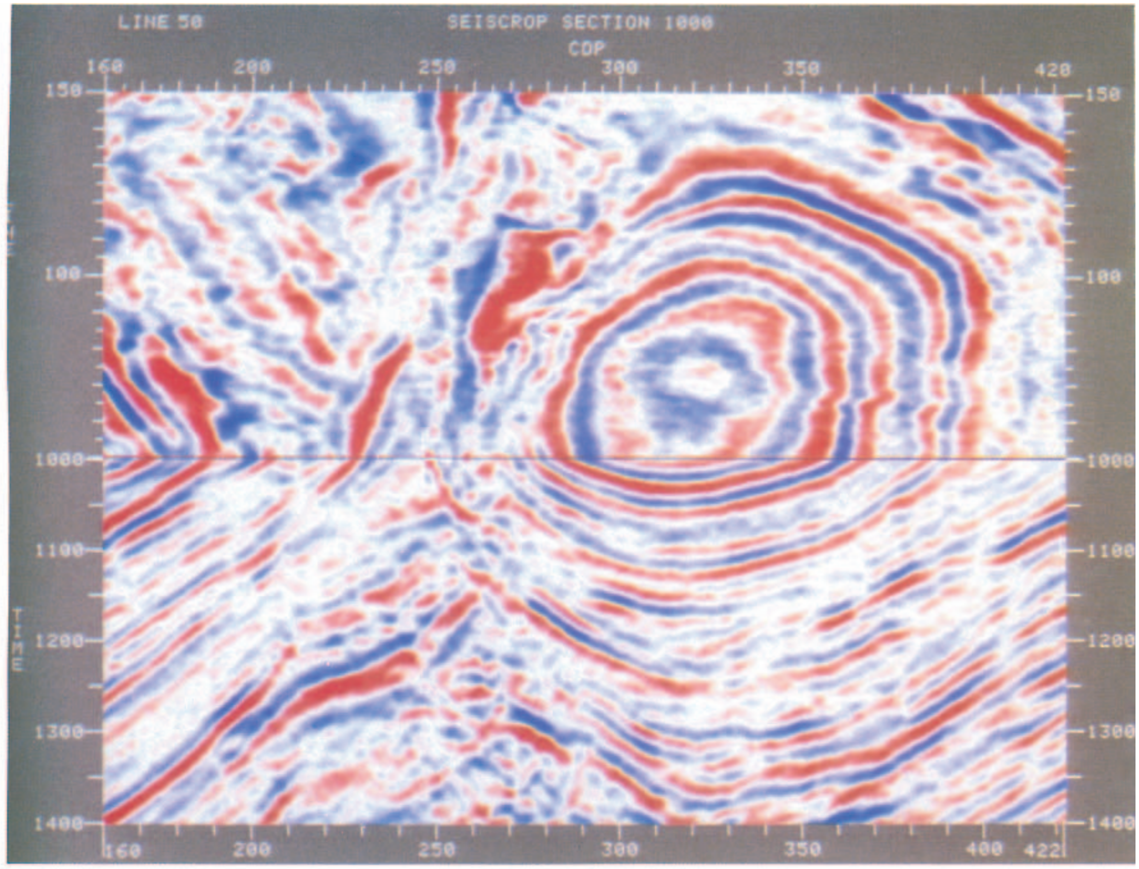


Fig. 3-24. Composite display of horizontal and vertical sections from onshore Europe. Vertical section segment lies beneath horizontal section.

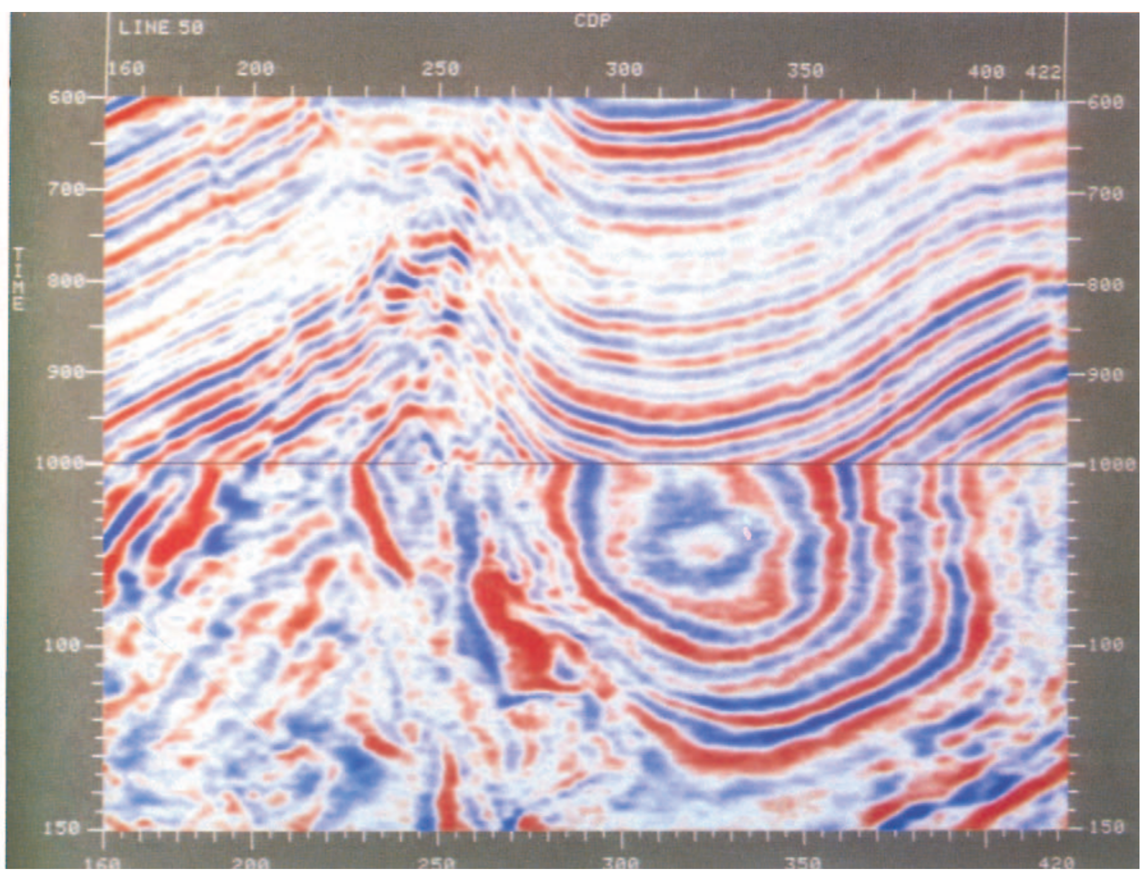


Fig. 3-25. Composite display of horizontal and vertical sections from onshore Europe. Vertical section segment lies above horizontal section.

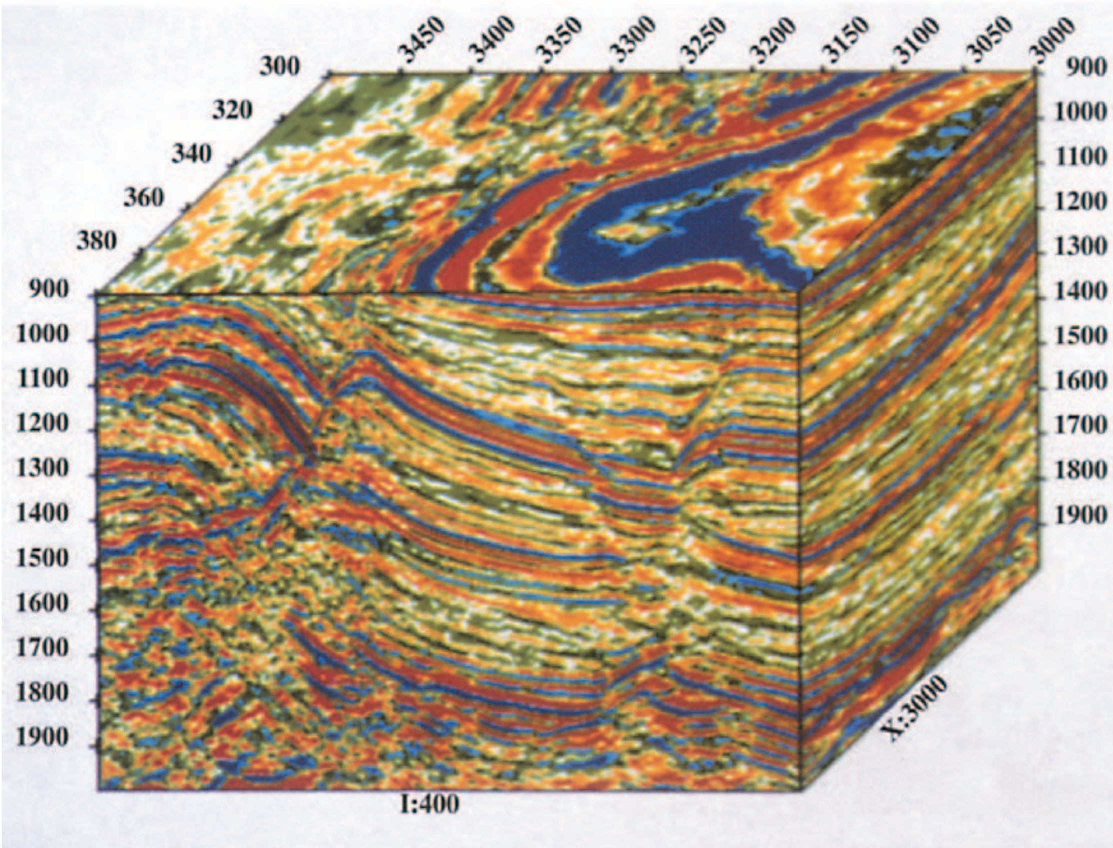


Fig. 3-26. Cube display made of two orthogonal vertical sections and one horizontal section. (Courtesy Western Atlas International.)

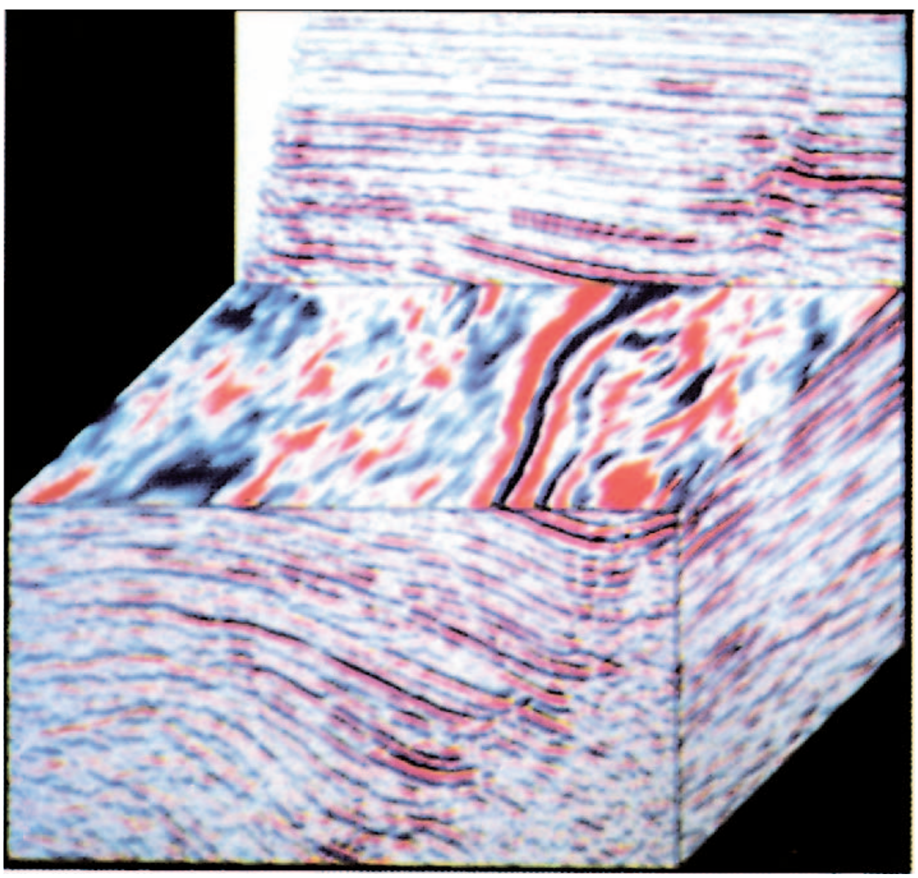


Fig. 3-27. Chair display of Gulf of Mexico data made of two lines, one crossline and one horizontal section. (Courtesy Geophysical Service Inc.)

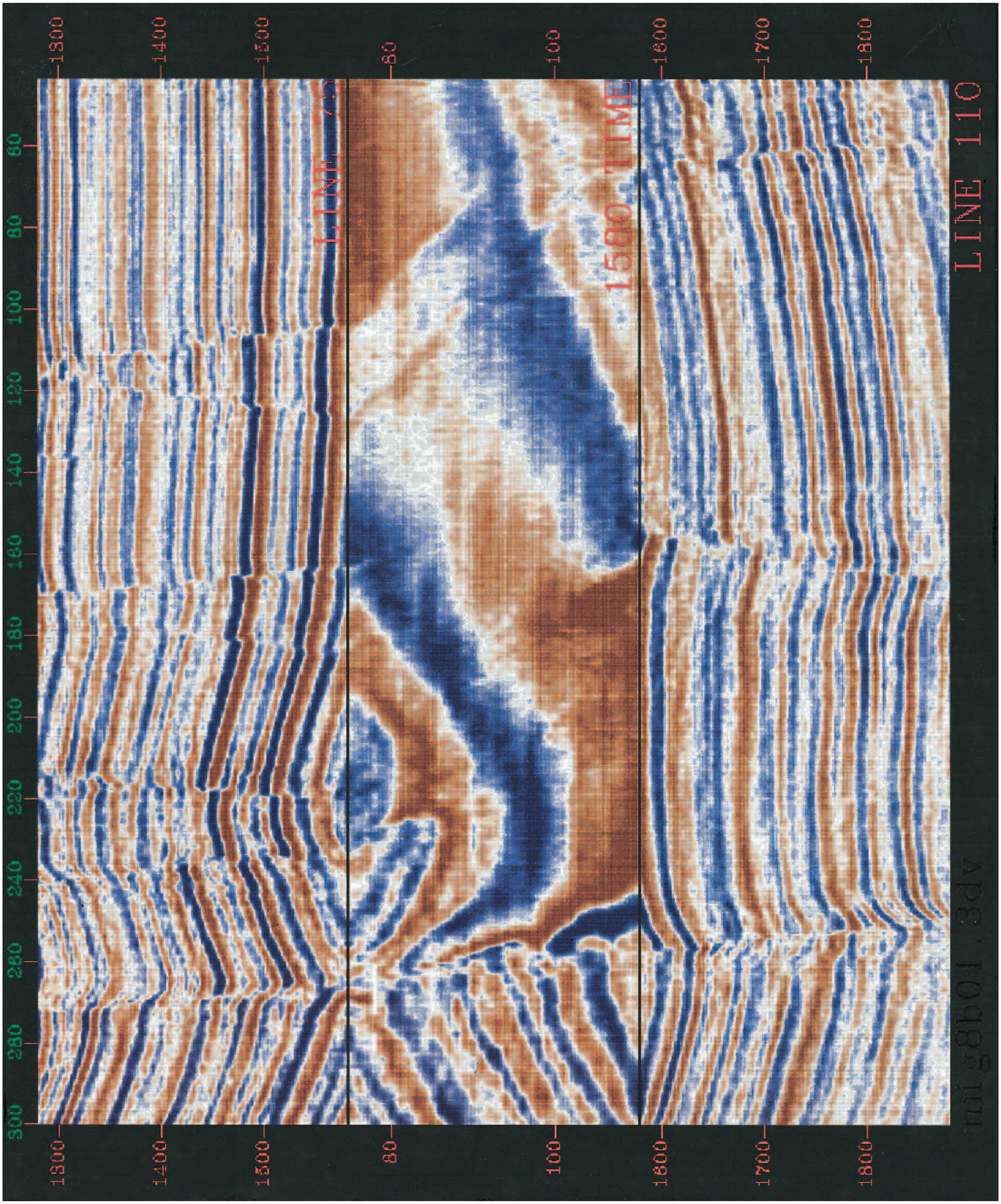


Fig. 3-28. Chair display made of two vertical sections and one horizontal section. Compare this with Figure 3-27 and note that here all the three sections are undistorted. (Courtesy Landmark Graphics Corporation.)

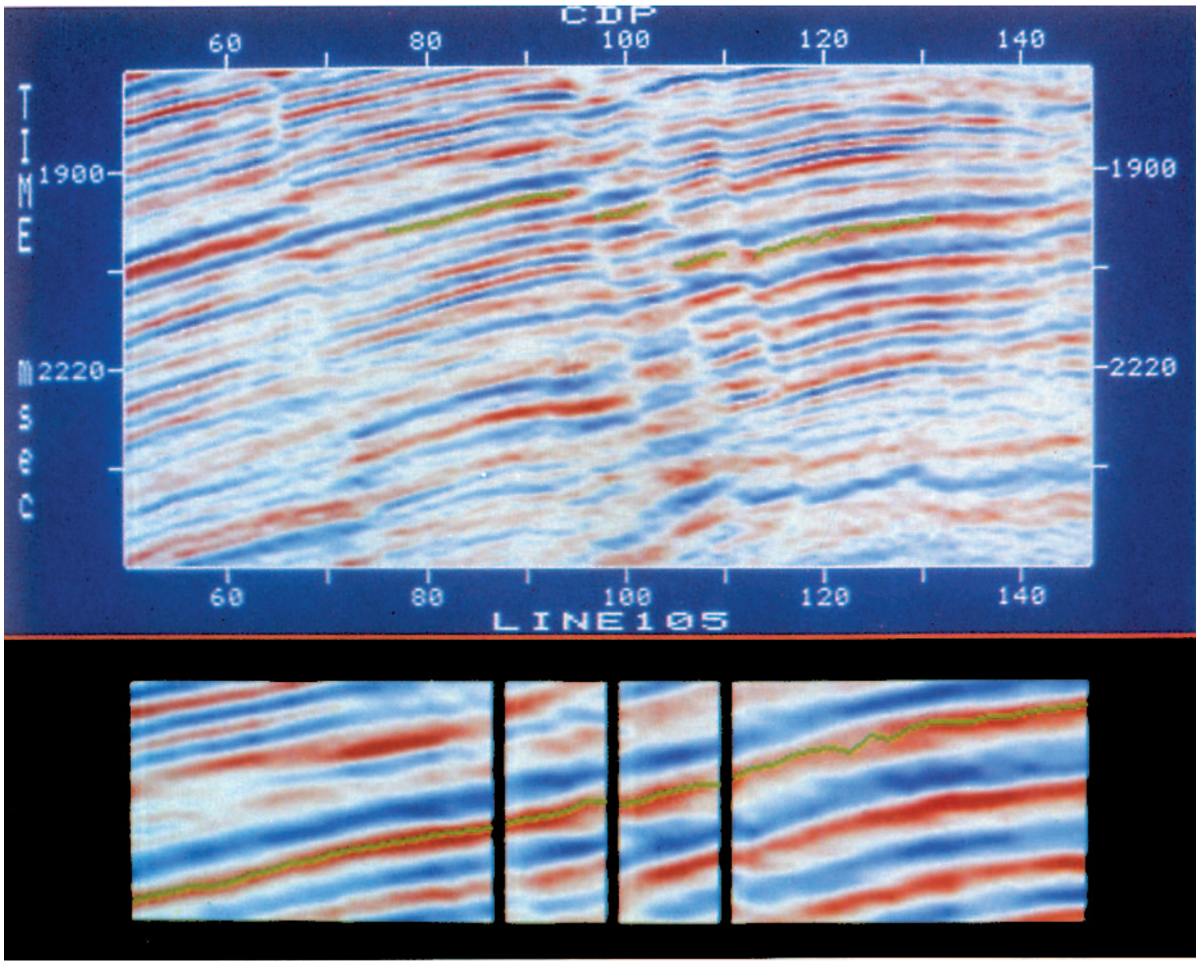


Fig. 3-29. Vertical section and magnified portions thereof designed to study fault correlations offshore Trinidad. (Courtesy Texaco Trinidad Inc.)

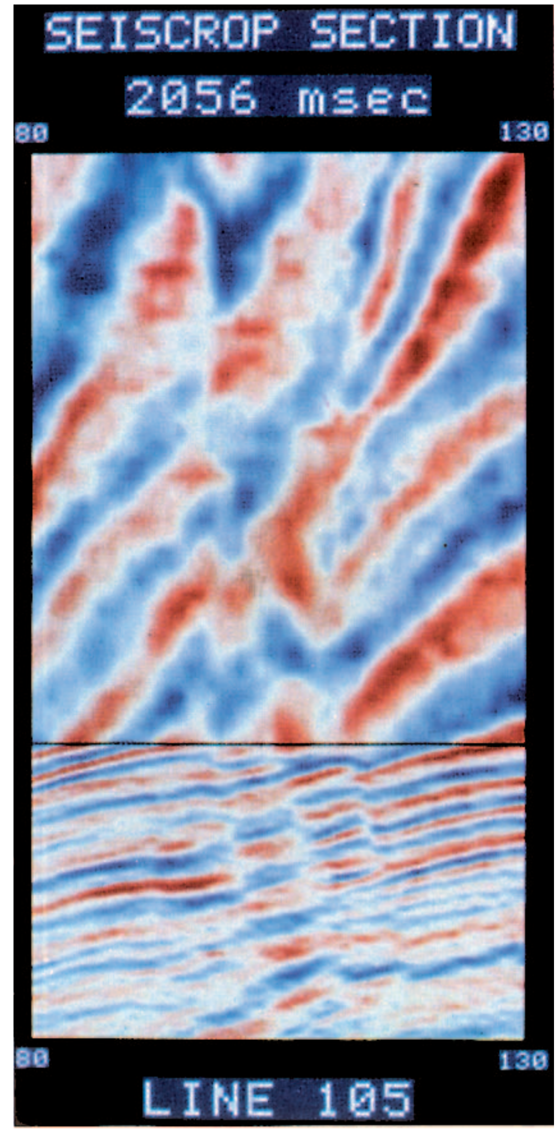


Fig. 3-30. Composite display of horizontal and vertical sections from offshore Trinidad showing horizontal extent of faults studied in Figure 3-28. (Courtesy Texaco Trinidad Inc.)

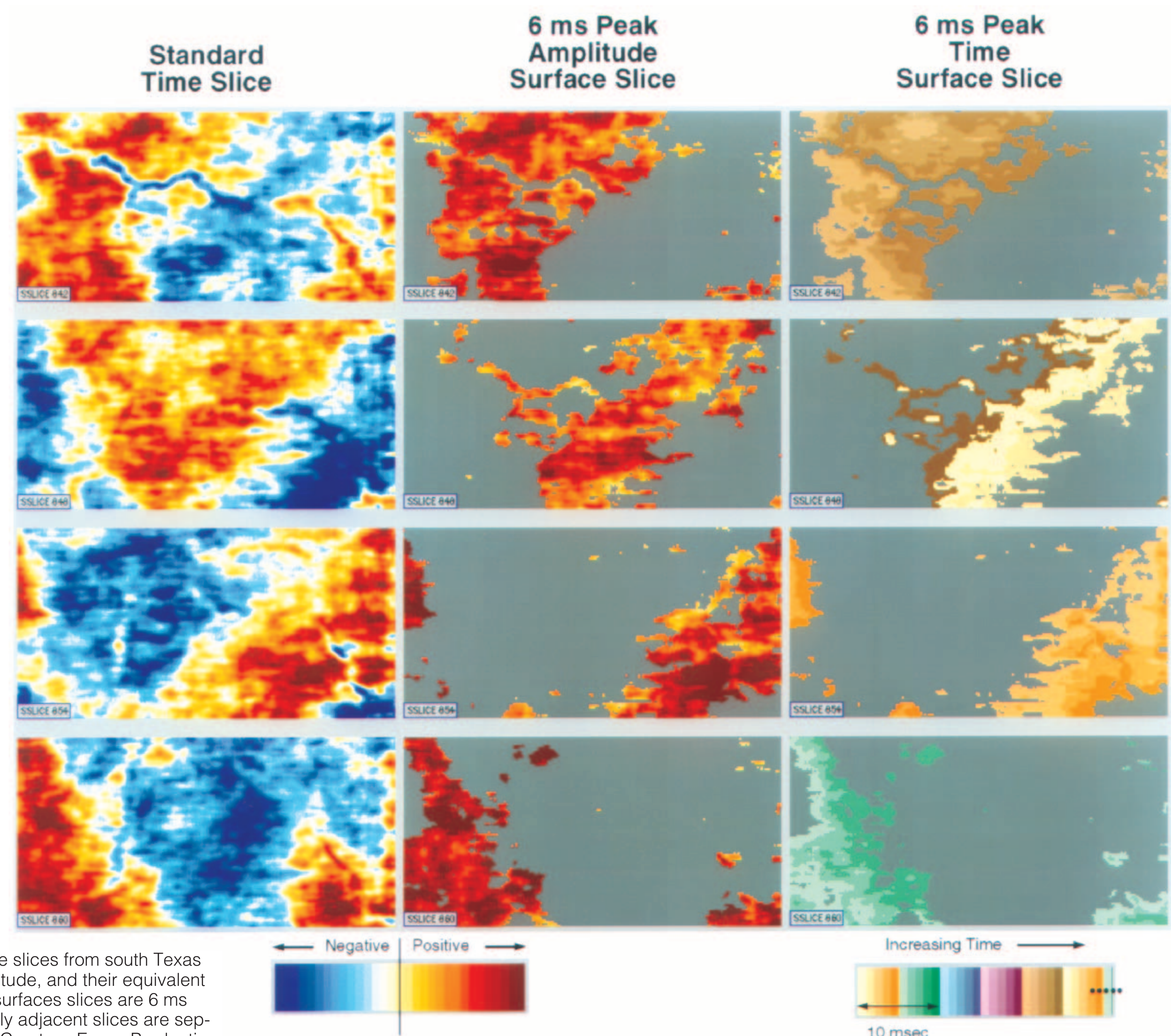


Fig. 3-31. Surface slices from south Texas in time and amplitude, and their equivalent time slices. The surfaces slices are 6 ms thick and vertically adjacent slices are separated by 6 ms. (Courtesy Exxon Production Research Company.)

Interpretation Procedures

The interpreter of 3-D data has a real opportunity to generate more accurate subsurface time and depth structure maps but to do so a large amount of data must be studied. Furthermore *all* the data must be used to ensure proper information extraction. Thus the interactive workstation is an essential data management tool.

We will first discuss the interpretation procedure used with the Seiscrop Interpretation Table. Although this device is used rarely if at all today, it teaches an important component of 3-D structural interpretation — the use of the horizontal section. In the late 1970s and early 1980s, interpreters concentrated too much on horizontal sections through the use of the Seiscrop Interpretation Table. Today, most interpreters concentrate too much on vertical sections, because vertical sections can be manipulated and tracked easily on interactive workstations and because the interpreters' previous experience makes them prefer that perspective.

Initially the interpreter will pick faults and make a preliminary interpretation on a selected set of vertical sections in the line and crossline directions, for example on a one kilometer grid. This will provide the approximate extent of the first fault block in which mapping will begin. Normally the interpreter will identify the horizon to be followed at a well. Using the selected set of vertical sections the approximate fault locations are marked on the base map on the screen of the table. The event to be mapped is then identified on one horizontal section and followed up and down within the first fault block, drawing contours from the horizontal sections at the desired interval. The faults surrounding the first fault block are marked in detail at the same time. Several iterations through the sections covering the structural relief of the horizon in this first fault block may be necessary before the interpreter is satisfied with the contours drawn. Selected vertical sections are revisited to establish the correlation into the next fault block and the procedure then repeats in that fault block. The interpreter thus works from fault block to fault block until the prospect is covered; alternatively the same horizon may be carried in two or more blocks at the same time. When the interpreter encounters a problem in understanding the data at a particular location, reference to vertical sections through that point in line, crossline, and other directions is made. Arbitrary lines may be specially extracted from the data volume for the purpose. Once the problem is resolved, the interpreter should be able to return to the horizontal sections to continue contouring.

This experience with time slices (horizontal sections) underlines the value of the strike perspective discussed earlier. Continuing experience in 3-D interpretation consultation has taught the author that proper use of time slices is one of the most difficult but important hurdles for everyone wishing to master the technology. Not only do time slices provide an essential view of the data which reveals various subtle features, they also add significant efficiency to the total project. Most interpretation procedures today involve use of automatic spatial tracking to ensure that all the data is used and that high precision is obtained. The autotracker needs control or seed points and horizontal sections should be used along with vertical sections for this purpose. Once some vertical sections have been examined to establish general structural relationships, spatial continuity should be followed on appropriate time slices. These directly drawn structural contours then give the autotracker plenty of seed points to tie it down. A successful way of building time slices into the interpretation procedure is to use composite displays such as Figures 3-24 and 3-25 or chair displays such as Figure 3-28. In this way the relationship between horizontal and vertical section is apparent.

Another way of incorporating the efficiency of the strike view into interpretation procedures is to use **surface slices** (Stark, 1996). A surface slice displays either time or amplitude of one chosen point on the seismic waveform, for example the crest of a peak, over a defined time interval (typically three samples). A surface slice can thus, in a sense, be regarded as a thick time slice. However, the surface slice displays one data phase only over that thickness, in contrast to the time slice which shows all seismic phases at one unique time. A surface slice thus has no frequency dependence and

Fig. 3-32. Recommended interactive 3-D interpretation procedure.

RECOMMENDED PROCEDURE

1. Preview of data on composite displays and movies.
2. Horizon identification at wells.
   Assessment of data phase and polarity.
3. Recognition of major faults on widely-spaced vertical sections.
4. Fault framework by tying together with horizontal sections.
5. Initial horizon control using vertical and horizontal sections.
   Horizontal sections provide efficiency of coverage.
6. Automatic spatial tracking to complete horizon on every point.
   Autotracking provides precision picking.
   Get to this point as quickly as possible.
7. Scrutiny of intermediate horizon products for new features and for validation of tracking:
   Color-posted time structure (including lineations of untracked points)
   Color-posted horizon slice (for lineations and patterns in amplitude)
   High spatial frequency residual
   Dip magnitude and azimuth, difference, edge detection and illumination
8. Revision of horizons and faults, and rerun of autotracking.
9. Final time structure maps and horizon slices with chosen amounts of gridding or smoothing.
10. Isochron, isopach and depth maps.
11. Detailed stratigraphic and reservoir studies.

provides true dip magnitude. Figure 3-31 contains a sequence of time slices and the equivalent amplitude surface slices and time surface slices. The surface slices are 6 ms thick and contain only peaks, either their horizon amplitudes or their travel times. Slices on the same row are from the same time, and the rows are separated by 6 ms. Vertically adjacent surface slices are thus independent and it can be seen that the edges of the colored areas fit together. This is the procedure with surface slices — a kind of jigsaw puzzle of horizon segments.

Figure 3-32 charts a recommended procedure for 3-D interpretation using an interactive workstation. The interactive capabilities required to follow this procedure include:

(1) automatic and manual tracking of horizons on vertical and horizontal sections;
(2) automatic spatial horizon tracking and editing through a 3-D data volume;
(3) correlation of vertical sections with well data;
(4) extraction, storing and manipulation of seismic amplitudes;
(5) manipulation of maps;
(6) flexible use of color; and
(7) extraction and use of seismic attributes.

This approach incorporates many of the notions from the previous procedures but utilizes the greatly extended capabilities. The procedure of Figure 3-32 also addresses

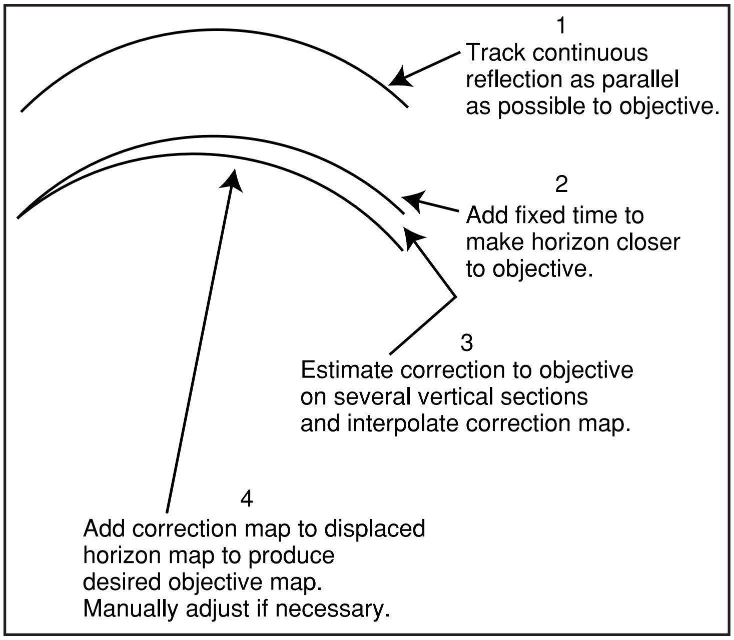


Fig. 3-33. Method for establishing a horizon through poor data or along an unconformity — the 3-D equivalent of a phantom horizon.

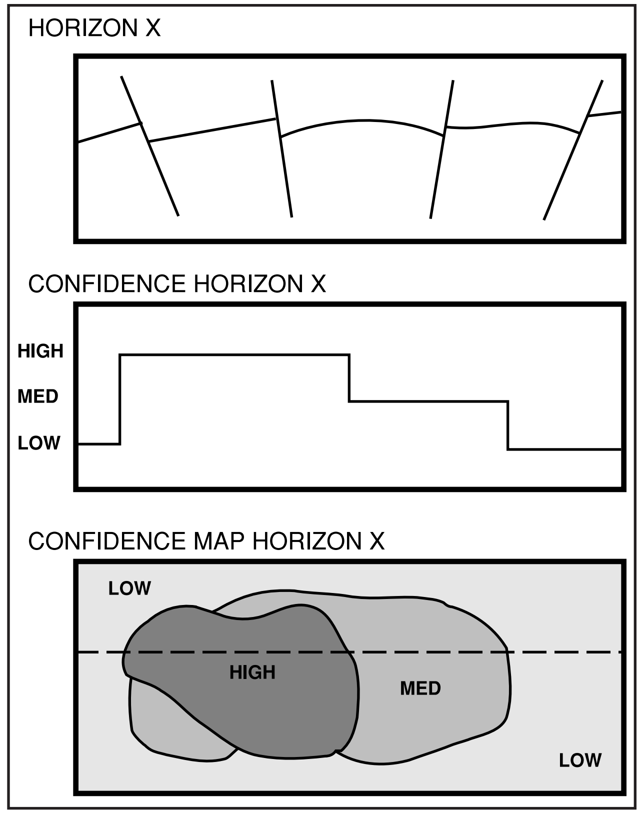


Fig. 3-34. Method for generating a confidence map to help qualify interpreted results.

several areas of stratigraphic and reservoir interpretation which will be discussed in later chapters.

Some of the important principles implicit in the procedure of Figure 3-32 are that you

- understand the phase of data *before* embarking on the mainstream interpretation,
- use horizontal sections to full advantage; benefit from the efficiency of strike,
- study only as many vertical and horizontal sections as is necessary to provide initial input control for automatic spatial tracking,
- use intermediate horizon products to full advantage for refining the interpretation,
- do not smooth any map or map-style product until degree of smoothing required can be judged intelligently, and
- engage in stratigraphic and reservoir studies in order to get the most out of the data.

Autotracking is central to the procedure of Figure 3-32. More discussion on its use appears later in this chapter and also in Chapter 8. Today's autotrackers are fairly robust and will handle poorer data than many people think. However, there are always horizons of interest that have continuity too poor for acceptable autotracker performance.

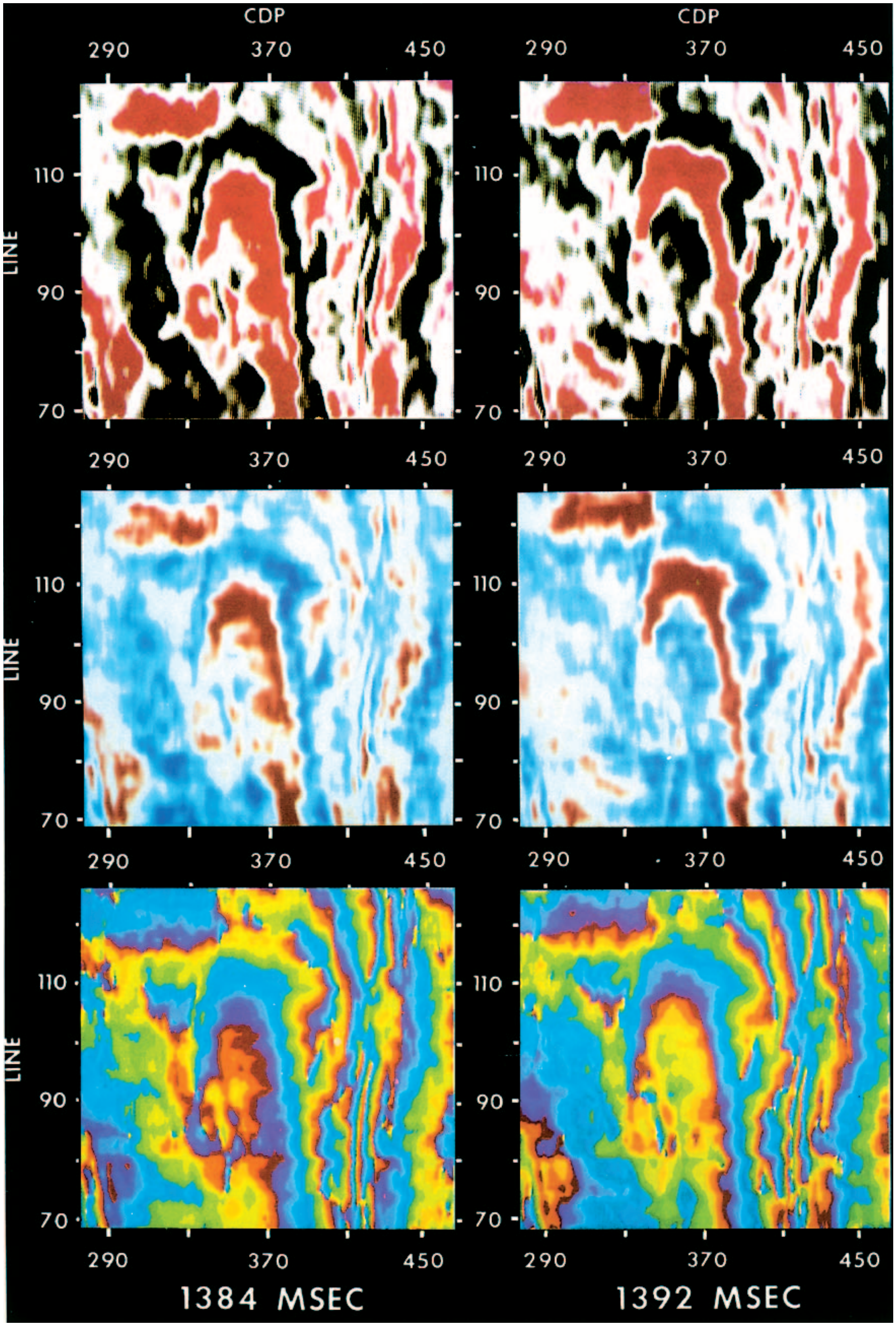


Fig. 3-35. Horizontal sections, 8 ms apart, from Gulf of Thailand displayed in dual polarity variable area (upper row), with seismic amplitude coded to color (middle row), and with instantaneous phase coded to color (lower row). (Courtesy Texas Pacific Oil Company Inc.)

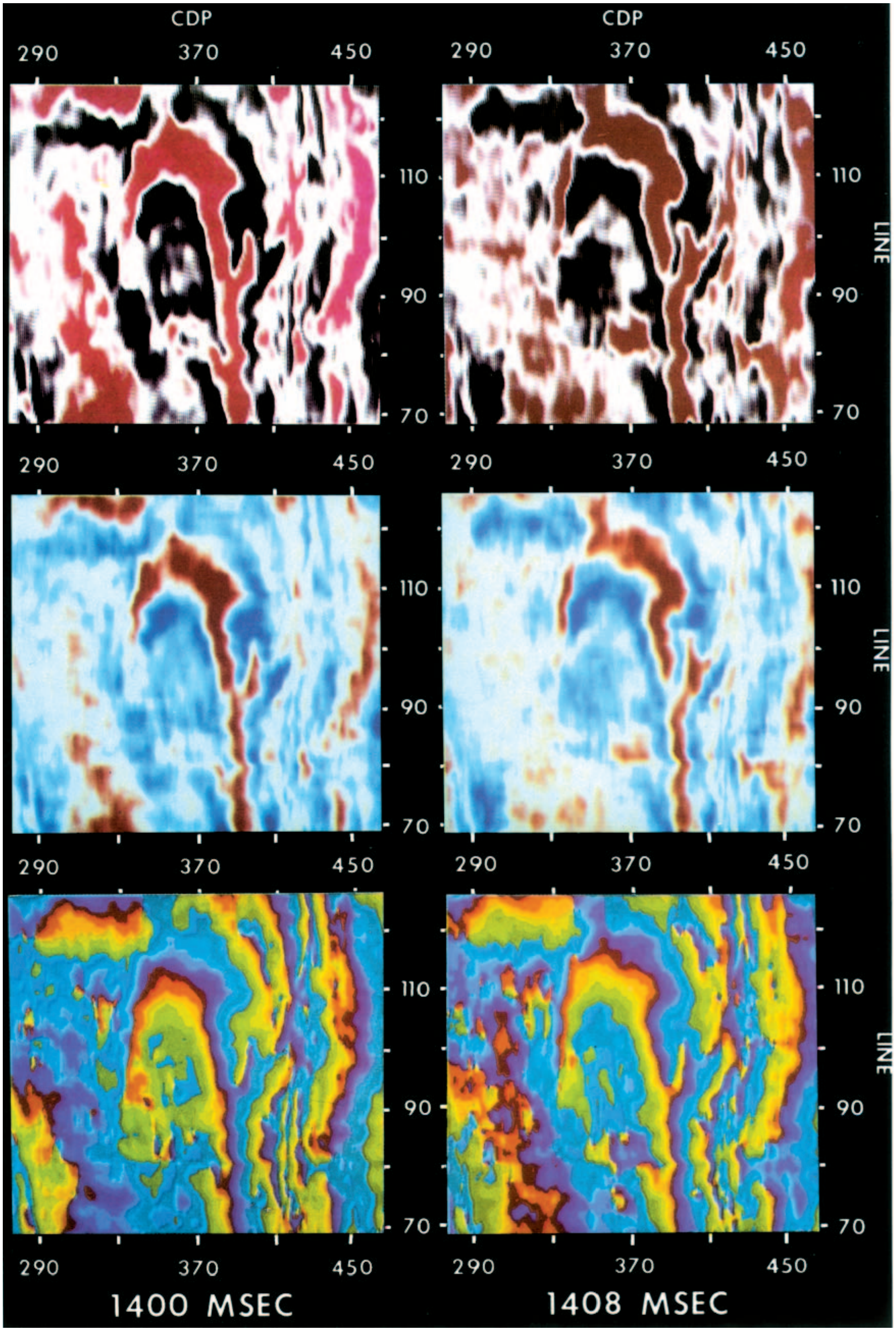
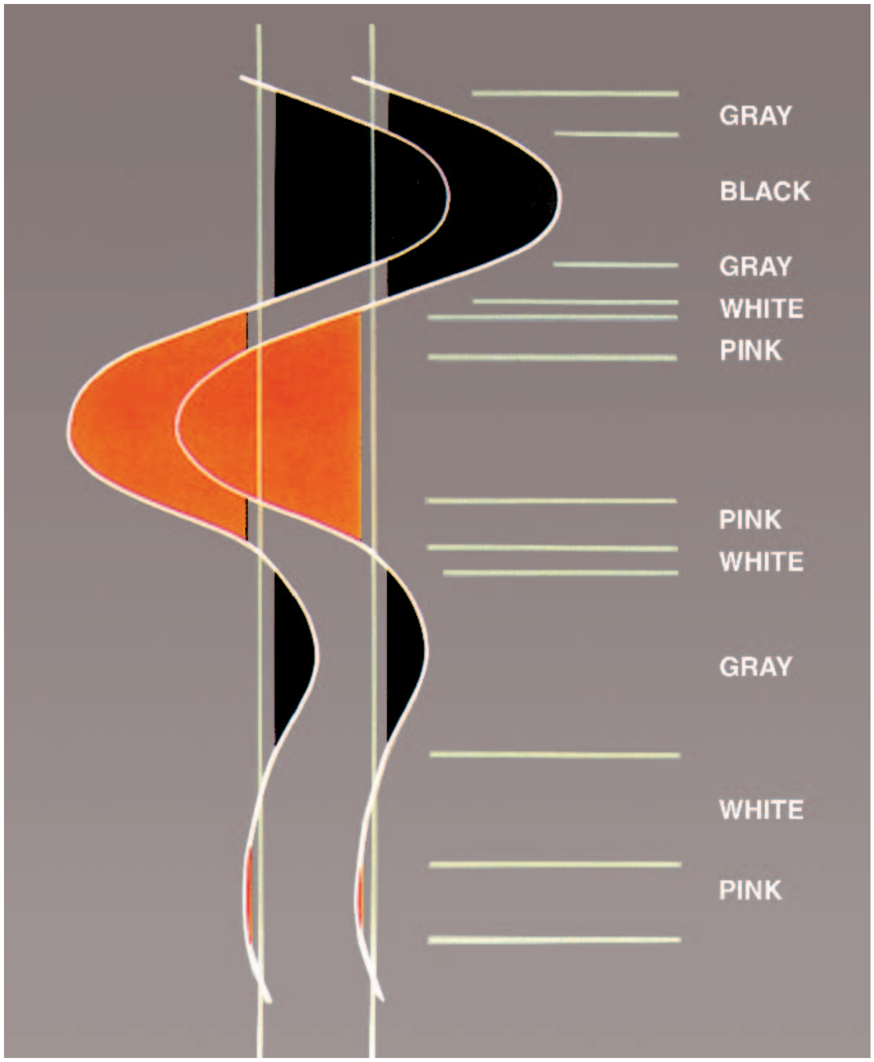

CDP
CDP
290
370
450
110
90
70
LINE
1400 MSEC
1408 MSEC

Fig. 3-36. Waveform definition using dual polarity variable area sections. The troughs are shown as excursions to the left; in practice sections are displayed with the troughs rectified and hence swinging to the right.



In 3-D interpretation we studiously avoid drawing old-fashioned phantom horizons. Figure 3-33 shows the preferable alternative. We track a horizon above the objective horizon and displace it down with a constant time shift. Then we estimate the mistie between this and the desired horizon at several locations and interpolate a mistie, or correction, map. By adding this to the displaced horizon map we should obtain something close to what is desired. We can then manually adjust as necessary, but the amount of manual work should be small compared with the traditional manual approach for the whole project.

Figure 3-34 illustrates a way of generating a confidence map to communicate to managers, engineers, clients, and others the confidence we have in the interpreted maps we produce. Qualitative assessment of confidence, here using three levels, is made occasionally based on data quality and whatever interpretation difficulties may occur. The resultant interpolated confidence map can be included with final maps for the benefit of those who later use them.

Advantages and Disadvantages of Different Displays

With increasingly successful amplitude preservation in seismic processing, interpreters are increasingly suffering from the limited optical dynamic range of conventional seismic displays. Too common are the variable area sections where some events of interest are heavily saturated and others have barely enough trace deflection to be visible. This applies to all displays, vertical and horizontal, made with variable area techniques. Horizontal sections, historically, were first made with variable area using

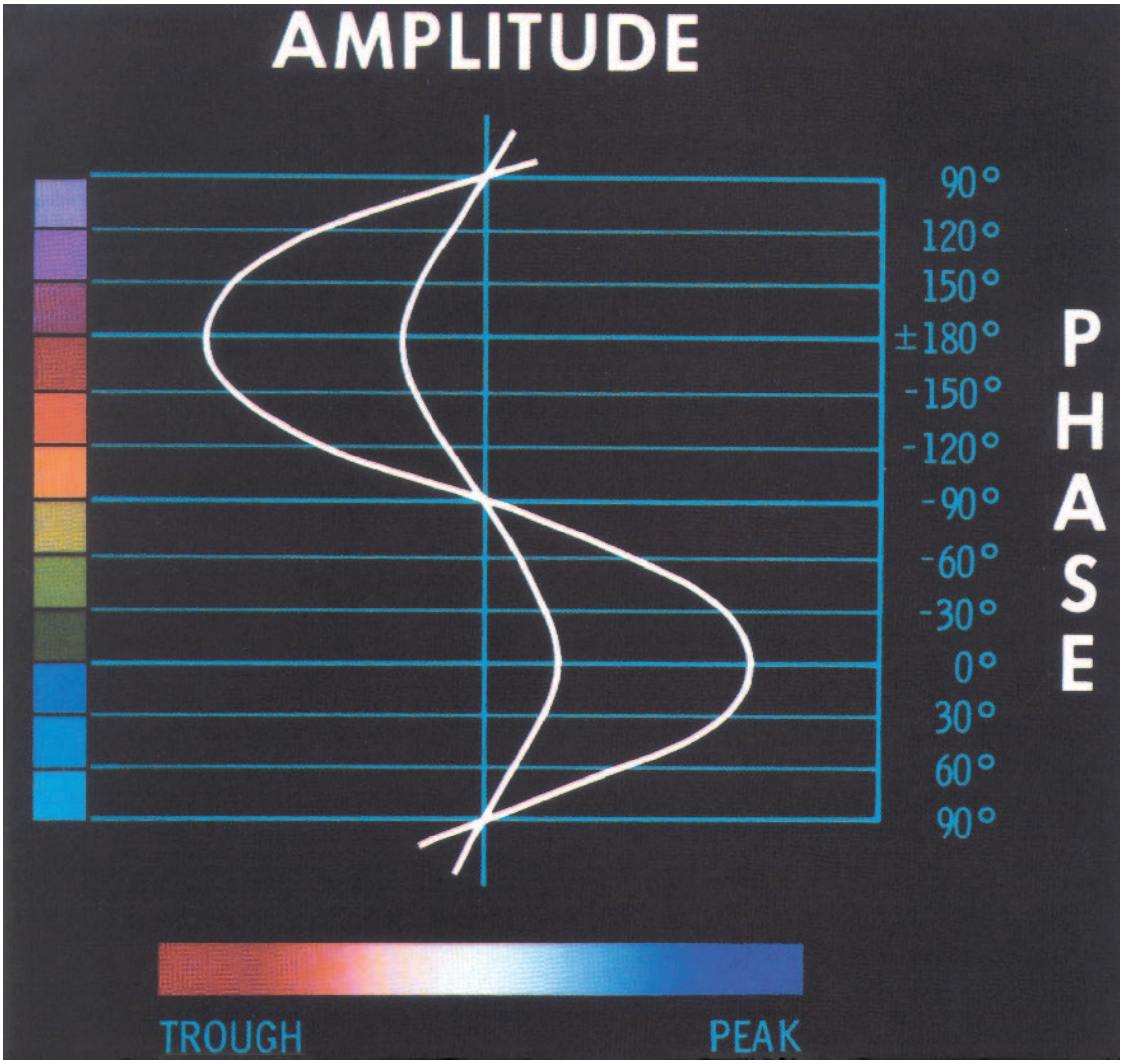


Fig. 3-37. Waveform definition using amplitude and phase color sections.

one polarity only, normally peaks. This soon evolved into dual polarity variable area giving equal weight to peaks and troughs (see Chapter 2). This is exemplified by the upper row of sections in Figure 3-35 and explained in detail by the diagram of Figure 3-36.

Dual polarity variable area provides five clearly discernible amplitude levels. The highest amplitude peaks are saturated and appear as continuous black areas; the medium amplitude peaks do not coalesce and appear as discontinuous black areas which look gray; the lowest amplitudes are below the variable area bias level and appear white; the medium amplitude troughs appear pink; and the highest amplitude troughs are continuous red areas.

If the detail in the seismic waveform provided by dual polarity variable area is inadequate, which is commonly the case today, then the increased dynamic range of full variable intensity color is required. The many ways of using color to interpretive advantage are discussed in Chapter 2. Gradational blue and red is a most useful application; this is illustrated in the middle row of sections in Figure 3-35 and explained in detail by the diagram of Figure 3-37. On such a display the interpreter can see the local amplitude maxima of a peak (or a trough) and draw a contour along the locus of those maxima, thus picking the crest of the seismic waveform.

A further option available to the structural interpreter is horizontal sections displayed in phase, using instantaneous phase derived from the complex trace (Taner, Koehler and Sheriff, 1979). This approach is illustrated by the lower row of sections in

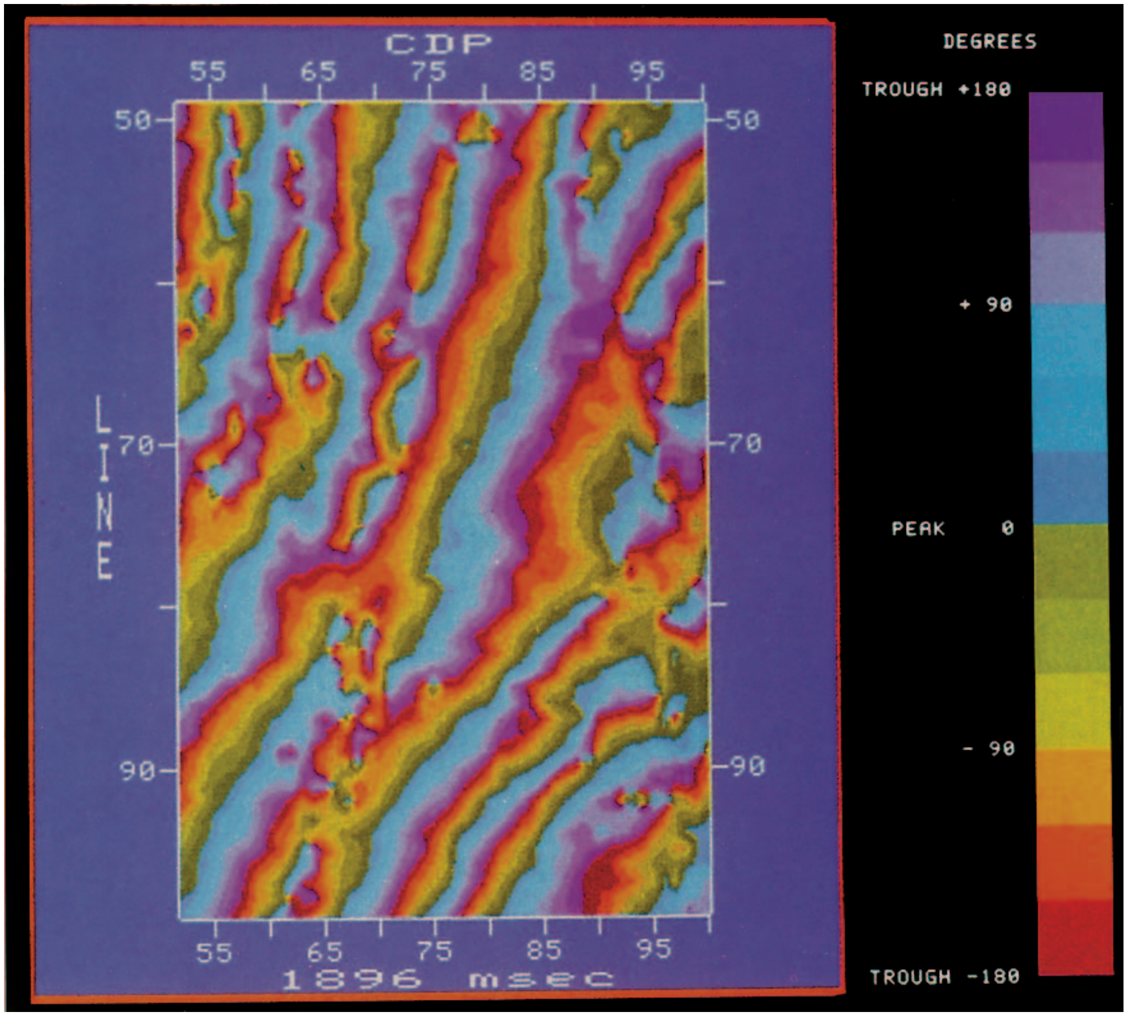


Fig. 3-38. Horizontal section at 1896 ms in instantaneous phase from offshore Trinidad. (Courtesy Texaco Trinidad Inc.)

Figure 3-35 and explained in detail by the diagram of Figure 3-37. Phase indicates position on the seismic waveform without regard to amplitude, making a phase section like one with fast AGC (Automatic Gain Control), destroying amplitude variations and enhancing structural continuity. A phase section is displayed with color encoded to phase over a given range, for example 30°. Color boundaries occur at significant phase values such as 0° (a peak), 180° (a trough), +90° and –90° (zero crossings). By following a chosen color boundary on a horizontal section displayed in this way, the interpreter is drawing a contour for his horizon map picked at a specific phase point. Thus the interpreter can also, if necessary, compensate for any estimated amount of phase distortion in the seismic wavelet.

Figure 3-38 is a horizontal phase section from a different area; the structural continuity is clear. Figure 3-39 shows the same section in edited phase, a simple modification of the display colors. A few degrees of phase centered on 0° have been colored black; a few degrees of phase centered on 180° have been colored red; and all other phases have been colored white. This gives the appearance of an automatically picked section with all the peaks and troughs at that level indicated. The interpreter simply selects the one he wants. A combination of these phase and amplitude displays is provided by Figure 3-40, where edited phase highlights the positions of the maximum amplitudes of peaks and troughs.

Subtle Structural Features

Some form of strike view of the data is very helpful in recognizing subtle faults and establishing the spatial patterns of faulting. Figure 3-22 shows many small faults affecting a thin limestone that are much more easily recognized horizontally than vertically.

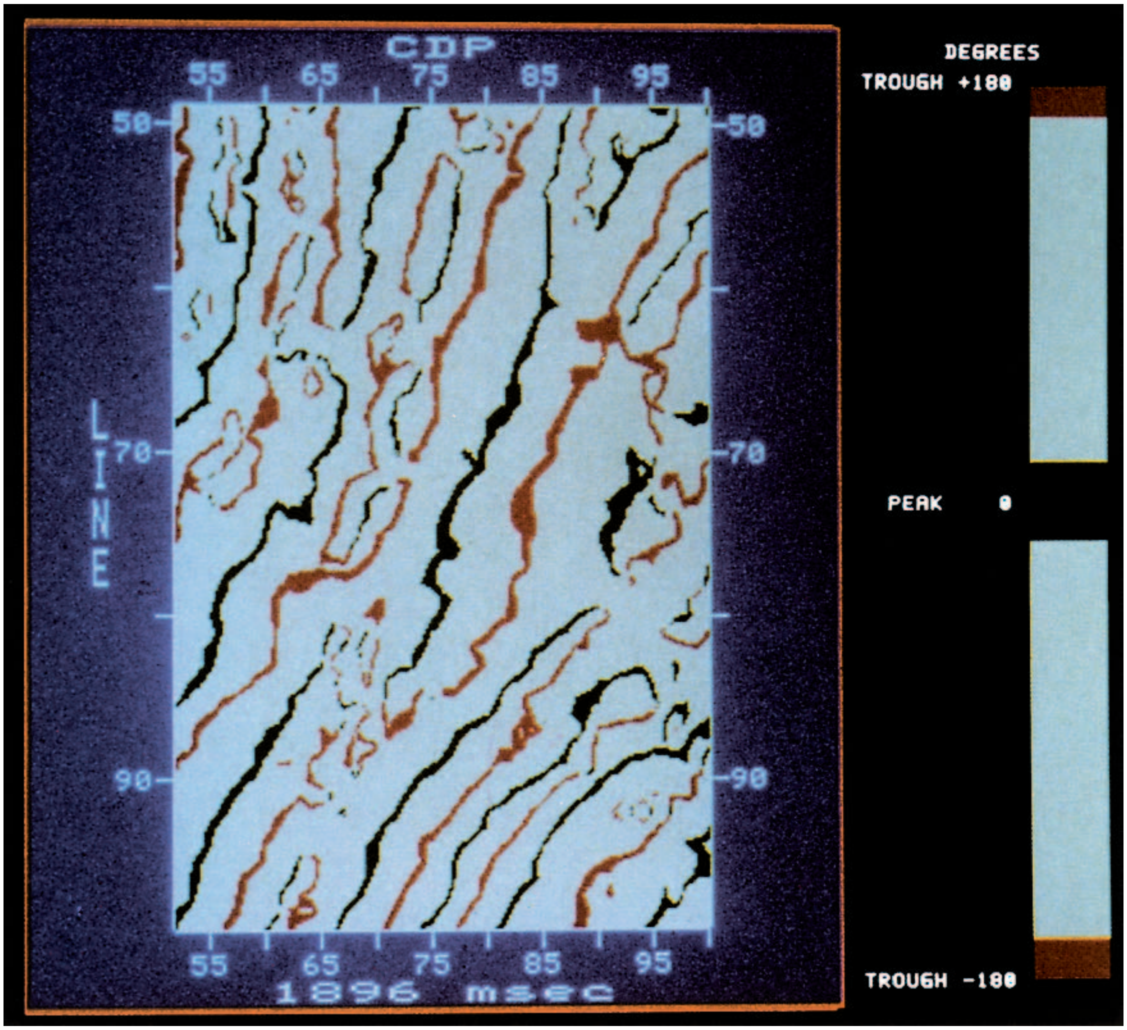


Fig. 3-39. Horizontal section at 1896 ms in edited phase from offshore Trinidad. (Courtesy Texaco Trinidad Inc.)

Figure 3-41 is a horizontal section, or time slice, from a data volume in which a subtle, small-throw fault became a significant part of the interpretation at the target level. Figure 3-42 shows the structure map and the fault under discussion running in a direction just east of north. By reference back to the time slice of Figure 3-41 it is possible to identify the small discontinuities which are the basis of interpreting this fault. The interpreter working on the data first noticed these on the horizontal sections and considered the fault real because it preserved its character over many contiguous sections.

Figure 3-43 shows several straight lineations, principally through the black structural event, that are caused by subtle faulting and jointing. These are so subtle that they would never be recognized on vertical sections. Here they are identified by the linear patterns that appear in the strike view.

Horizontal sections are thus undoubtedly valuable in the study of faults, subtle and not so subtle. Coherence applied to seismic data and then viewed in time slice form is an extension of this value for both fault recognition and mapping. Coherence as an aid to discontinuity detection is very powerful and is discussed at length in Chapter 8. Other attributes are also helpful, particularly when applied to horizon surfaces. These are also subjects of Chapter 8.

Visualization and Autotracking

Visualization pervades all stages of 3-D interpretation starting with the volume of data (Chapter 1) and concluding with the extensive discussion on horizon attributes (Chapter 8). The time slice, or horizontal section, so central to this chapter on structure,

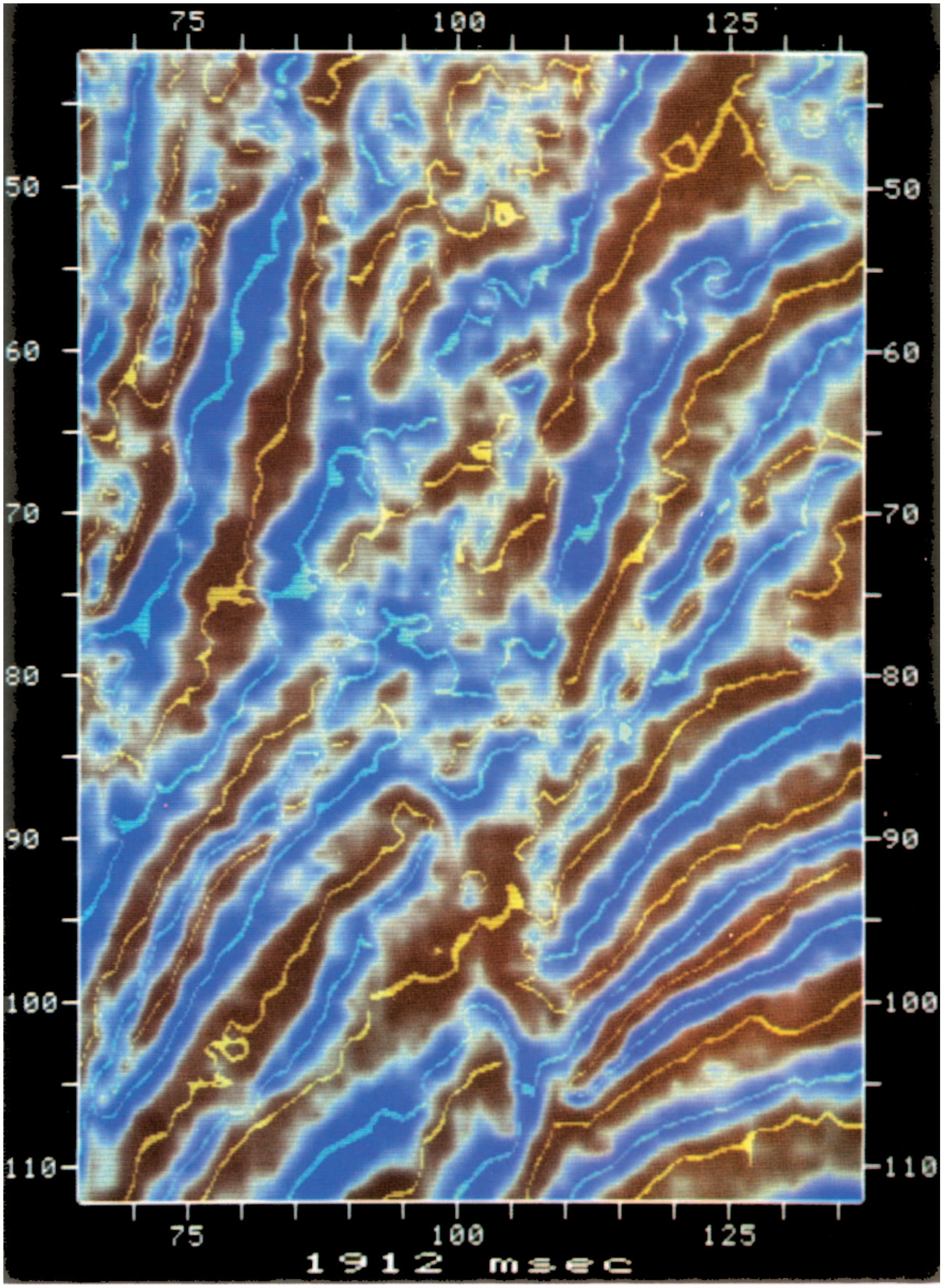


Fig. 3-40. Horizontal section in edited phase superimposed on amplitude. The edited phase in cyan follows the maximum amplitude of the peaks which are blue. The edited phase in yellow follows the maximum amplitude of the troughs which are red.

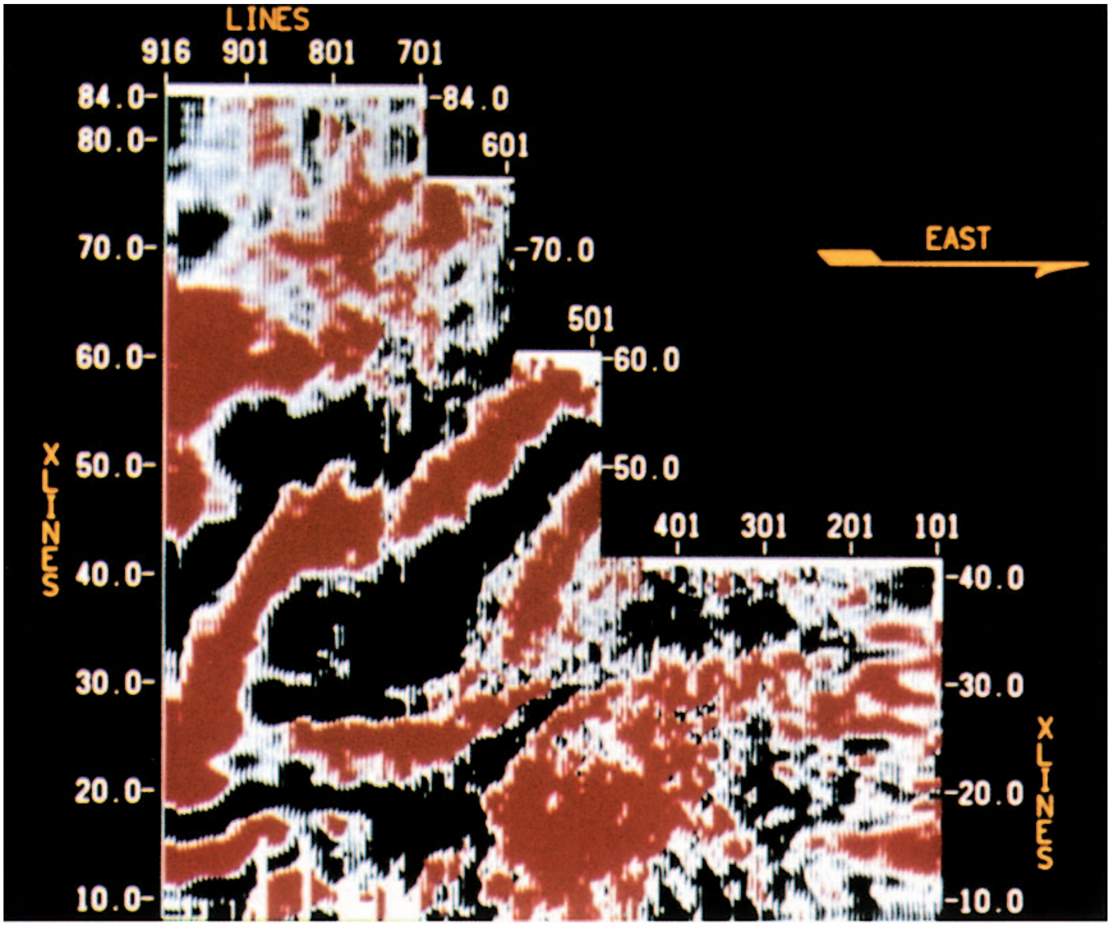


Fig. 3-41. Horizontal section at 2340 ms from south Louisiana marsh terrain. (Courtesy Texaco Inc.)

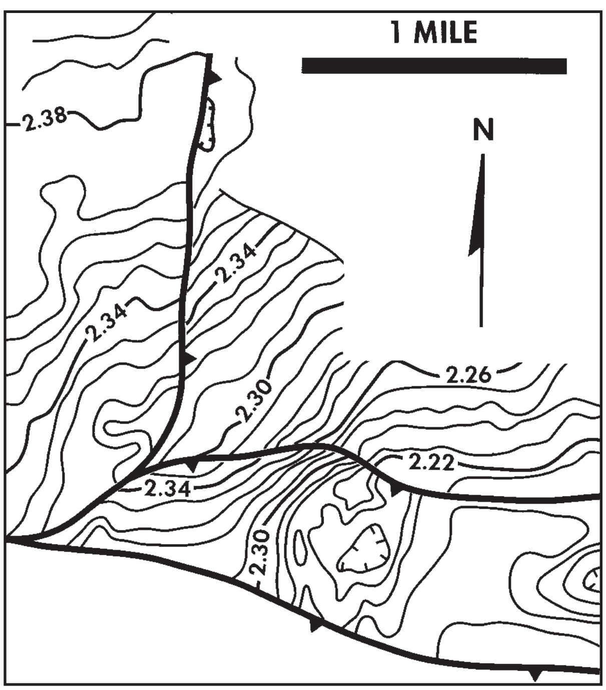


Fig. 3-42. Structural contour map showing subtle fault identified on horizontal section of Figure 3-41. (Courtesy Texaco Inc.)

Fig. 3-43. Horizontal section at 646 ms from high resolution 3-D survey at Ekofisk field in the North Sea. Note lineations due to faulting and jointing. (Courtesy Phillips Petroleum Company Norway.)

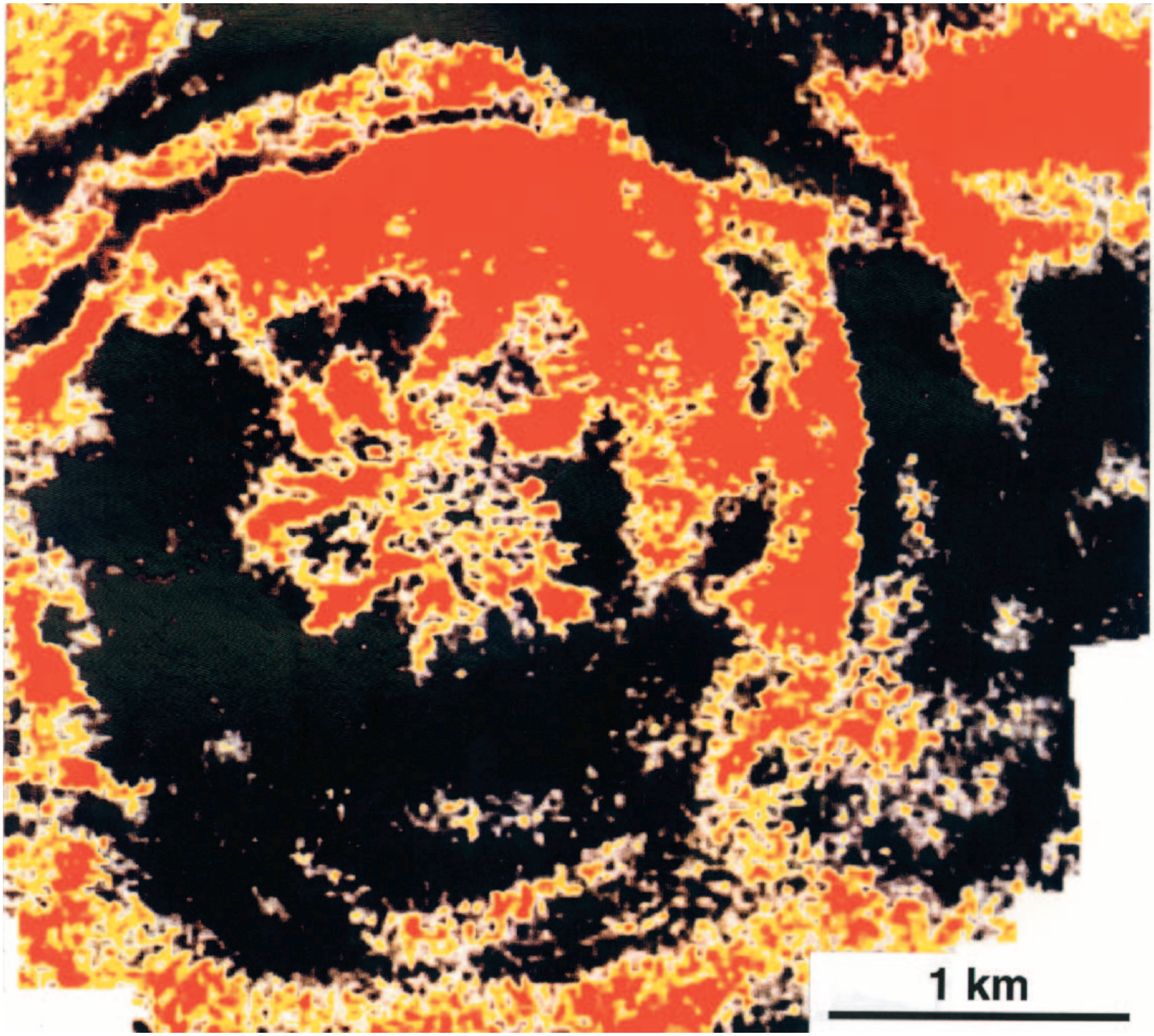


Fig. 3-44. Impact crater of Devonian age seen on time slice 776 ms from the USA mid-continent. (Courtesy Texaco Exploration and Production Inc.)

is itself a major visualization aid and should be used as such. One vertical section and one horizontal section often provide an early visualization of the structure under study.

Figure 3-44 is a time slice at 776 ms showing a distinctly circular feature about 3 km in diameter and occurring at a depth of about 1000 m. It is a very striking view of an impact crater, or astrobleme, of Devonian age. The radial patterns in the center strongly suggest ejecta from the central uplift.

Once horizons and faults have been interpreted they can be visualized as surfaces (Figure 3-45). The relationship between the surfaces can then be studied to help in validation of the interpretation and in placement of the wells to intersect multiple objectives. Many new tools for visualization have recently been created and these are mentioned in the Preface to the Fifth Edition.

The horizon surfaces above will have been produced using automatic spatial tracking starting from seed, or control, points on vertical and horizontal sections. This

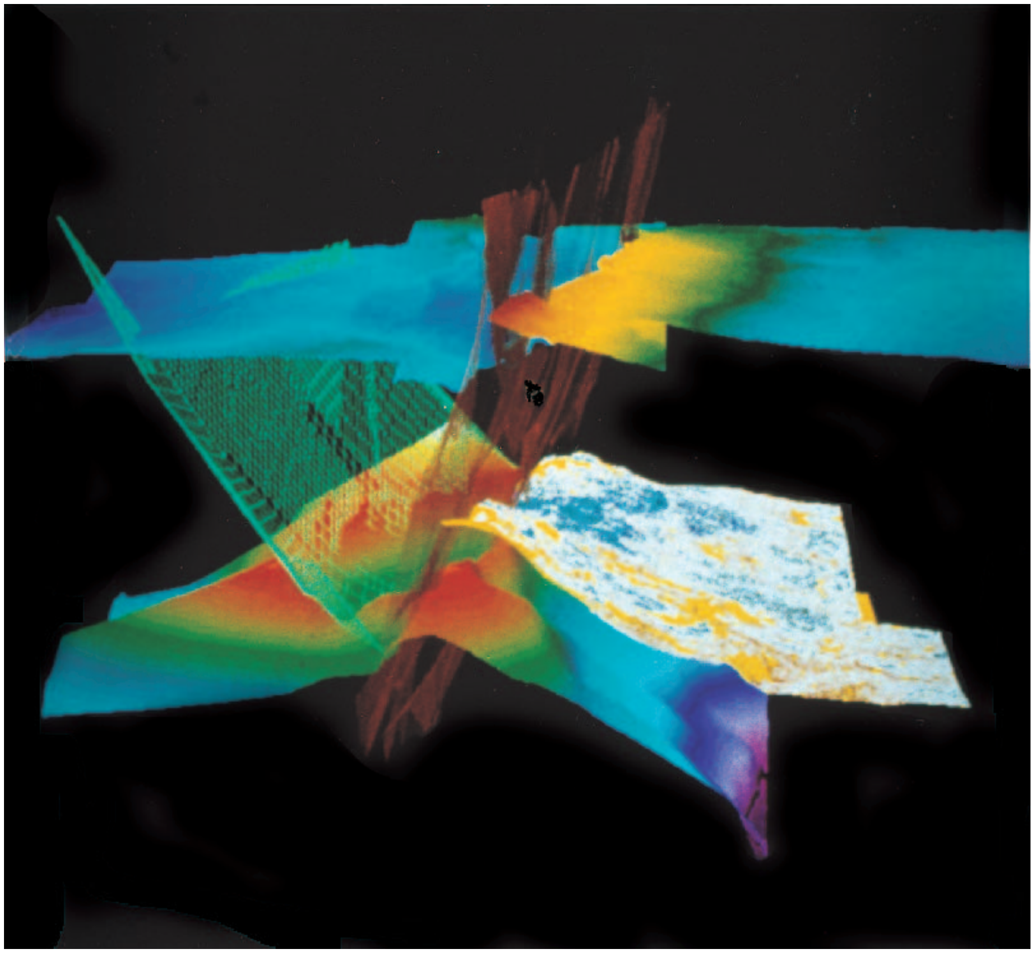


Fig. 3-45. Interpreted horizons and faults seen together as surfaces for validation and visualization. (Courtesy Landmark Graphics Corporation.)

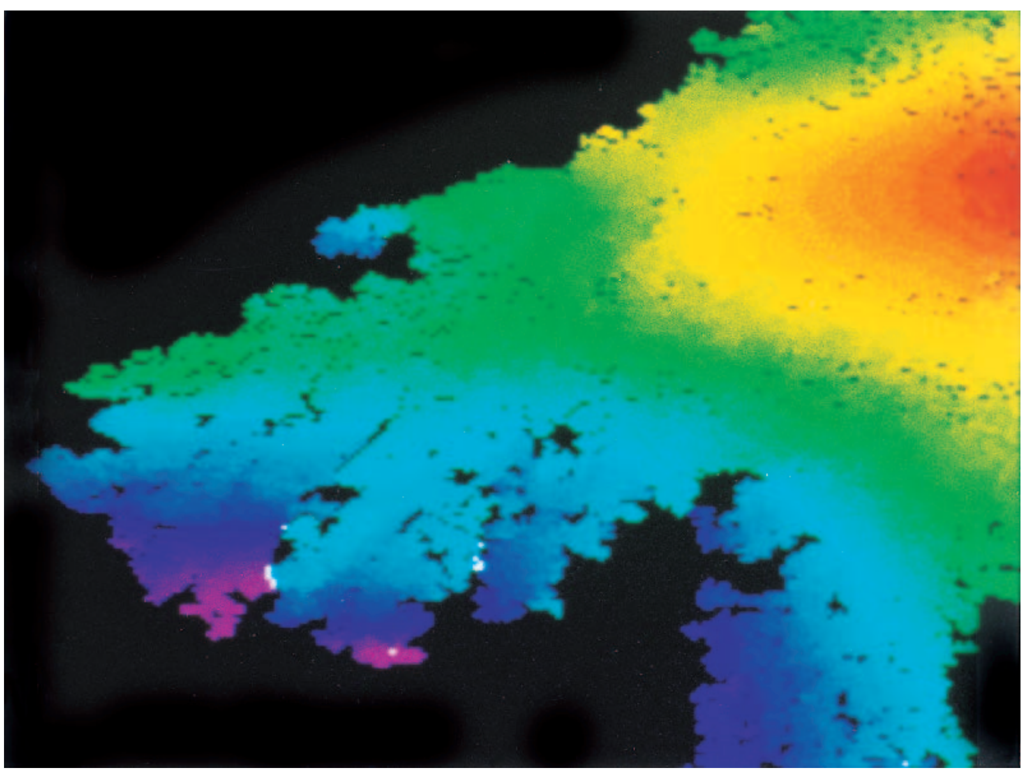


Fig. 3-46. Time structure map generated by automatic spatial tracking operating in an extrapolatory manner from minimum seed points located in the northeast. (Courtesy Landmark Graphics Corporation.)

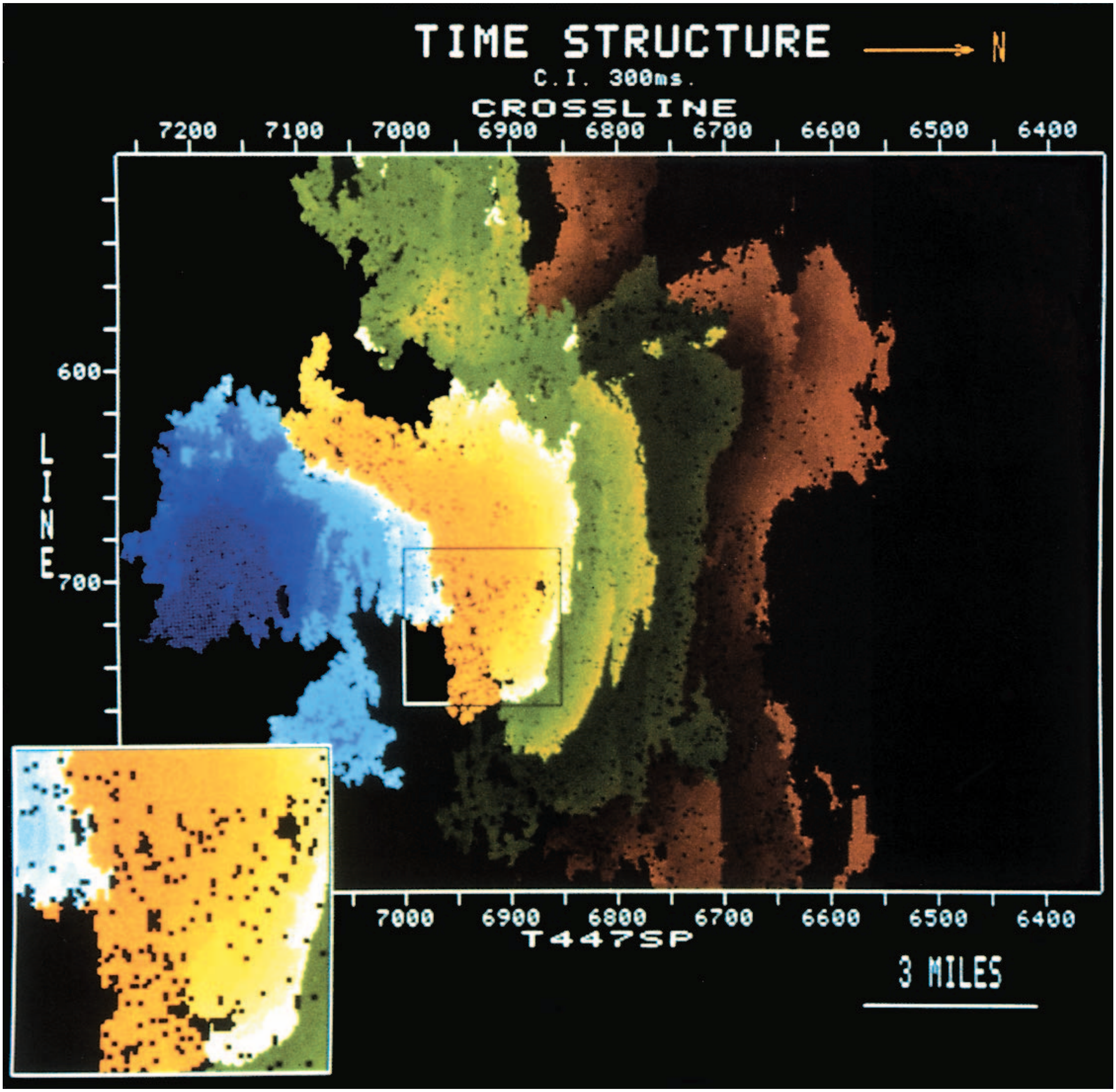


Fig. 3-47. Time structure map generated by automatic spatial tracking, showing lineations of untracked points. (Courtesy Geophysical Service Inc.)

procedure, discussed earlier, uses the tracker in a controlled interpolatory manner, that is it is operating between points where the interpretation has been prescribed. With good data the automatic spatial tracker can be used in an extrapolatory manner from minimum seed points. Figure 3-46 is an example where the tracker was seeded in the northeast and moved outwards independently to define several fault blocks and the faults between them. Notice along the faults, and in some other places, untracked points where the tracking criteria could not be satisfied.

Untracked points are also evident in Figure 3-47 and in several places they line up. These lineations of untracked points indicate places where the tracker had difficulty and may indicate subtle faults, sharp changes of dip, facies changes or other boundaries. Thus lineations of untracked points can be used as a source of geologic information.

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