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Three-Dimensional Methods in Seismic Exploration

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Summary. Two-dimensional seismic prospecting methods are inadequate to solve the three-dimensional geological problems that arise in petroleum exploration. The three-dimensional seismic technique is a data collection and processing system that samples the subsurface adequately. The structure and lithology of rocks are mapped accurately by imaging their acoustic reflectivity with the scalar wave equation. In oil industry economics, the expense of three-dimensional seismic methods is justified by their usefulness for discovering additional reserves and for reducing the growing costs of developing oil and gas fields.

Seismic reflections continue to be the most important tool in the search for new petroleum reserves. During 1978 expenditures in geophysical exploration were more than $1 billion worldwide. About 95 percent of that amount was spent by the petroleum industry and, as in past years, seismic studies accounted for over 90 percent of all outlays in geophysical activity. The success of seismic reflection surveys is due to their accuracy, high resolution, and deep penetration in outlining potential gas and oil fields.

The physical basis for the seismic reflection method is the change of elastic properties associated with different rock types. The elastic properties of rocks determine the velocity with which an elastic disturbance is propagated, hence rock boundaries in the earth can be detected and mapped by recording elastic waves that have traveled through these rocks. The velocity of compressional waves in rocks of economic interest varies from 500 meters per second for unconsolidated materials to 6000 meters per second for hard rocks. In field practice, a source, such as a small dynamite explosion set up near the earth's surface, generates an elastic wave train that moves away from the source. At rock boundaries the elastic impedance (the product of rock density and velocity of elastic wave propagation) changes abruptly, and part of the energy is reflected back to the surface, where it is recorded by the seismic instruments. The seismic records are processed to correct for source-receiver geometry, to eliminate noisy wave trains unrelated to the seismic reflection process, and to suppress multiple reflections from the rock interfaces. The arrival time of the primary reflection events, plus the amplitude and phase information carried by the seismic pulse, permit reconstruction of the elastic impedance distribution that characterizes the rocks in the subsurface. Then this physical description of the subsurface is translated into geological terms to outline targets for drilling.

John C. Karcher observed seismic reflections from subsurface layers in 1917 and demonstrated their application to petroleum prospecting in Oklahoma in 1921. In the 1930's this new exploration method revolutionized oil prospecting. Two events contributed to further development of the seismic reflection method in the 1950's. The first was the application of information theory to seismic signal processing, which was pioneered by the geophysical analysis group at the Massachusetts Institute of Technology. Seismic data quality was also greatly enhanced by the common-depth-point (CDP) method, which provides significant improvement in the signal-to-noise ratio by exploiting redundant subsurface coverage.

In exploring for new hydrocarbon reserves, seismic reflection surveys are conducted along profile lines that are spaced several kilometers apart; receivers are placed tens of meters apart. While this mode of two-dimensional operation provides adequate data for reconnaissance mapping, the need for three-dimensional seismic surveying becomes increasingly important for detailed mapping of known oil and gas fields. The need for the method in this case is twofold: (i) accurate subsurface images require the use of all of the reflected data and (ii) delineation of the field requires reflection information in an areal sense.

In the three-dimensional seismic method, the reflected wave field must be adequately sampled spatially to ensure proper imaging of the subsurface by means of the three-dimensional wave equation. The difference between two- and three-dimensional seismic methods is explained by the experiment illustrated in Fig. 1 (*1*). Figure 1A is a model of typical structures (two domes and a fault) where hydrocarbons accumulate. A three-dimensional seismic survey was simulated by collecting reflection data over the model along 96 closely spaced lines. For a conventional two-dimensional survey, data would be obtained from only one line or profile. The seismic data recorded over the model along profile 6 are shown

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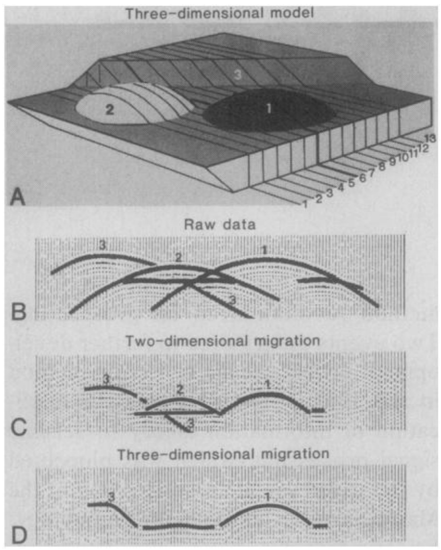


Fig. 1. (A) A three-dimensional model depicting the relationship of survey line 6 to domes 1 and 2 and fault 3. The model scale, 25 centimeters on a side, corresponds to 2500 m in the field. The velocity of sound waves in the model is lower than that of the surrounding medium. (B) Reflection profile recorded with collocated source and receiver moving along survey line 6 at an equivalent height of 1000 m above the top of the model. Each trace displays the seismic signal recorded at one source-receiver location; the distance between traces is 34 m. The apex of event 1 occurs at a two-way travel time of 0.66 second. (C) The raw data from the reflection profile have been imaged from a mathematical operation that uses two dimensions. Sideswipe events 2 and 3 are reflections that originated outside the vertical plane through line 6. (D) A true vertical section through line 6 was obtained by three-dimensional imaging from 48 consecutive seismic profiles spaced 34 m apart. [Published with permission of Gulf Science and Technology Company and the Society of Exploration Geophysicists]

in Fig. 1B, which is a seismic section in the CDP mode. In this type of display each seismic trace is the response of a receiver to the upgoing wave field reflected and diffracted from the surface of the model. The source that generates the downgoing wave field is located at the same position as the receiver. The CDP seismic section can be modeled according to geometric optics; normally incident rays (perpendicular to the surface) are traced from the common source-receiver location to the surface of the model, producing a profile with features such as the three shown in Fig. 1B. (i) Event 1 is the specular reflection from dome 1 in Fig. 1A. The reflection changes into a diffraction tail, which is caused by the sharp corner between the surface of the dome and the horizontal plane on which it is situated. Since line 6 crosses dome 1 symmetrically, the normally incident rays all lie in the same vertical plane. Within that vertical plane, individual rays are not vertical, except for the ray to the apex of the dome; thus when the reflection events are plotted as seismic traces on a vertical line underneath the source-receiver locations, a distorted picture of the dome results. (ii) Arrival 2 on the CDP section is caused by energy returned from dome 2 (Fig. 1A). This dome, located to one side of line 6, is plotted by the CDP method on the survey profile. (iii) The fault scarp 3 (Fig. 1A), which is crossed at a 45° angle, is also plotted in the wrong spatial position on the CDP section.

The data presented in Fig. 1B would be difficult to interpret unambiguously without knowledge of the physical model. One method for mapping the reflection events in correct spatial position and collapsing the diffraction tails—migration—has been applied by geophysicists for many years. In Fig. 1C, a two-dimensional migration algorithm of the data of Fig. 1B, all the diffraction curves have been eliminated and event 1 has been mapped correctly because the condition for two-dimensional migration is met for this part of the profile. However, the arrival of the sideswipe (a reflection event that originates at a point outside the vertical plane) from dome 2 is still present and the fault plane 3 has not "migrated" to its correct spatial position. On the basis of the two-dimensional migrated section alone, dome 2 and fault plane 3 would not be located correctly, and a drilling program based on this information would miss these structures.

The vertical section resulting from three-dimensional migration, which was obtained from seismic data recorded on 24 parallel lines on either side of reference line 6, is shown in Fig. 1D. In this seismic picture, all the reflectors have been correctly imaged, producing the true vertical cross section of the model along line 6.

Data Collection

The field system for collecting seismic data consists of a source for generating elastic waves in the subsurface and receivers connected to seismic instrumentation for recording the seismic signal returned from the earth. A surveying system is required to identify the sites of field work with geographic coordinates and to record the relative position of source and receivers. The seismic source must generate a pulse of high energy, short duration, and sufficiently high frequency (up to 100 to 200 hertz) to resolve the exploration objectives. Normally, 48 or 96 receivers are active for each source excitation, and each detector generates an electrical current whose intensity is proportional to the amplitude of the seismic signal. The receivers are connected by cables to instrumentation that am-

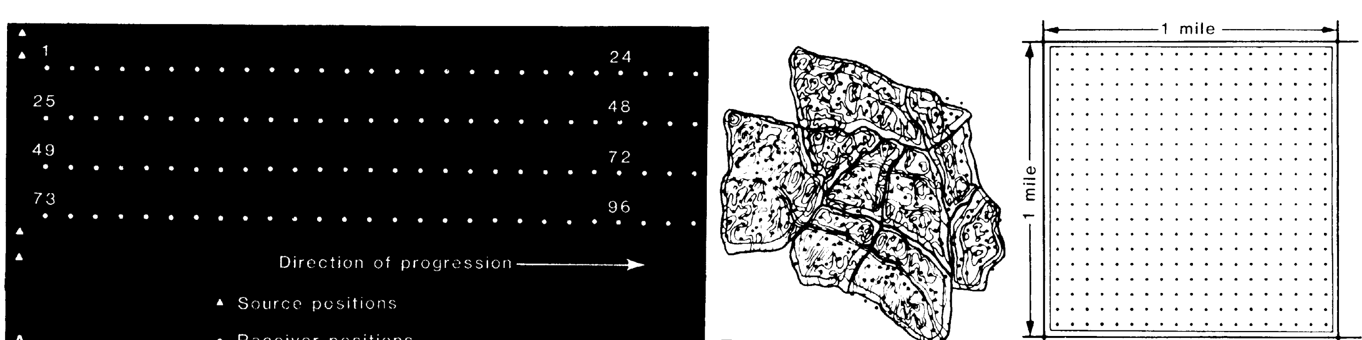


Fig. 2. (A) Swath shooting for collecting three-dimensional seismic data is used in terrain where seismic operations can be carried out directly over the area of interest. (B) The Seisloop (Geophysical Service Inc.) method makes possible coverage in three dimensions in mountains or jungle without leaving major roads or trails. Geophones are placed around the loop and recorded as the energy source moves around the loop. (C) In areas where section lines and other roads dissect the prospect site into rectangles, the Seisquare (Geophysical Service Inc.) variation gets the same result with more geometric symmetry.

plifies the weak analog signal and records it in digital form on magnetic tape at a sample rate of 0.004 second or less.

The most popular source for generating elastic waves in the ocean is the air gun, which releases a bubble of compressed air that generates a compressional wave that propagates away from the source. The seismic signal is recorded by a "streamer," a marine cable up to 3 kilometers long that typically has 96 active sections containing pressure hydrophones. The marine streamer is towed behind an oceanographic vessel that travels 10 km per hour and activates an array of air guns at controlled time intervals.

The three-dimensional marine layout consists of a series of lines spaced 75 m apart with source points at 25- or 50-m intervals. The streamer has a tendency to deviate from a straight course because of marine currents, and a tracking system is required to monitor these deviations. The most modern navigation systems locate boat and streamer position continuously and record this information on magnetic tape. Three-dimensional marine data collection produces uniform coverage along the recorded lines and acceptably uniform spacing across lines.

Dynamite placed in drilled holes is the best land energy source but, because of safety hazards and environmental harm, other sources are frequently used. Vibroseis (Continental Oil Company) generates a frequency-controlled wave train in the earth by means of a pad coupled to the ground by the weight of the vehicle it is mounted on. The standard land receiver is a velocity phone that generates an electrical signal with an amplitude proportional to the velocity of the particle motion of the ground induced by the reflected energy. In field practice, arrays of detectors are usually laid out in patterns to increase the sensitivity of the receiver group to weak returns and to attenuate surface waves generated by the source.

The three-dimensional land layout is constrained by economic considerations and surface accessibility. The ideal conditions are a dense, even areal coverage of the subsurface with multiple subsurface coverage as well and a wide range of source-receiver spacings. This ideal configuration is best implemented by "swath" shooting, where receiver cables are laid out on the ground in parallel lines (Fig. 2A). In a typical application, the spacing between the lines would be 250 m, and the receiver group interval along the lines and the shot interval along and across the lines would be 125 m. In areas where access to the land is restricted by topographic or man-made obstacles, undershooting schemes may be used (Fig. 2, B and C). For undershooting, the receiver cable is spread around the perimeter of the survey area, and the source moves along the cable. This method is less expensive than swath shooting, but produces less even subsurface coverage.

Data Processing

The objective of processing seismic data is to extract the useful signal from the field records and to image the reflectivity of the subsurface by means of the reflected wave field.

Noise attenuation is accomplished through frequency-wave-number filtering designed to discriminate against waves traveling horizontally such as surface and air waves. The reflected pulses are normalized by removing the oscillatory wave trains caused by water layers. Whitening the frequency components, that is, adjusting the amplitudes to the same level within a bandwidth, shortens the reflection pulse and increases its resolution. Corrections must be applied to land data to account for changing surface

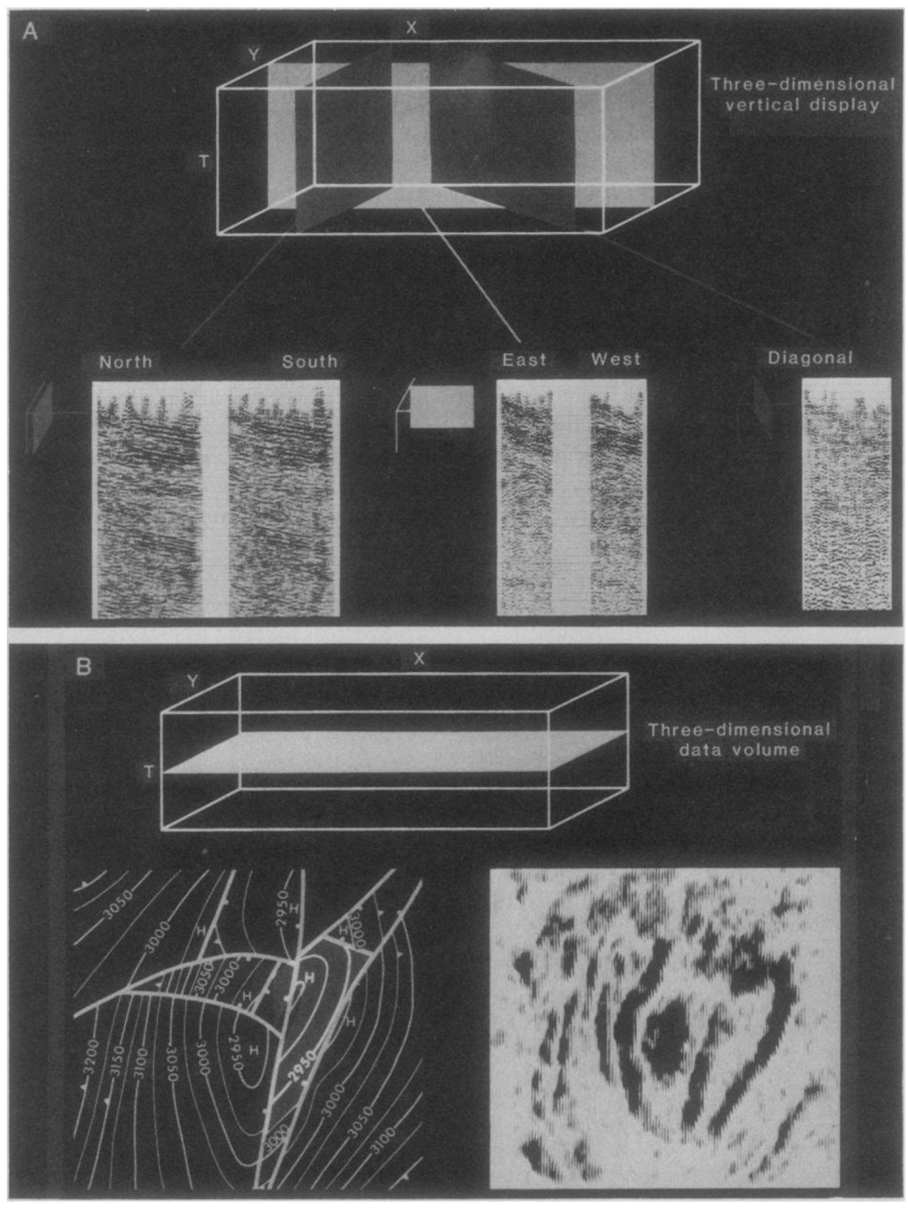


Fig. 3. (A) The three-dimensional seismic data base contains seismic traces referenced to a horizontal coordinate system X, Y. The vertical axis is two-way vertical travel time, that is, the time required for the seismic pulse to travel from the surface of the earth to the reflector and back along the vertical path. The three-dimensional data volume supports retrieval of vertical seismic sections in any desired direction. (B) Seiscrop maps are horizontal slices through the three-dimensional seismic data base and display the areal extent of exploration targets. The contour map (bottom left) was prepared from a series of Seiscrop sections such as the one at 3020 msec shown on the right. The shaded area in the contour map represents the hydrocarbon-water contact interpreted from a two-level Seiscrop section.

elevations and near-surface inhomogeneities.

The distribution of material velocity needs to be determined for the common methods of seismic imaging because curving horizons act like lenses in optics, focusing or defocusing wave fronts. The low-frequency component of the velocity field, which is required for image reconstruction, is extracted from the curvature of the reflected wave front. The high-frequency component, which carries lithologic information, is extracted from the amplitude and phase of the reflected wave front and is the objective of seismic inversion efforts, which are beyond the scope of this article.

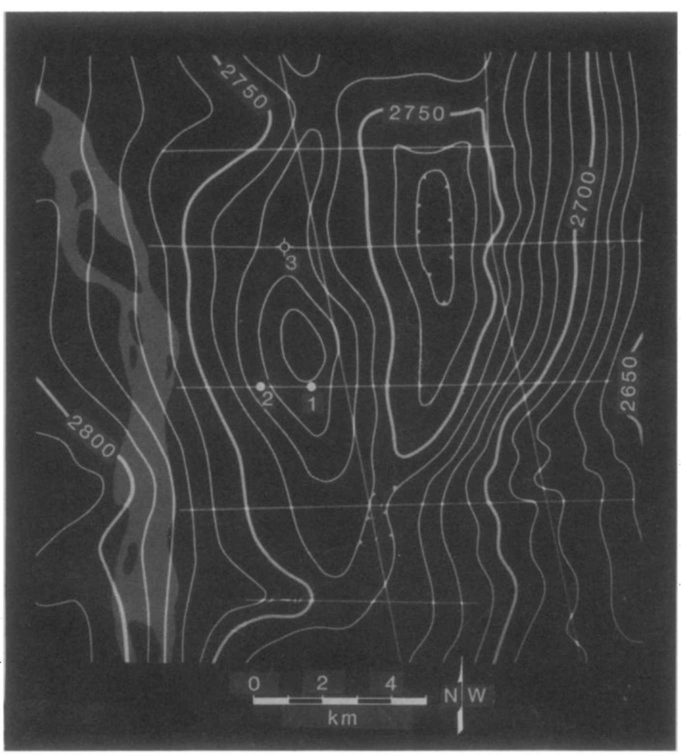
Wave front curvature is measured by the normal moveout (NMO), which is the difference in travel time of a reflection observed at variable source-receiver offsets. To a first approximation, the relation of the reflection travel time T_y to the shot receiver distance y is hyperbolic and is expressed by

$$T_y^2 = T_0^2 + \frac{y^2}{V_{NMO}^2} + \text{higher order terms} \qquad (1)$$

where T_0 is the travel time for the receiver coincident with the source, and V_{NMO} is the normal moveout velocity, which is a function of material velocity and layering of the earth. In velocity analysis, the V_{NMO} is determined from the field data collected along a straight traverse by exploiting the hyperbolic NMO relation shown in Eq. 1. The V_{NMO} is used to transform the offset seismic traces to zero offset by means of Eq. 1 as part of the preliminary imaging process known as the CDP stack. The material velocity derived from V_{NMO} is required for migration, the final image reconstruction.

The CDP stack is a method of imaging seismic data to produce the wave field that would have been recorded with collocated sources and receivers. In the case of three-dimensional data, obtained from source and receiver pairs that are referenced to a common midpoint but are, in many instances, not aligned in a common direction, the V_{NMO} must be corrected for this angle-dependent effect (2). The corrected traces are added together to improve the signal-to-noise ratio of the primary reflections by attenuating random noise, multiple reflections, surface waves, refractions, and so forth. The CDP stack is not a true representation of the subsurface reflectors except in the case of horizontal layering. In the presence of structural dip, the reflectors will be plotted vertically underneath the common midpoint between source-receiver pairs, instead of in the true position, which is determined by the ray path of the wave front. In analogy with the optical case where a light incident on a screen with an aperture is diffracted, abrupt lateral discontinuities in the rocks such as geologic faults cause the backscattered energy to fall along diffraction surfaces that tend to obscure the picture of the reflectors (Fig. 1B).

The shortcomings of the CDP imaging method are overcome by the migration process. Early implementations of migration were based on geometrical optics (3). Claerbout (4) put migration theory on firm ground, imaging the reflectivity within the earth by means of the scalar (acoustic) wave equation solved numerically by the finite-difference method. An approach to three-dimensional implementation of what became to be known as wave equation migration was posed as an integral solution to the homogeneous wave equation with an inhomogeneous boundary condition of the Dirichlet type. This formulation of migration leads to the Kirchhoff integral solution of diffraction in optics (5). The solution in frequency-wave-number space (6) is advantageous for digital computer algorithms. Ideally, the field data should be used in wave equation migration; however, economic and practical constraints dictate the use of the CDP stack as the starting point for three-dimensional migration.



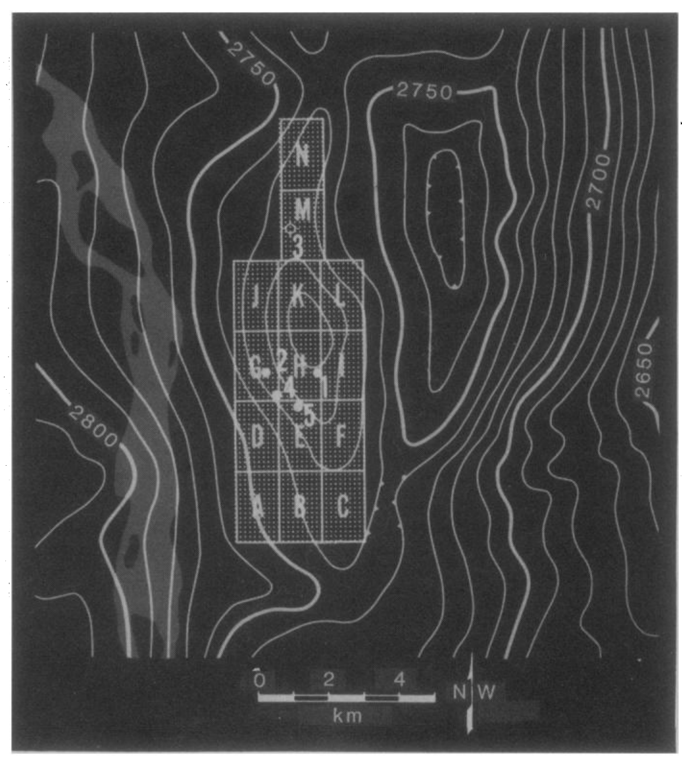


Fig. 4 (left). Contour map of a producing horizon based on seven two-dimensional seismic profiles. Wells 1 and 2 were successful, but well 3 was dry. Fig. 5 (right). Field layout for recording the three-dimensional seismic data. Sources and receivers were located around the perimeter of rectangles A through N. Seismic traces were referenced to the locations by dots inside the area surveyed.

Data Display and Interpretation

In contrast to conventional seismic prospecting with two-dimensional profiles, three-dimensional methods generate seismic data for a volume of the earth. These data, which can be displayed by a series of vertical slices similar to conventional seismic sections, have two important advantages over two-dimensional seismic sections. (i) A three-dimensional seismic section represents the true vertical cross section of the reflectors, whereas sections in two dimensions will be contaminated by energy returned from reflectors that are located outside the plane of the section. (ii) Whereas two-dimensional seismic sections are restricted to the direction of the survey line, three-dimensional sections can be extracted in normal vertical format along any desired direction (Fig. 3A). This option allows the interpreter to investigate features of interest along the optimum direction—for instance, along maximum dip. The geophysicist may also construct an arbitrary cross section that traverses well locations in the prospected area. Such a cross section combines geophysical and geological data allowing for interpretation of subsurface structure and lithology.

An innovative development in three-dimensional display involves the construction of horizontal seismic cross sections. This display has been named a Seiscrop (Geophysical Service Inc.) map because of its similarity to the subcrop map—a map that shows the geologic formations immediately overlying an unconformity. The similarity between the conventional structure contour map derived from seismic data and the corresponding Seiscrop map is illustrated in Fig. 3B, which represents a slice through the three-dimensional data volume at a vertical travel time of 3020 milliseconds. Continuous events outline the contour levels for different reflectors at a vertical time of 3020 milliseconds. The map in Fig. 3B outlines a single reflector by means of different contour levels for vertical travel time. This contour map was prepared by outlining the contour levels of one specific reflector on a sequence of Seiscrop maps extracted from the data volume at different vertical times. The procedure of mapping horizons by Seiscrops is considerably less time-consuming than the conventional method of identifying reflectors on vertical seismic sections in order to resample them in space and then contour the spatial samples by either manual or computer methods.

Motion pictures are used in conjunction with a Seiscrop interpretation table for more efficient mapping from full suites of Seiscrop data recorded on movie film. Interpretation by this method also aids identification of geologic faults and correlation of reflectors across faults.

Another way to display three-dimensional seismic data involves a solid model. Vertical seismic sections are presented on separate transparent plates to simulate the seismic data volume physically. Geologic interpretation is facilitated because all the data are seen simultaneously. The three-dimensional seismic data have also been displayed by means of optical holography.

A Case History of Two- and Three-Dimensional Seismic Surveying

A three-dimensional seismic survey was carried out in Peru for the Occidental Petroleum Company in conjunction with Petróleos del Perú (7). The prospect site is in the Amazon Basin; it is densely covered with vegetation and traversed by numerous rivers, making seismic operations difficult. A two-dimensional seismic survey had produced the structure map from which the drill sites for the first three wells were selected. Figure 4 shows the location of the seven, two-dimensional seismic profiles, the three wells, and the resulting contour map (in two-way travel time) for the Agua Caliente horizon, a Cretaceous sandstone whose good porosity provides a pay zone for this prospect, that is, a formation that contains hydrocarbons of commercial value. On the basis of this struc-

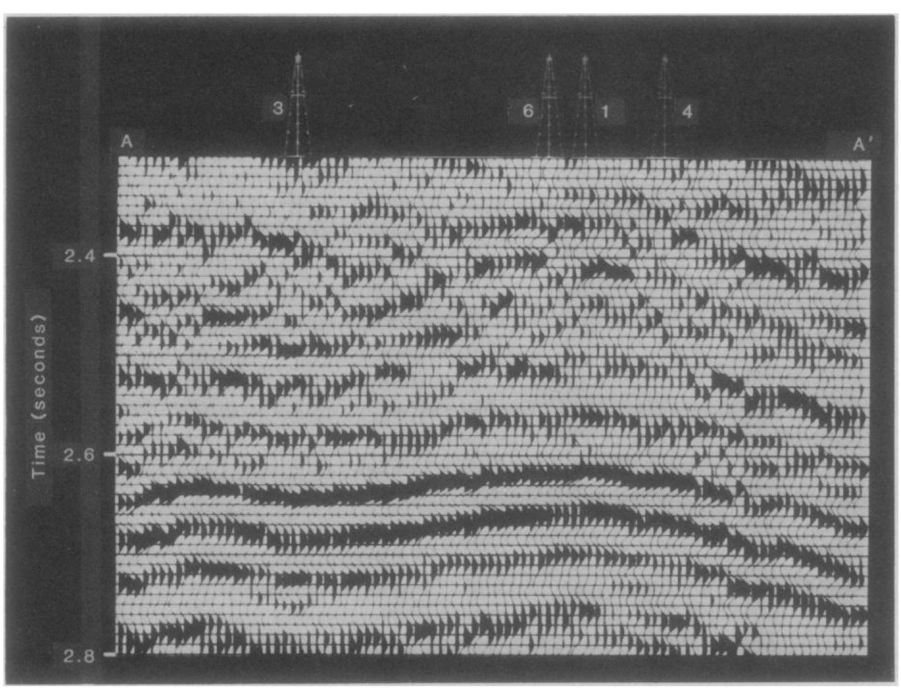


Fig. 6. This three-dimensional migrated section of a traverse assembled through several wells shows that well 3 is located between two structures.

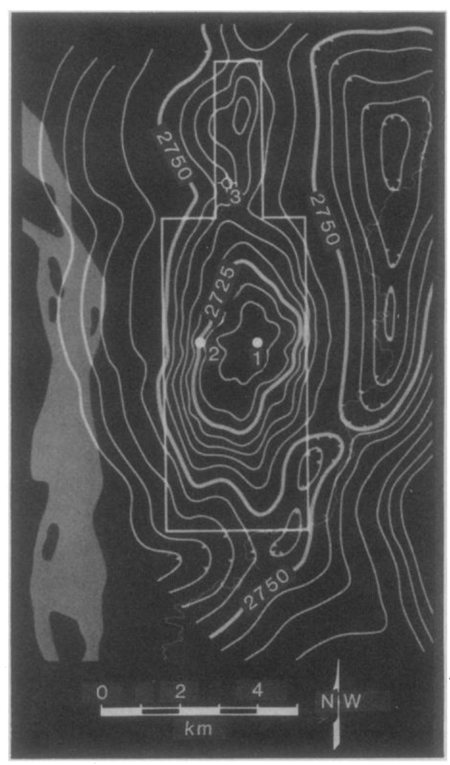


Fig. 7. The same geologic horizon as in Fig. 4 contoured from a three-dimensional seismic survey conducted over the outlined area. This map shows the true structure of the target horizon and that well 3 was drilled on a structural low.

ture map, it was anticipated that well 3 would be a producer like wells 1 and 2. However, well 3 was a dry hole, and it was recognized that a three-dimensional seismic survey would improve the structure map required for locating additional productive wells.

Figure 5 shows the field layout for the three-dimensional survey in relation to the contour map obtained by the two-dimensional seismic survey. A total of 14 rectangles (1.2 by 2.0 km) were surveyed. Receiver groups and sources were both spaced at 134-m intervals. Each dot in the surveyed rectangles indicates the location of a seismic trace. Figure 6 is a three-dimensional migrated section extracted from the seismic data base along a traverse through several wells. It shows that well 3 is actually situated over a structural low; since oil and gas usually migrate to a trap in a structural high, this explains why well 3 did not produce. The contour map for the Agua Caliente horizon generated from the three-dimensional seismic data is shown in Fig. 7. Although well 3 is clearly misplaced, the three-dimensional survey outlined a drillable structure north of well 3 that was entirely missed by the two-dimensional seismic method.

Conclusions

The three-dimensional seismic method contributes to the cost-effective delineation and development of petroleum reserves. Dense sampling of the subsurface ensures that small features, which are becoming increasingly important as producers, are detected and outlined correctly. In areas where access to the land is difficult, the three-dimensional method still provides seismic coverage to meet exploration objectives. Accurate mapping of the reservoir configuration allows engineers to determine an optimum field development plan that minimizes the number of dry wells.

References and Notes

1. W. S. French, *Geophysics* **39**, 265 (1974).
2. P. Hubral [*ibid.* **41**, 233 (1976)] gives a solution to the problem of deriving the material velocity and reflector depth for a three-dimensional layered model of the earth from surface measurements of normal incidence time T_0 and normal moveout velocity V_{NMO} measured along the seismic survey line. Hubral's method can also be used to predict V_{NMO} in the direction required for normal moveout of seismic traces whose source-receiver pairs do not fall on the survey line.
3. J. G. Hagedoorn [*Geophys. Prospect.* **2**, 85 (1954)] describes a method of migration based on the complementary properties of wave front curves and diffraction curves. This method is applied to two- and three-dimensional migration of reflection events by means of graphs prepared for specific velocity distributions within the earth.
4. J. F. Claerbout, *Fundamentals of Geophysical Data Processing: With Application to Petroleum Prospecting* (McGraw-Hill, New York, 1976), pp. 236–246. Finite-difference solutions of migration are implemented by transforming the wave equation to a coordinate system that moves along with the upgoing wave front. The resulting partial differential equation is then approximated for the cases of wave fronts approaching the surface with an angle smaller than 15° or smaller than 45°.
5. W. A. Schneider [*Geophysics* **43**, 49 (1978)] shows that downward continuation of the wave field $u(x, y, 0, t)$ recorded on the surface of the earth and application of the imaging principle based on the "explosive reflector model" leads to the following expression for the three-dimensional migrated wave field in the Cartesian image space x, y, z:

$$V(x, y, z, 0) = -\frac{1}{2\pi}\frac{\partial}{\partial z}\iint dx_0 dy_0 \frac{u(x_0, y_0, 0, R/C)}{R}$$

where $R = \sqrt{(x - x_0)^2 + (y - y_0)^2 + z^2}$ and C is the velocity of the compressional waves in the medium. The explosive reflector model assumes that the normally incident wave field estimated by means of the CDP method can be simulated by the hypothetical experiment of placing explosives on the reflecting interfaces. The strength of these sources is proportional to the reflection coefficients and, at time zero, all explode simultaneously generating a wave field that propagates upward with half the velocity C of the medium.
6. R. H. Stolt [*Geophysics* **43**, 23 (1978)] published the following expression for the migrated wave field:

$$V(x, y, z, 0) = (2\pi)^{-3/2}\int dk_x \int dk_y dw \times \frac{U\left(k_x, k_y, w\sqrt{1 + (k_x^2 + k_y^2)C^2/4w^2}\right)}{\sqrt{1 + (k_x^2 + k_y^2)C^2/4w^2}} \times e^{i(xk_x + yk_y - 2wz/C)}$$

where U is the triple Fourier transform of the normally incident wave field u recorded on the surface of the earth:

$$U(k_x, k_y, w, 0) = (2\pi)^{-3/2}\int dx \int dy \times \int dt\, u(x, y, 0, t)\, e^{-i(xk_x + yk_y - wt)}$$

This migration algorithm can be implemented efficiently on the digital computer with fast Fourier transforms. Application of this method to media with variable velocity C requires adjustment of the recorded data by means of a stretch operation.
7. This case history is adapted from B. F. Giles, J. A. Kerfuss, and M. R. Bone (paper presented at the annual meeting of the Society of Exploration Geophysicists, Calgary, Canada, in September 1977 and is published with permission of the Occidental Petroleum Company).

Organic Farming in the Corn Belt

William Lockeretz, Georgia Shearer, Daniel H. Kohl

Widespread use of chemicals—manufactured fertilizers, as well as synthetic herbicides, insecticides, and other pesticides—is one of the most characteristic features of the modern agricultural era. This period, dating roughly from World War II, has been marked by rapid and fundamental changes in agricultural production methods. Because agricultural chemicals have enabled farmers to obtain higher yields per unit of land with lower labor requirements and lower overall production costs, their use has become a standard feature of most of the country's major agricultural systems. Total use of fertilizers and pesticides has increased more than sevenfold since 1945 (*1*).

Despite the generally accepted benefits that fertilizers and pesticides provide, an initial period of unimpeded adoption and continuously increasing use was followed by a closer examination of their full range of implications and a growing concern over some of their unforeseen consequences. Thus, a recognition in the 1960's of the unintended effects of insecticides on nontarget organisms, possibly including man, eventually led to the banning in the 1970's of several important ones, especially chlorinated hydrocarbons. Nitrogen fertilizers have been implicated in some agricultural areas as a significant contributor to high nitrate levels in drinking supplies (often exceeding the U.S. Public Health Service recommended limit) (*2*). Finally, manufacture of virtually all major fertilizers and pesticides requires considerable inputs of fossil fuels (*3*).

Because of these concerns, farmers, agricultural researchers, and extension workers in the past several years have

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