A geophysical outlook—Part 3

3D seismic techniques aid exploration, development

H. Roice Nelson, Jr., General Manager, Allied Geophysical Laboratories, University of Houston

10-second summary

Three-dimensional (3D) seismic techniques are rapidly becoming more acceptable as a geophysical exploration tool, especially as a tool for field development. This article reviews the procedures for 3D seismic data collection, processing and interpretation used in both land and marine environments. This is the third article in a series on new geophysical exploration technologies.

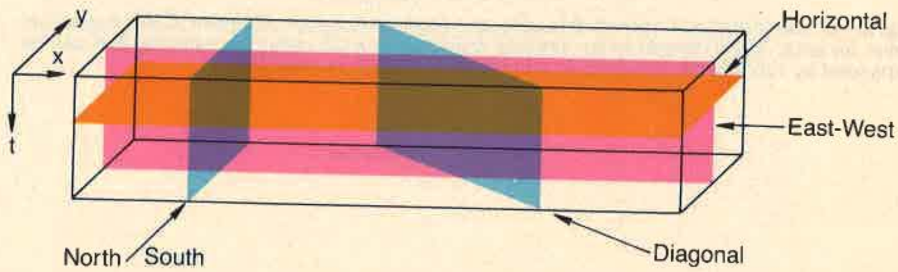

Fig. 1—A 3D data volume allows for a much more complete evaluation of the subsurface. The data can be vertically sliced in any arbitrary direction to allow interpretation along the lines critical to an accurate evaluation. Horizontal sections can also be generated from a data volume.

THREE DIMENSIONAL SEISMOLOGY has been established as a viable geophysical exploration method over the last five years. There have been more than 100 3D seismic surveys shot during this time over both land and marine projects. These surveys have covered a variety of land environments ranging from the Arctic to jungles, and from shallow water marshes to the Rocky Mountains; however, a majority of the surveys have been marine.

Seismic reflection surveys are normally carried out to solve a three-dimensional geologic problem. It is only logical to solve these problems with data sets that fill a 3D volume, rather than relying on 2D vertical seismic sections as has been historically done. With a 3D volume of data, traditional vertical seismic sections can be generated along any azimuth or direction (Fig. 1). This allows evaluation of seismic data between wells, or along arbitrary directions that define critical geologic dip or closure. Horizontal seismic sections can also be generated from this data volume.

Probably more than half of the 3D surveys to date have been associated with field development projects[1]. The 3D method provides a sufficiently accurate and detailed picture of the subsurface to be economically attractive in developing a field. There are two primary ways that the procedure is proving to be economical. The first is to shorten the time between a discovery and subsequent production. The second cost savings comes in the ability to reduce the number of development wells by using a 3D seismic survey to avoid dry holes and to allow more accurate well placement. Also, untested blocks are frequently identified. The tradeoff in cost of 3D seismic versus development wells is documented in Table 1.

3D ACQUISITION

Design of areal data collection systems can cover as many methods as the explorationists' ingenuity and the number of channels will allow. The distribution of sources and receivers over an area instead of along a line, as in multifold profiling, squares the possible trace locations.

When data are collected over an area, there are specific locations for the source and the receiver. The midpoint between a specific source and receiver combination is tradi-

TABLE 1—The Tradeoff: 3D seismic vs. wells[2]

Area	Dry Development Well Cost* ($K)	3D Seismic Cost/Square Mile ($K)
Peru	2,000-3,000	30-40
North Sea	2,000-4,000	30-40
Gulf of Mexico	1,200-1,800	25-30
Alaska Land	2,000-2,500	50-80
U.S. Lower 48	700-1,000	35-50

*Well cost based on 10,000 ft. depth.

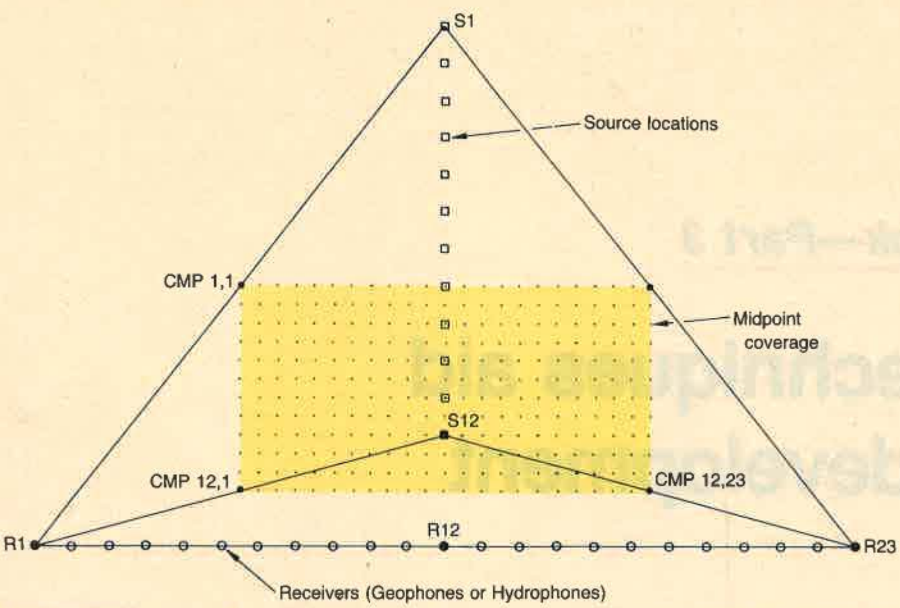

Fig. 2—Cross-spread or T-spread data collection provides common mid-point (CMP) traces that cover an area. The T-spread is the simplest reduction of a 3D collection scheme, and can be expanded by running the receivers or sources in any arbitrary direction.

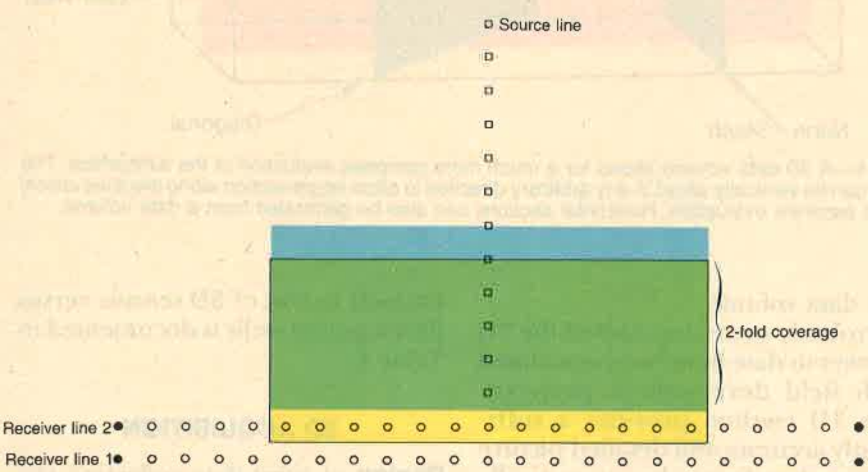

Fig. 3—By shooting multiple source lines into the same receiver array, any desired CMP redundancy can be achieved. In the example above there is 2-fold coverage in the overlapped area and single fold coverage elsewhere. When there are two traces with different offsets at the same CMP, the data is referred to as 2-fold. Most 2D data collected today is 24, 48 or 96-fold, and by adding this redundant data together it improves the signal-to-noise ratio.

tionally referred to as a CDP (common depth point). However, the more geometrically correct title of CMP (common midpoint) is coming into use also. The four variables defining areal data are the CMP latitude and longtitude coordinates, the offset from source to receiver and the azimuth of the offset. Linear profiling, on the other hand, usually has only two defining variables, a CMP location number and the offset distance.[3]

The two most common methods of 3D acquisition are **parallel CMP profiles** and **cross-spreads,** the most straight forward method being the collection of a set of closely spaced parallel lines, which is most common with marine 3D surveys. If there are strong cross currents the deflection of the cable from the planned survey line can be much larger than the spacing between the lines. This problem can be solved by using a cable with a set of digital compasses to compute the location of each hydrophone group for each shot.[4]

The simplest geometrical representation of all other types of 3D seismic surveys is the **T-spread** (Fig. 2). A T-spread consists of a line of receivers and a perpendicular line of sources. The CMP's cover an area half of that defined by multiplying the source line length by the receiver line length. It is important to note that each CMP has a different offset, and so a different NMO (normal moveout) correction is required for each trace.

A cross-spread is an extension of the T-spread where the source and the receiver lines cross. Cross-spreads have been used for marine work but are generally used on land where the cost of parallel line profiling is too high and the necessary access is often denied. Normally, several parallel lines of geophones can be used to record each shot simultaneously. The overlapping of cross-spreads results in multifold data for each CMP (Fig. 3). The cost of these surveys is reduced by increasing the number of channels recorded per shot. With over 500 channels per shot, the cost of 3D and 2D acquisition are about equal.[3]

A further generalization of the T-spread is to place the receivers in a square or a loop and to shoot at stations around the square or loop. The advantage is that both in-line CDP data and areal data are collected. The multifold in-line data can be used to estimate state corrections and velocities, using standard programs, while the areal data sample the interior of the loop.

Although it is desirable to keep source and receiver lines straight and perpendicular to each other when collecting areal data, it is more important to place them so that the generation and detection of the signals will be reliable and repeatable. The most generally known example of this is G.S.I.'s Seisloop™. An example of this type of data collection is where receivers are placed along roads surrounding an inaccessible area of interest. As seismic sources are activated around this perimeter, CMP trace locations are generated that cover the area inside the loop. A set of bins are defined, and all of the traces that are spatially located in one of these bins are processed as being at the same CMP. By proper planning, a set of these data volumes can be put together to provide seismic coverage over an otherwise inaccessible area. Access may be denied to a specific area of interest for reasons varying from culture, to topography, to vegetation, to a lack of permits.

Missing shots or receivers will remove a row or a column from the CMP trace location grid. Isolated gaps will have no appreciable effect on the results. However, if the data are not sampled densely enough over the area or in time, there can be spatial or temporal aliasing. Aliasing, or a loss of frequency information, occurs when there are less than two samples per cycle; thereby an input signal at a high frequency results in output at a lower frequency. For a 330-foot (100 meter) surface sampling interval (165 feet or 50 meters subsurface), and a 30 Hz. signal, spatial aliasing will occur for dips over about 30 degrees. As a general rule in 3D data aquisition, it is better to place the receiver groups and shot arrays closer together than is customary for in-line work and to have a smaller fold. Land surveys with shot and receiver spacings of 80 feet (25 meters) have been successfully executed.

Accurate surveying is critical in collecting a useable 3D data volume. The purpose of the surveying is to determine (x,y) coordinates and elevations for every source and receiver station, to relate the data to the corresponding CMP seismic trace, and to relate the (x,y) coordinates to fixed geographic markers.[3] Although straight forward, this is often one of the hardest steps to properly plan and efficiently carry out. In a typical 3D survey there may be several thousand stations and several million traces.

There have been many improvements in surveying techniques as was discussed in the first article of this series. Leo Romeyn with Geodetic Surveys pointed out to the author that using satellite point positioning techniques and applying rotation and scale can result in a 2-meter accuracy for 40 satellite passes in, for example, Wyoming. With a previously surveyed geoidal profile and using the translocation short-arc techniques, ±40 cm (x,y,z) positions can be obtained.

In order to relate the location information to each CMP trace it is helpful to decide on an indexing scheme. For example, each station can be indexed by the source number on a named source line, and the receiver number on a named receiver line. If these indices are recorded on magnetic tape along with the coordinates and elevations, then the order of the traces on the tape is not important. This has been found to work well in practice.[3]

Receiver arrays, can be designed to efficiently attenuate surface waves and air waves along a 2D line. However, it is much more difficult to design effective 3D receiver arrays. Point receiver stations have provided excellent processed results for 3D data sets.[1] It is also much easier logistically to do the "jug hustling" (placement and retrieval of the geophones) with point receiver stations. The point receiver stations can be combined in different manners during processing to remove the noise trains. This is one major reason why it is better to use as many active recording channels as possible, as discussed in the second article of this series. By using a 1,000-channel crew, a multi-arm cross-spread can be set out with receiver stations close enough together to allow 3D receiver array simulation in the computer. It is useful to be able to do some processing in the field in order to evaluate the noise attenuation.

PROCESSING 3D DATA SETS

The volume of data produced by a 3D survey is staggering. A 48-fold marine survey with 125 lines having 100 shotpoints and recording 5 seconds of 4 ms data results in 7.5×10^8 digital samples, each a 32-bit word, which equals 2.4×10^{10} bits of data. The processing produces an output of about 5×10^8 bits. Each of these output bits results from thousands of manipulations during the processing steps.

The need to handle large amounts of data quickly in seismic processing has been a major motivating force in the development of the modern array processors and the new super vector computers. The increase in the number and size of 3D seismic surveys is certain to have additional impact on the future development of computer technology along with the economics of the energy crisis.

Seismic processing of 3D data sets includes all of the processing steps required in standard 2D work. However, there are some additional problems that must be addressed in 3D work, starting with the amount of data that has to be handled simultaneously. In addition, it is important that there is sufficient multifold coverage for accurate velocity analysis and statics corrections. This can be accomplished with cross-spreads by shooting a standard multifold line along specific lines of receivers, or by laying out receivers for a multifold line along the line of sources.

The three issues of statics, velocity and migration are critical for sucessfully processing a 3D survey. Statics are the time shifts in data due to near surface velocity changes caused by weathering, permafrost, etc. The redundancy of large-fold CMP data can be used to reduce the uncertainty of statics estimates. Statics can have a major impact on velocity estimates and the choice of velocity affects the migration or focusing of the data.

Defining the proper velocity is of central importance to both stacking and migration. The velocities used in these two processes are normally different. Stacking velocities are related to NMO analysis of the reflection events in CMP gathers (groups). Normal moveout is the correction that needs to be applied to traces with different offsets located at the same CMP. Once these traces are corrected, they can be added together or stacked to improve the signal-to-noise ratio. Stacking velocities depends on layer velocity and interface dip, while migration velocities are independent of the dip of the reflecting surface.[5]

Migration is a focusing procedure that moves data into a proper position in space. The removal of fault diffractions are an example of the focusing accomplished using a standard 2D migration algorithm. Because seismic waves in the earth propagate in 3D and subsurface geology is 3D, vertical sections normally show energy from outside the plane. It has been clearly shown that 3D migration is necessary to construct accurate vertical profiles.[6]

The full 3D migration of a volume of seismic data requires that all of the data within the radius of the migration aperture be available for the computation of each output trace. The simultaneous storage and manipulation of this many traces is complicated and requires tremendous computer power. One simplification is to do a 3D migration in two steps, each step consisting of a 2D migration.[7] This reduces the computation effort from N^2 traces to $2N$, and simplifies the necessary data handling when the Kirchhoff-sum-

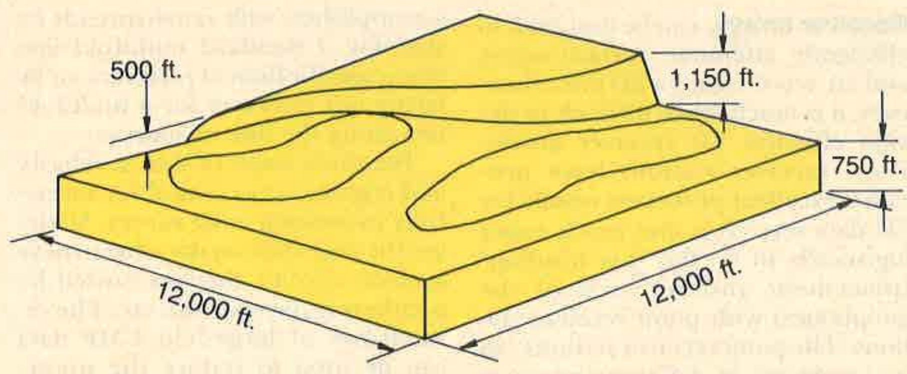

Fig. 4—Three dimensional physical or theoretical models, like 'SALGLF' provide a method of learning what to look for in a 3D field survey. The synthetic data collected over such a model can also be used to test 3D processing algorithms.

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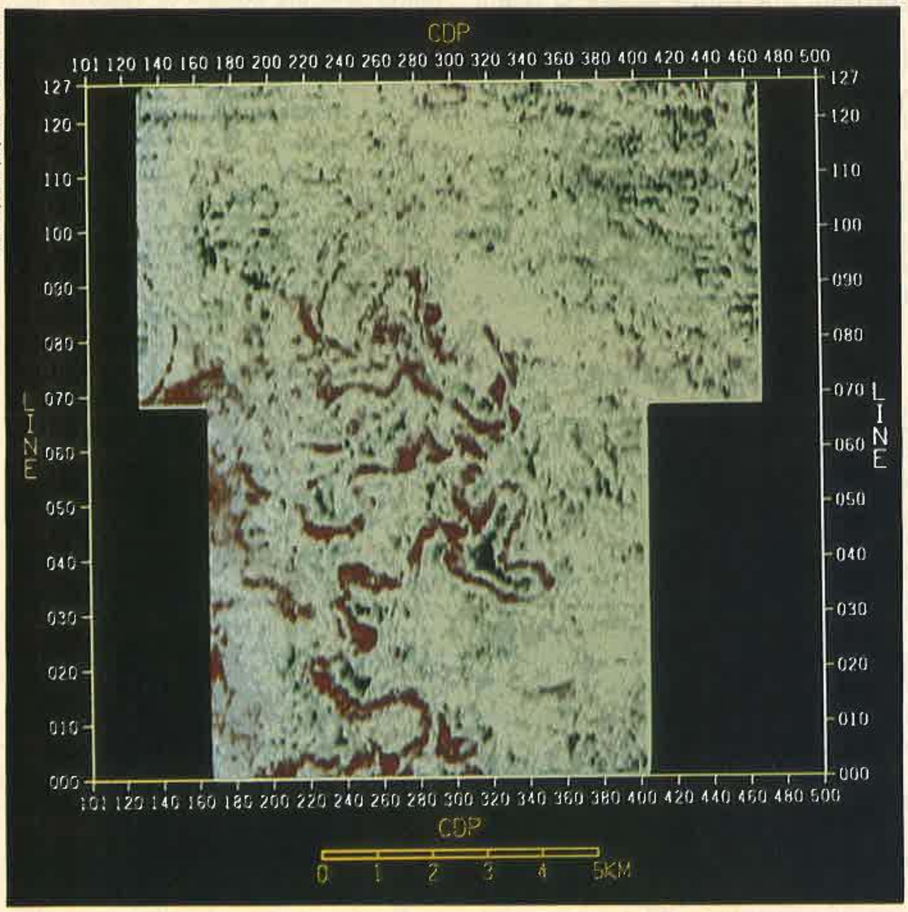

Fig. 5—The unique capabilities to interpret a subsurface geologic sequence with 3D data volumes is shown by this horizontal (SEISCROP) seismic section slicing a meandering stream channel in the Gulf of Thailand.

mation method is used. The two-step method fails to produce the same results as a full single-pass 3D migration when the medium velocity is not constant, but the error usually does not seriously affect the interpretation.

Modeling of the problem synthetically or using physical scaled models can greatly aid in evaluating the success of the 3D processing, as well as in testing a proposed field layout or checking an interpretation (Fig. 4).[6,8,9] For example, migration of a 2D line that runs obliquely across a simple basin model produces an apparent fault.[10] True 3D migration would image the basin accurately. Work done by Gulf Oil pointed out that areal seismic processing techniques for detecting reefs were considerably aided by making use of experimental model data.[11]

3D INTERPRETATION

Interpretation methods have had to change to meet the quantity of data associated with a 3D survey. These changes are still happening and cover a wide range of techniques. For example, a display box is used that has many vertical profiles on film. The interpreter will pull out a section of interest and mark it, then place the section back in 3D space to see how well it fits the other data. Reflection holography has also been used to display data, although once displayed this data cannot be changed or interpreted. One of the best ways of working with 3D data sets is with animated movies of horizontal sections. These movies can be tied to an interpretation table so that as the sections are stepped through the interpreter can make a contour map.[12]

Horizontal sections have been shown to be worthwhile interpretation aids.[11] Most of the examples available come from the contractors, one example being shown in Fig. 5. Coloring the complex attributes of the seismic traces on horizontal sections give another dimension of understanding. A horizontal section with the same number of data points as a vertical section will cover an area at least 10 times as large, because spatial sampling is so much larger than the distance represented between time samples along a seismic trace.[13]

Display technology has improved to the point where it can be used for interactive interpretation of 3D data volumes (Fig. 6).[14,15,16] This is an area where there is presently a lot of development taking place. It is reasonable to project that within a few years most interpretation groups will have access to some form of interactive interpretation console. The merging of this technology with data base management systems that provide interaction between landsat, geochemical, potential, well-logs and surface geology data sets is not very far over the horizon. If all of this were tied to real time 3D migration and velocity analysis and interpretation techniques we could catch up to the tremendous advances that have occured in data collection and processing procedures and hardware.

SUMMARY

Three-dimensional seismic techniques have been established as a viable geophysical exploration tool. The most common use of the procedures described is in field development. The extension of seismic data

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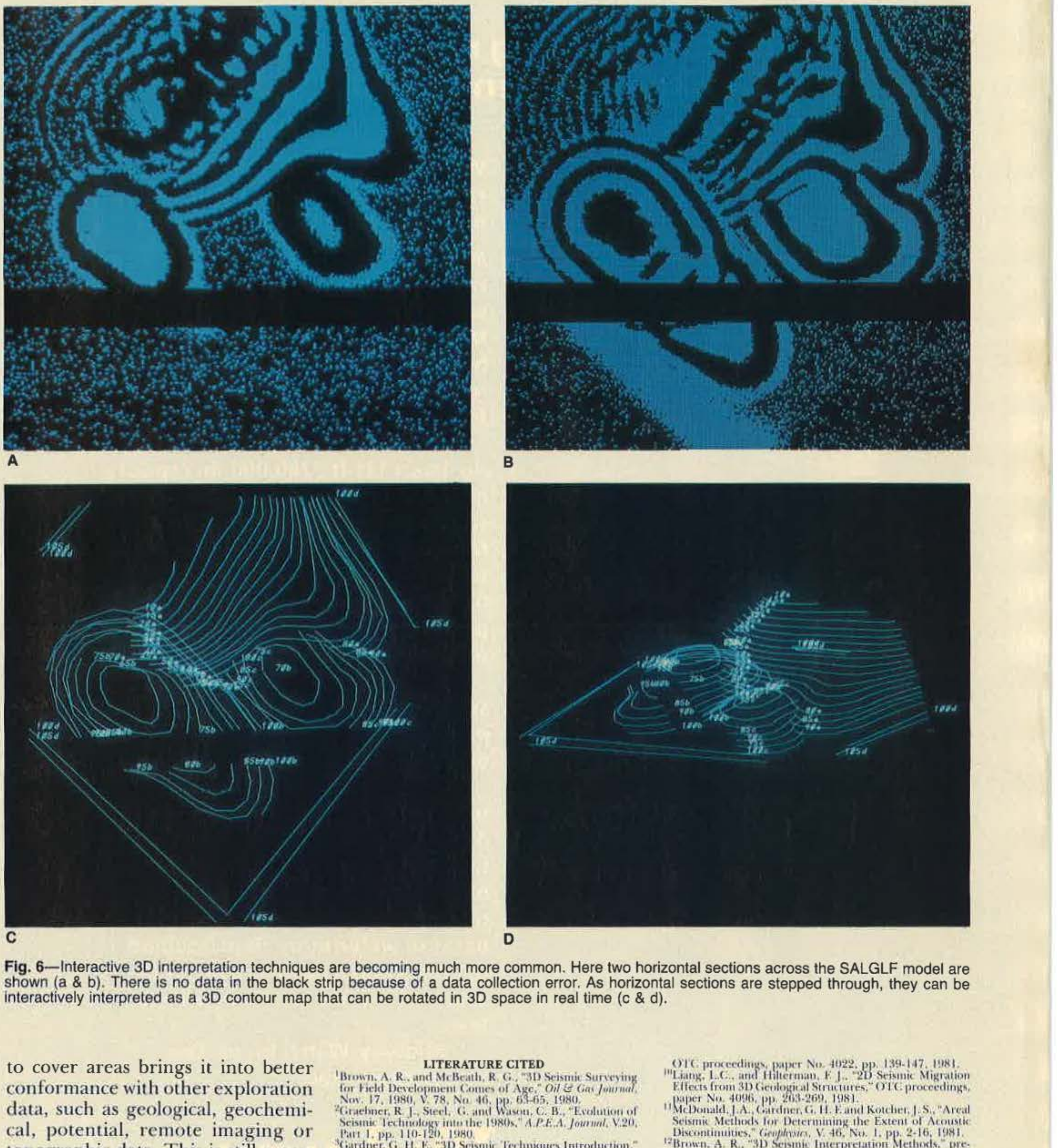

Fig. 6—Interactive 3D interpretation techniques are becoming much more common. Here two horizontal sections across the SALGLF model are shown (a & b). There is no data in the black strip because of a data collection error. As horizontal sections are stepped through, they can be interactively interpreted as a 3D contour map that can be rotated in 3D space in real time (c & d).

to cover areas brings it into better conformance with other exploration data, such as geological, geochemical, potential, remote imaging or topographic data. This is still a new technology. Therefore, there are many changes and improvements presently being developed in acquisition, processing, and especially interpretation procedures.

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