A Geophysical Outlook—Part 5

Modeling resolves complex seismic events

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10-second summary

Physical and theoretical seismic modeling techniques are old and yet new technologies. Traditionally these procedures have been used by researchers as tools to better understand the relationship of the seismic trace to the various geologic acoustic discontinuities that generate the recorded response. This article, the fifth in a series on new exploration technologies, briefly summarizes the historic development of modeling techniques, reviews a few current lessons being learned from modeling and shows how modeling can aid interpreters.

SYNTHETIC SEISMIC TRACE generation has evolved into today's theoretical and physical modeling techniques. Synthetic seismic traces are of interest to explorationists because the only material information about subsurface geology comes from sparsely spaced well information in the form of cores or logs. From this one-dimensional information the explorationist must correlate and interpret to explain three-dimensional geologic structures and stratigraphic sequences. Creating a synthetic seismic trace from a sonic log and matching this to a seismic trace from a 2D or 3D seismic survey enables the explorationist to expand available well information along a line or over an area. In short, available data are extrapolated into a probable three-dimensional, geologic setting. But how much reliance can be placed on such extrapolation?

The information on each individual unprocessed trace is the acoustic response from three-dimensional subterranean geological surfaces. This is true whether the trace is from a check shot survey, a seismic line or a seismic volume.[1] Even after the most sophisticated processing algorithms have been applied and the best possible interpretation made, these geologic surfaces are still unknown. One way to gain confidence in the interpretation of these geologic sequences is to model them. Modeling techniques start with precisely known interfaces. If the information on the seismic traces derived from this known model interface is completely understood, there is more confidence in the interpretation of similar events from field generated data. Many different methods have been used to model these interfaces.

ONE-DIMENSIONAL MODELING

Most major oil company research groups used some form of physical modeling before digital computers provided simpler testing. Frank Levin, now at Exxon Production Research, was doing 1D (one-dimensional) physical model experiments as early as 1949.[2] These experiments consisted of measuring the air wave that traveled through long thin tubes with changing diameters. In this type of a model, the cross-sectional area is proportional to the density, and the "springiness" to density times velocity. An impulse was generated by a magnet on a propeller that passed an induction coil. The signal was displayed on an analog oscilloscope.

Synthetic seismic traces from well logs are the most common example of 1D theoretical modeling. An example of early 1D modeling that predates active use of digital com-

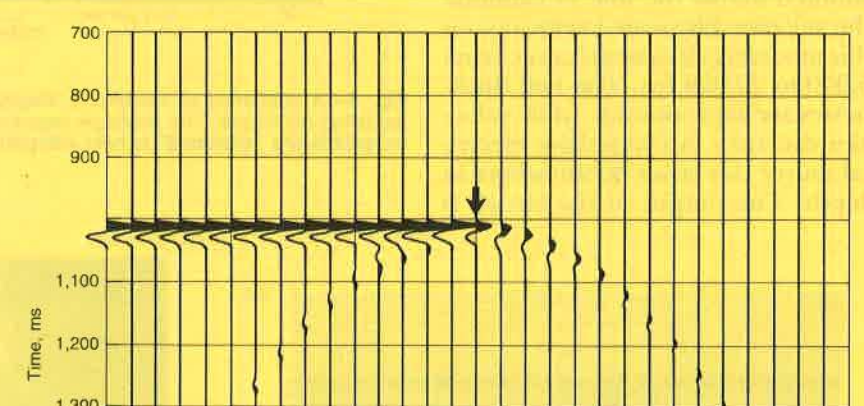


Fig. 1—Wide-band seismic response from a flat boundary. Note that the response amplitude drops by half at the edge. Also, the diffraction has the same polarity beyond the reflector, but is 180° out of phase on the same side as the reflecting boundary.

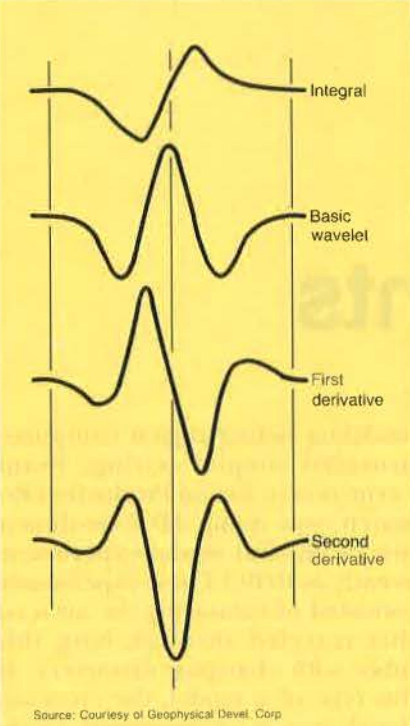


Fig. 2—A graphical representation of a basic wavelet and its integral and derivative shapes in the time domain.

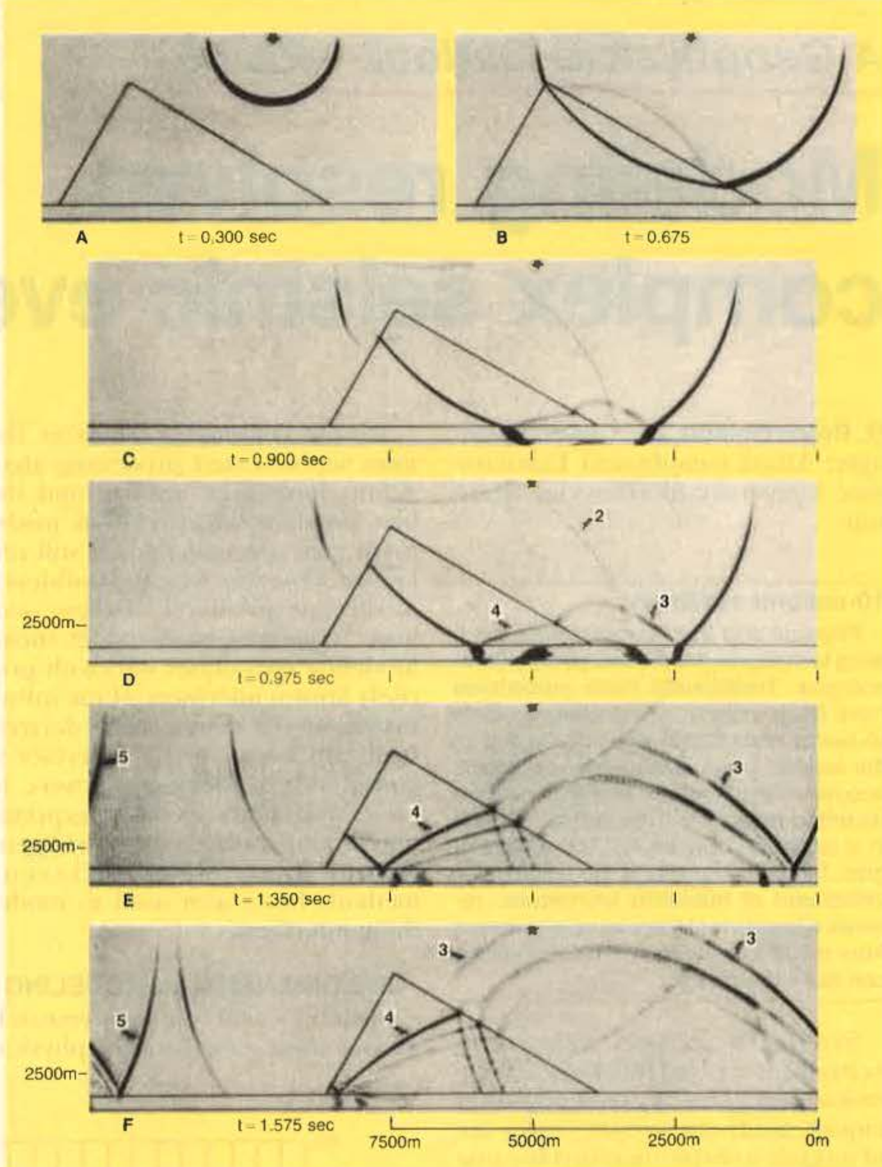
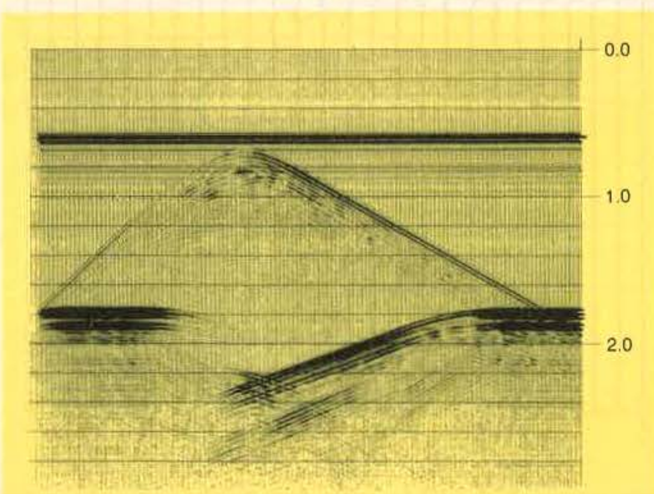


Fig. 3—A sequence of wavefront "snapshots" calculated using the Kosloff, Baysal Fourier modeling technique. The pressure response is calculated at specific time steps and then the snapshots are "animated" to help interpret specific events as numbered.

puters is the Seismoline. This device, built by John Sherwood at Chevron, models the wave equation solution with an electric circuit. The seismic response in this unit is generated by an electric delay line. In this circuit, an inductance series is proportional to mass while a variable capacitor is shunted across the line to calibrate the velocity. The scaled velocities on this modeling device can range from 5,000 to 22,000 fps. The bed thicknesses are kept constant, while velocities can vary. An impulsive electrical source can be set off anywhere in depth. The output of the circuit is



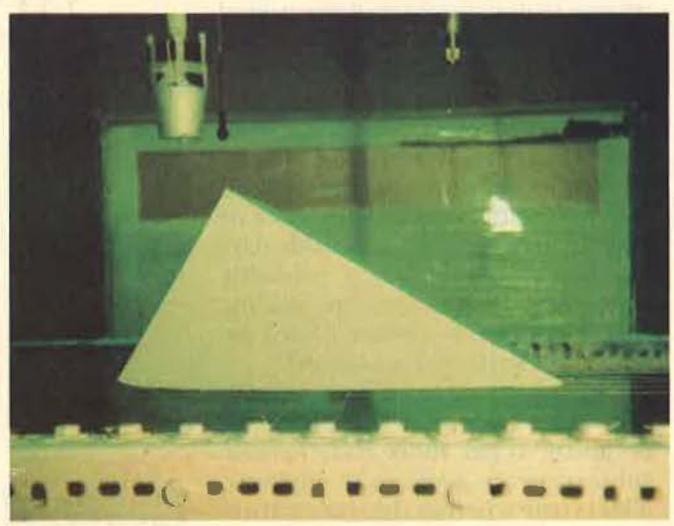


Fig. 4—A 2D wedge physical model is shown accompanied by a seismic section across the model.

monitored by an analog oscilloscope.[3] The response can thus be evaluated in real time. Back in the early 1960s every division in Chevron had one of these units, because they were more convenient than using digital computers.

TWO-DIMENSIONAL MODELING

One of the first publications on physical modeling was the work of Oliver, Press and Ewing in 1954.[4] This experiment studied 2D (two-dimensional) seismology problems using ultrasonic pulses propagating in small scale models. Thin discs (1/16 in. thick and 20 in. in diameter) were used as a medium for studying surface waves propagating around the circumference of the disc. By building the disc from concentric rings of various materials, more complex models were generated. The source pulses were initiated at one position on the edge of the disc and then measured at some other position on the edge.

Southern Methodist University has a 2D modeling system that was built and used at Mobil Field Research for many years. This modeling system used thin sheets of various metals with various thicknesses to simulate vertical 2D cross sections. A 2D faulted horizon is represented by connecting two different sheets of metal with a matching step. Piezoelectric transducers are used as the source and receiver. These transducers are placed at specific positions along the top of the cross section where a seismic trace is desired, and then moved across the cross section to generate a seismic section.

Similar physical modeling research was done by most major oil companies. The author is aware that there also has been extensive work at Amoco, Exxon, Gulf, Texaco and by Russian geophysicists. Other variations of 2D modeling systems included milling the metal cross section sheets to different thicknesses at interface boundaries, drilling small holes in the sheets to vary the velocity, and attaching plastic sheets or other materials to change the thickness of the thin cross sections. An important factor in this work is that the wave length be long compared to the thickness of the cross sections. These techniques are not used widely today, but they are good for illustration purposes.

Another related physical model experiment was carried out by John

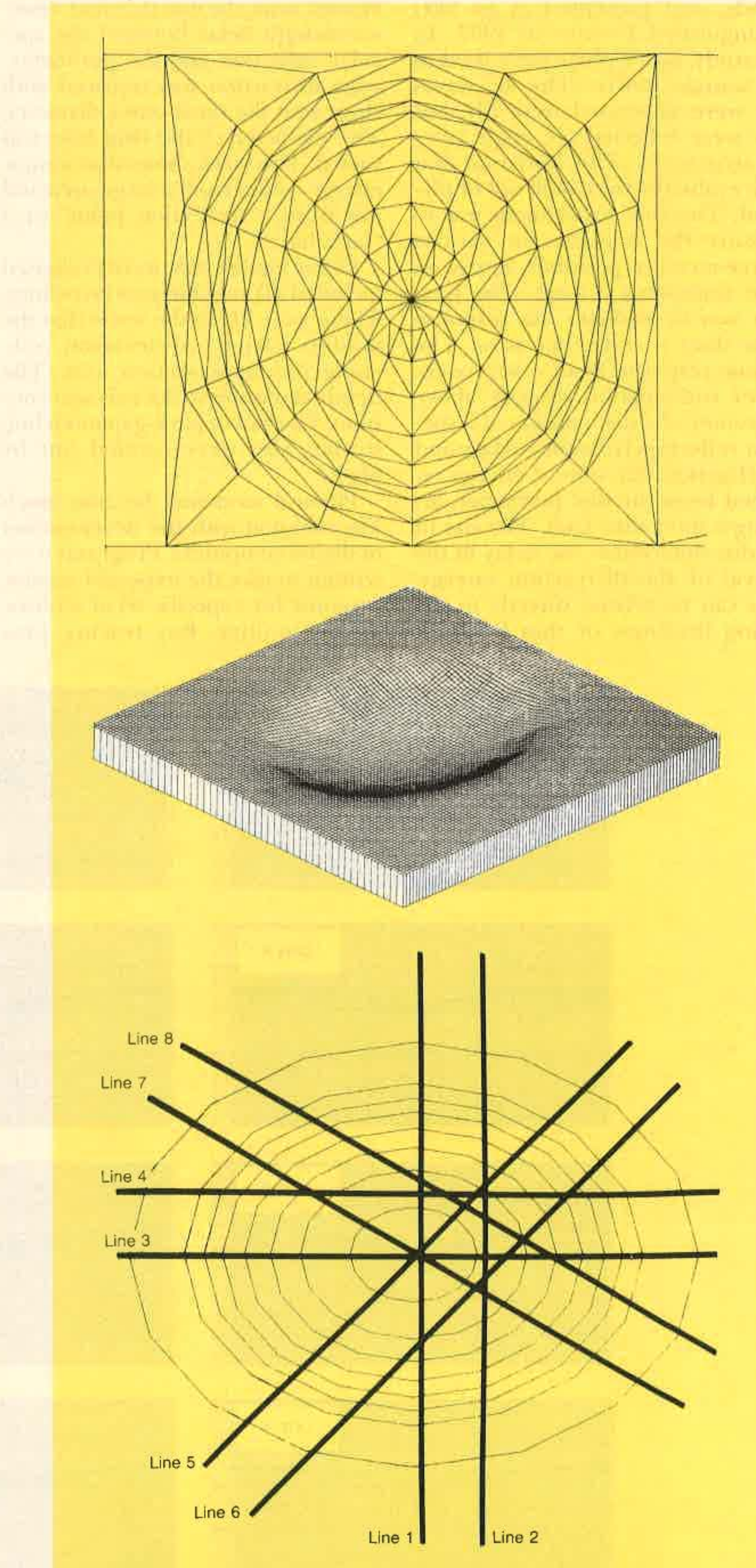


Fig. 5—The definition of a theoretical basin for Kirchhoff forward modeling is illustrated here. A map view of the triangular plates for a symmetrical basin is shown, followed by an isometric view of the oblong basin and a location map for specific synthetic sections called Lines 1-8.[16]

Woods, and presented as an SEG Distinguished Lecture in 1967. In this study, spark plugs were used as the seismic source. The air waves that were generated were 3D, but they were reflected off single layer 2D structures. The horizons that were evaluated were built out of plywood. The first experiment was to measure the response for various source-receiver positions across an edge simulating a fault. The next step was to evaluate the response from discs of different sizes. The seismic response from a source-receiver combination directly above the center of a disc consists of a specular reflection from the surface and a diffraction, the sum of energy reflected from the disc perimeter, arriving a short time later. The size of the disc determines the delay in the arrival of the diffraction energy. This can be related directly to the tuning thickness of thin beds. In Woods' work the disc that had a two-wavelength delay between the specular reflection and the perimeter edge diffraction was replaced with rings with the same outer diameter. The diameter of the ring hole was varied. This work shows that seismic energy comes from a large area and not from a "reflection point" or a "fault line."[5]

Other models that were evaluated included 2D anticlines and synclines. These were 2D in the sense that the models varied in elevation only along the cross section axis. The depth along the strike axis was constant. Extensive spark-gap modeling studies also were carried out by Shell.[6]

Physical modeling became much less common with the development of digital computers. Programs were written to give the expected seismic response for a specific set of acoustic discontinuities. Ray tracing programs have been used for the last 10 years on storage tube computer terminals to help interpreters visualize where recorded energy is coming from. This has been very helpful in defining what portions of complex 2D structures are expected to be seen on the seismic section. However, these techniques are being used less as theoretical modeling techniques become more sophisticated.

Kirchhoff forward modeling is one widely used method of making 2D and also single layer 3D theoretical models. This theory is based on the theoretical diffraction response shown in Fig. 1.[7] Note that the synthetic seismic profile across the fault edge is composed of two parts, a reflection and a diffraction. A normal incidence reflection from the boundary occurs up to the edge, and a positive diffraction event with the same polarity occurs beyond the ter-

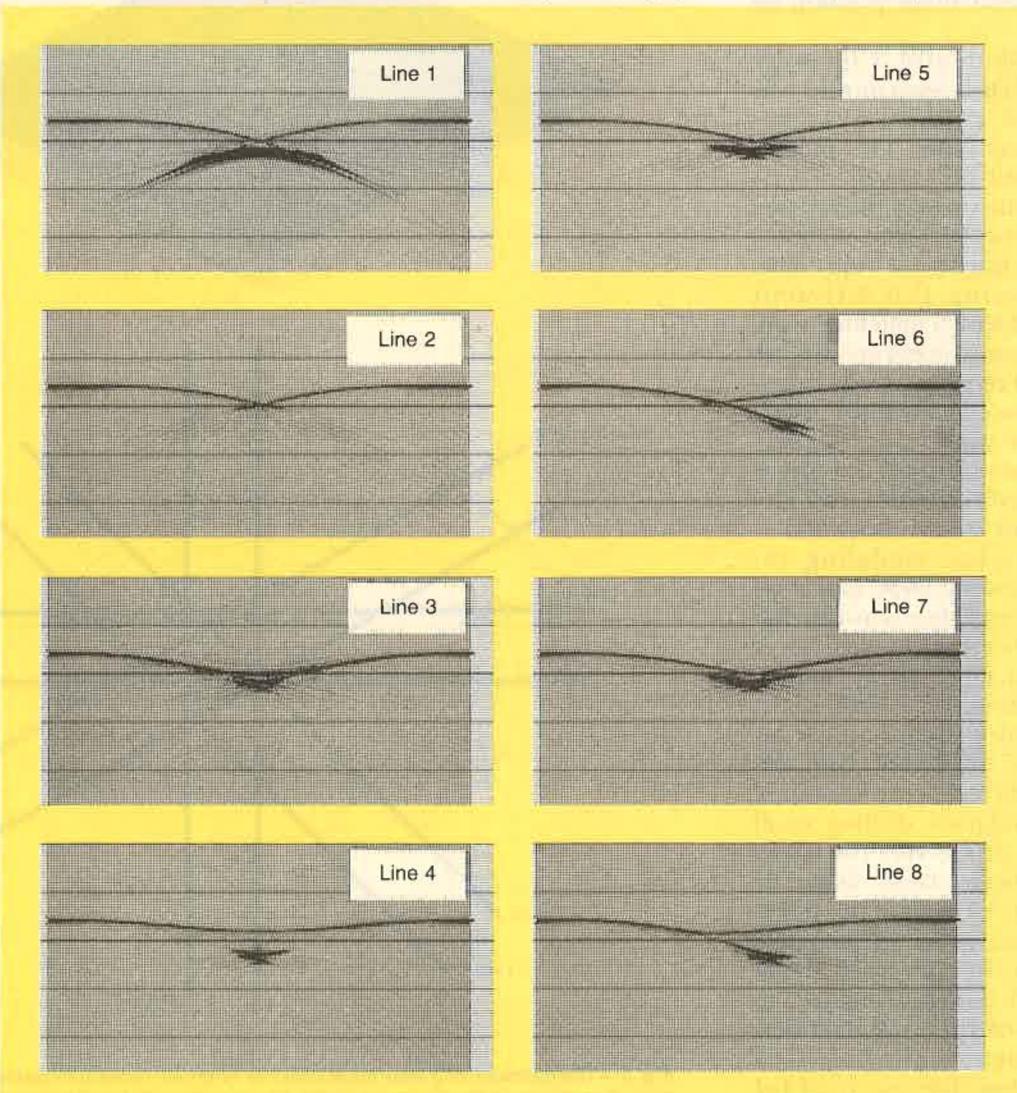


Fig. 6—Unprocessed or raw sections generated across the Fig. 5 oblong model show the complex seismic events generated by a simple model. Note the expected bow-tie effect on Line 1. Line 4 shows a 3D effect where focused energy from the far flanks of the structure are not connected to the reflected horizon.[16]

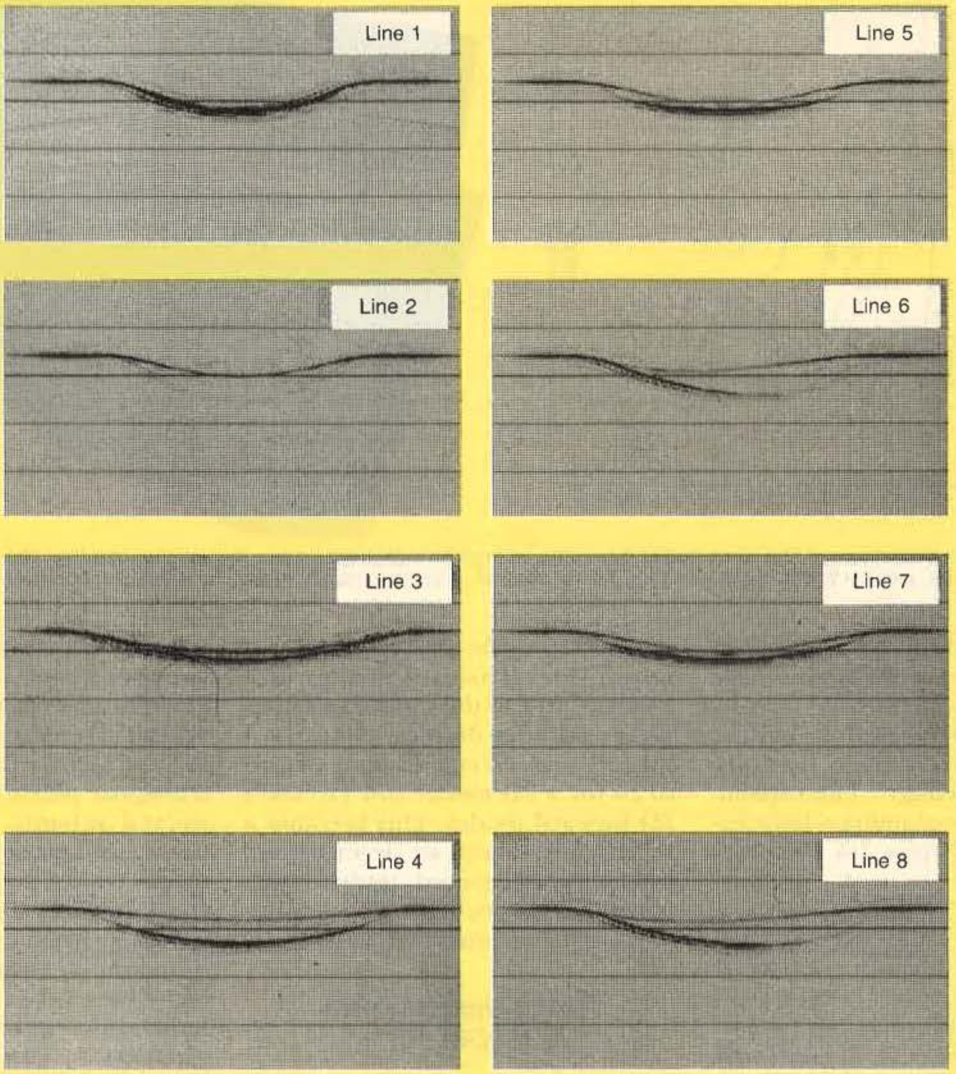


Fig. 7.—Migrated data from the Fig. 5 model illustrates that 2D migration does not properly image 3D structures. Note the apparent graben on Lines 5 and 7, and the large fault on Line 6.[15]

mination of the reflector. However, there is a negative diffraction event on the same side as the edge of the reflection. These diffraction events have opposite polarity (they are 180° out of phase) and represent the dipole nature of this type of modeling.[8]

In Kirchhoff forward modeling, the boundary is mathematically defined as a 2D strip that goes into and out of the plane described by the cross section in Fig. 1. The boundary is made very short into a strip. Then a series of these strips are put together to define faults, synclines, anticlines and other structures that can be related to subsurface geology. The synthetic seismic response for a single trace turns out to be the summation of the diffractions from these mathematical strips for a specific source-receiver position. By repeating the procedure for different source-receiver positions, synthetic seismic sections are created.

The Finite Difference method of modeling extends this single layer approach to multiple 2D layers. Each layer can be assigned a different density-velocity combination in order to represent the reflection coefficients or the acoustic impedance expected from different geologic interfaces. This method of forward modeling has been presented in the literature by Amoco researchers.[9,10] The seismic modeling algorithms that use finite differences operate on a discrete mesh. This mesh is filled with the elastic constants that describe the geologic model, including density and velocity. The pressure response is then calculated for each time step to create synthetic traces.

Each of the forward modeling methods requires that a derivative of the waveform be calculated as part of the algorithm. Fig. 2 gives a graphical summary of a wavelet and the integral and derivative shapes in the time domain. With finite difference modeling there needs to be about 10 samples per wavelength in order to approximate the derivative of the waveform.[9] This is a critical factor in attempting to expand this forward modeling technique to three dimensions.

Overall, the finite difference approach is simple and may be implemented readily. This method of forward modeling provides proper relative amplitudes for the various seismic wave arrivals. Contributions from converted waves, Rayleigh wave, diffractions from faulted zones and head waves are all included in the seismic response.

One of the advantages of this type of theoretical modeling procedure is

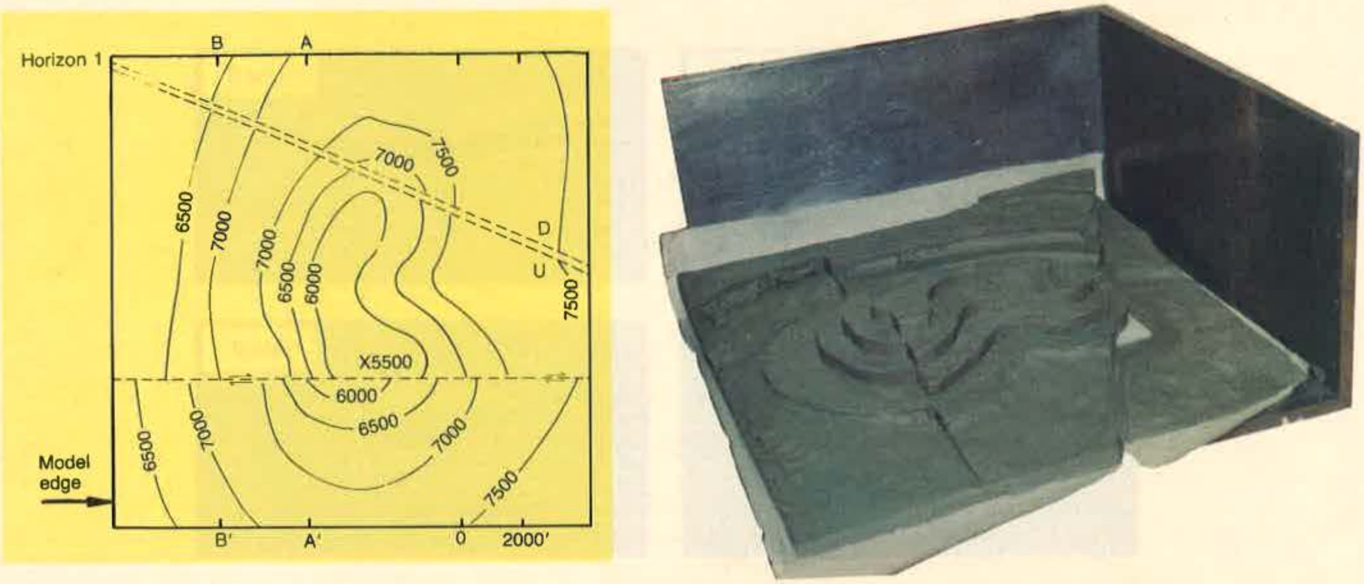


Fig. 8—The contour map shown is first converted to clay contours to make a physical model. The contours are then filled in with clay. A plaster negative cast is made, and the silicon rubber, or other model material, is poured into this cast. The physical model shown is called SALFAN.

that the wave front can be stopped in time. This allows a "snapshot" of the position of the wave front for any specified time to be plotted. Kelly, *et al*, described this capability for finite difference modeling.[10] This capability is useful in evaluating where energy is coming from for different models.

When these "snapshots" are animated, the interpreter is given a tool that allows him to watch the various seismic waves move through a model. By displaying "snapshot" movies both forward and backward, events that cannot otherwise be interpreted can be followed from the time they were recorded back to the time when they were generated. This is shown in the sequence of wavefront "snapshots" in Fig. 3, taken from an animation of work by Dan Kosloff and Edip Baysal at the University of Houston's Seismic Acoustics Laboratory (SAL).[11] The movie brings the wave fronts "alive."

The interpretational usefulness of this technique is shown in Fig. 3 through the explanation of a "mystery event" (labeled 'E') from a 2D wedge physical model experiment. It turns out that this is a diffraction from the top of the wedge. Both the physical model and a physical model section are shown in the sequence of events in Fig. 4.

Fourier forward modeling by Dan Kosloff is a hybrid technique that calculates the derivatives in the frequency domain. The major benefit here is that only two samples per wavelength are needed in order to approximate the derivative of the waveform.[11] This is a savings of a factor of five in the number of samples required to define a 1D forward model. This savings factor expands to 25 for a 2D model and 125 for a 3D forward model. This becomes a significant factor in determining whether multilayered, multivelocity 3D models can be run using a realistic amount of computer time.

THREE-DIMENSIONAL MODELING

Frank Levin also was involved in some of the early 3D physical modeling studies. In one project, a two-bed model consisted of 3 in. of cement over a 1-in. sheet of marble. Ultrasonic pulse generators were used as the source.[12] Although the model was really 2D, in that it did not vary along one spatial axis, there were some interesting results. One conclusion (taken for granted today) was that two in-line detectors could reduce surface waves.

The biggest problem with the physical model approach is that once the models are built it is necessary to start over from the beginning to change the model. However, this is not a problem if 3D models are generated theoretically using a computer algorithm.

One widely used 3D modeling **theoretical technique** is Kirchhoff forward modeling. For example, the Geoquest AIMS modeling package is based on this method. The 3D Kirchhoff technique uses triangular plates to represent a 3D surface. In the same way that the diffraction responses from small strips were added to give the reflection response for the 2D case, the 3D method adds the diffraction responses from the triangular plates to arrive at the expected seismic response.[13] The source and receiver can be arbitrarily placed in 3D space above the defined surface. This allows for the synthetic generation of single traces, seismic lines, multi-fold lines or seismic volumes. The literature only describes this type of modeling for single surfaces. However, Fred Hilterman has developed a multilayered version of this algorithm.[8]

The Fourier method of forward modeling is presently being vectorized at the University of Houston's Research Computation Laboratory (RCL).[14] When this is operational, it will be possible to generate synthetic seismic traces over any arbitrary multilayered, multivelocity 3D model. It is also planned to generate 3D "snapshot" sequences and to eventually animate them on a true 3D display device. It is not feasible to do this with finite difference modeling because the number of samples required makes storage and computation time requirements unrealistic.

There are many interpretative lessons that can be learned using the 3D forward modeling techniques. Fred Hilterman[13] and Luh-Cheng Liang[15] have presented illustrations of these lessons. Synthetic sections taken across a geologic basin are good examples of their work.[16] Fig. 5 illustrates example theoretical models with three drawings showing

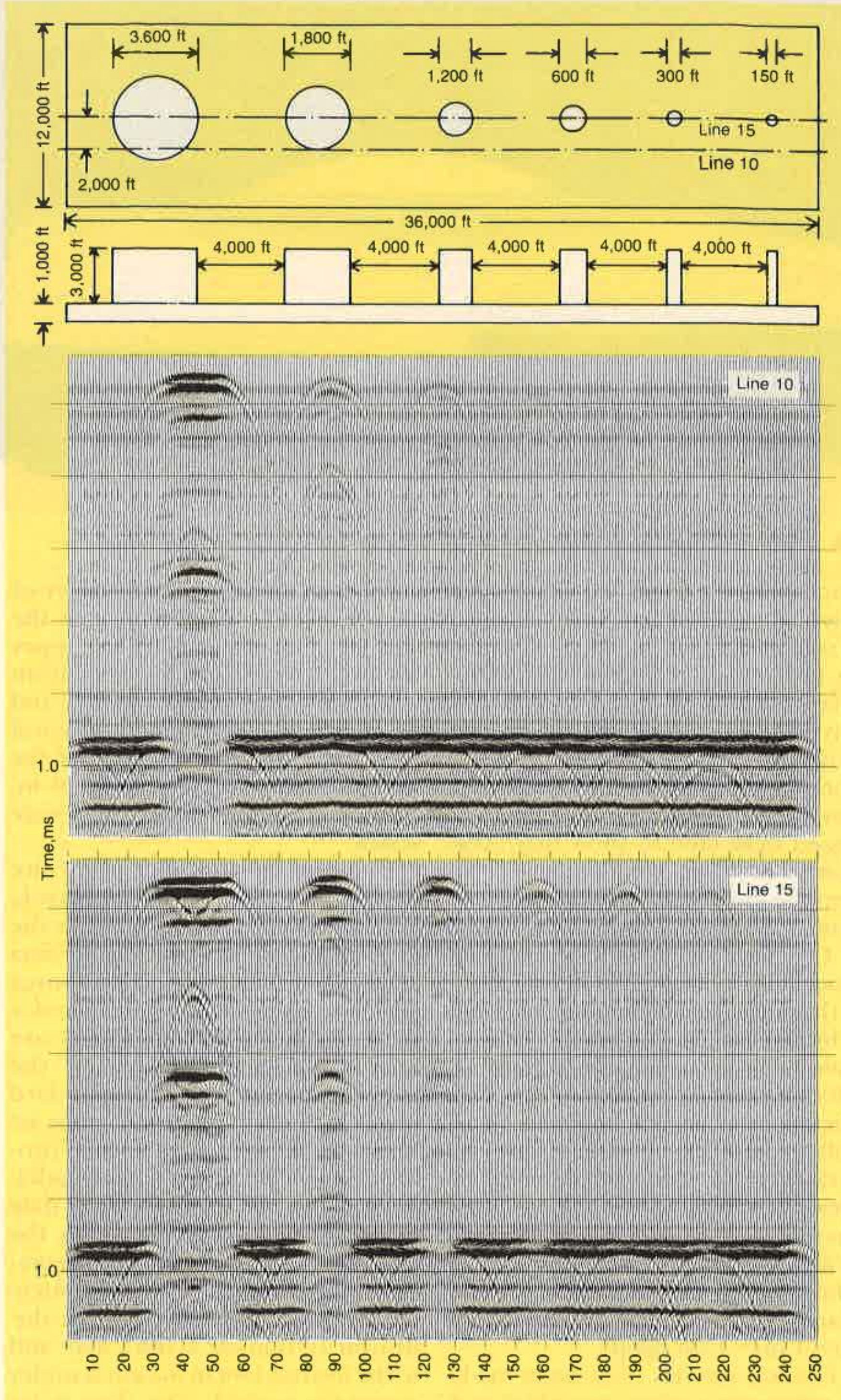


Fig. 9—A map view and side view of physical model SALFRS is shown. Note the expected response on the seismic section for Line 15 as the discs get smaller. The 2,000-ft separation between the sections shows the importance of proper spatial sampling in order to see events that can indicate significant hydrocarbon prospects.

the triangular representation of a symmetrical basin, an isometic drawing of an oblong basin and the location of eight synthetic sections overlain on a 100-ft contour map of the oblong basin. The scaled radii of curvature in the two principal planes of this oblong basin are 4,000 and 7,000 ft, respectively. The scaled velocity down to the modeled interface is 12,000 fps. The basin is 750 ft deep and the square edge of the isometric drawing scales to 12,000 ft on a side. Fig. 6 depicts the raw sections generated for a source-receiver placed 5,500 ft above the model. One 3D effect is shown on Line 4. Here, focused events from the far flank of the structure are not connected to the upper horizon. Fig. 7 reveals 2D migrations of the sections in Fig. 6. Note that there appears to be a fault on Line 6 and a graben on Lines 5 and 7. Much of the ringiness on the migrated sections is due to spurious events from out-of-plane lips of the basin.

It is important to note that each of the theoretical modeling methods is forced to assume the characteristics of seismic noise. In many cases, diffractions, multiples and thin bed "noise" of the real world *cannot* be represented as well by theoretical modeling as by physical modeling.

A **3D physical modeling** box using the spark gap method was described by Fred Hilterman in 1970.[17] However, Bill French designed and built a water tank that has proved more effective for 3D physical modeling. This was built for Gulf Research and Development in Pittsburgh. A paper in 1974 describes how the system was used to collect data over 3D models. These data were used to study 2D and 3D migration techniques.[18]

A more recent example of work done with this system is an article by John McDonald, *et al*, in 1981.[19] This

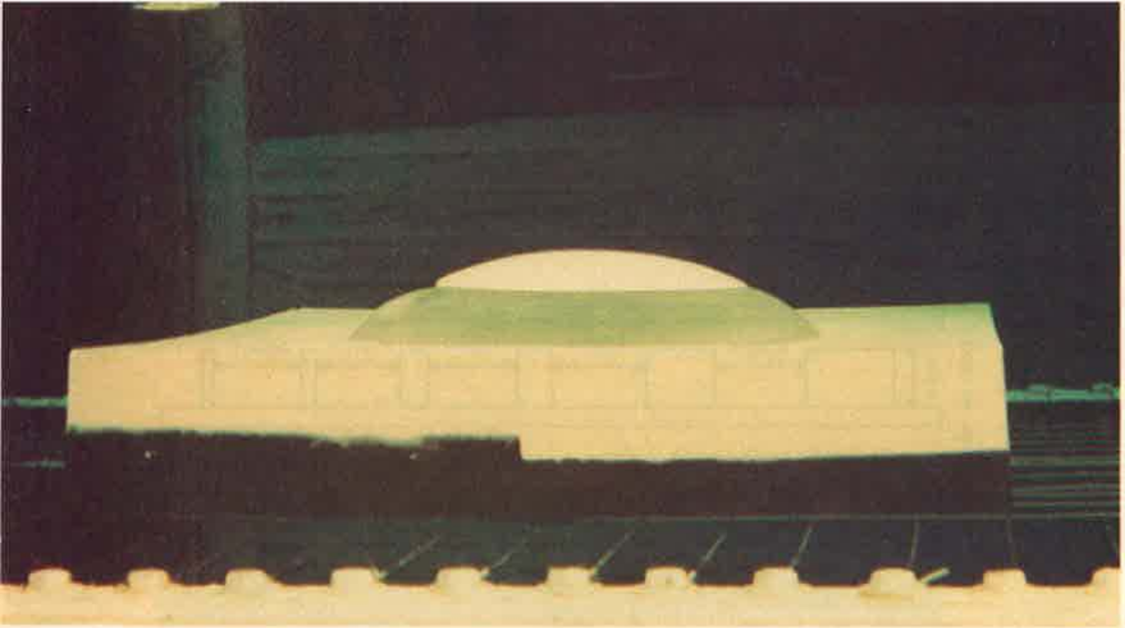


Fig. 10—The 3D model SALHCI is shown in the water tank.

work describes how the water tank physical modeling system was used to solve an interpretation problem in an area without appreciable structure in the subsurface. A volume of physical model data was processed to produce an instantaneous phase horizontal section. These sections were compared to similarly processed field data to show that areal seismic methods can be used to determine the extent of an acoustic discontinuity caused by a pinnacle reef.

This type of water tank physical modeling system has been expanded at the SAL. The SAL model tank is 8 ft by 6 ft by 5 ft deep. Everything is scaled so that 1 in. equals 1,000 ft, 130 kHz equals 30 Hz, and the 0.2 microsecond sample rate equals 1 millisecond (ms). Models of the subsurface structures are made out of plexiglass (scaled velocity 21,600 fps) or different silicon rubbers (scaled velocity around 8,000 fps). The models are normally smaller than 24 in. by 24 in. by 5 in. (scaled 4 mi × 4 mi × 1 mi deep).

Physical models have been made to represent various structural and stratigraphic sequences.[16,20] There have been several proprietary models built for individual SAL sponsors that represent specific exploration problems or fields being developed. Some of these multilayered models have been built directly from an interpreter's contour maps. Fig. 8 shows a simple example of a contour map that was converted to the two-layer, faulted anticline physical model named SALFAN.[21] This model was built by cutting the contours out of clay. The contours were then filled in with clay, and a plaster cast was made. The bottom layer of silicon rubber was poured into the cast from the bottom. The upper layer of this model was poured from a side, between the bottom layer and another cast. The resulting physical model is a 3D representation of the contour map. This model is 16 in. square, or about 3 mi on a side scaled.

These models are placed on a wire mesh in the center of the water tank, and then data are collected over the models in a manner similar to data collection in the field. The source and receiver are high frequency piezoelectric transducers that are moved above the surface of the model by a pair of plotters. Standard patterns of data collection can be set up to simulate any kind of field procedures. In fact, the physical modeling tank can be used to collect data that are difficult to obtain in the field, like tape sequential CMP (common midpoint) gathers. The plotters move under computer control to the nearest 10 ft in the x and y axes and to the nearest foot in the z axis under computer control. The data is recorded in tape sequential format on standard magnetic tapes.

It takes an average of 1.5 sec for the plotters to move to the next shot point position, to fire the transducers and to record the data on tape. The plotters can be moved according to a preset pattern, or by having each source-receiver position specified on cards or magnetic tape. A 24-fold line, five mi (8 km) long and with a 330-ft (100-m) trace spacing will take less than 2 hours to collect. A 3D T-spread survey with 48 receivers, 96 shots per receiver set-up, and 12 set-ups, will take about 24 hours to collect. Once the model is properly located and the data collection started, the system can be left to run itself for up to 16,000 traces, or about 7 hours, without even a change of tapes.

Simple models have proved to generate data sets that require detailed evaluation to understand all of the events. Also, it is often useful to do a theoretical model study before building the physical model. The physical models can be modified by adding and removing material on exposed surfaces. It is easier to build the model right the first time. However, when compared to the cost of a well drilled in the wrong place, building a new model to answer an exploration problem is not much trouble.

Fig. 9 is an example of a simple model, called SALFRS, that can be used in many ways to help interpreters understand some exploration problems. This model is a series of plexiglass cylinders sitting on a flat base plate.[22] Fig. 9 shows two single-fold sections across this model. Note the difference in the reflection as the discs get smaller. If the exploration objective were the size of one of these Fresnel discs, note the response from that size disc on Line 10 where the line passes 2,000 ft from the center of the object.

Another simple physical model example is the multi-velocity structural model SALHCI. The model is shown in the water tank in Fig. 10. This geologic model is an asymmetrical, double plunging anticline with scaled relief of 1,750 ft. The upper

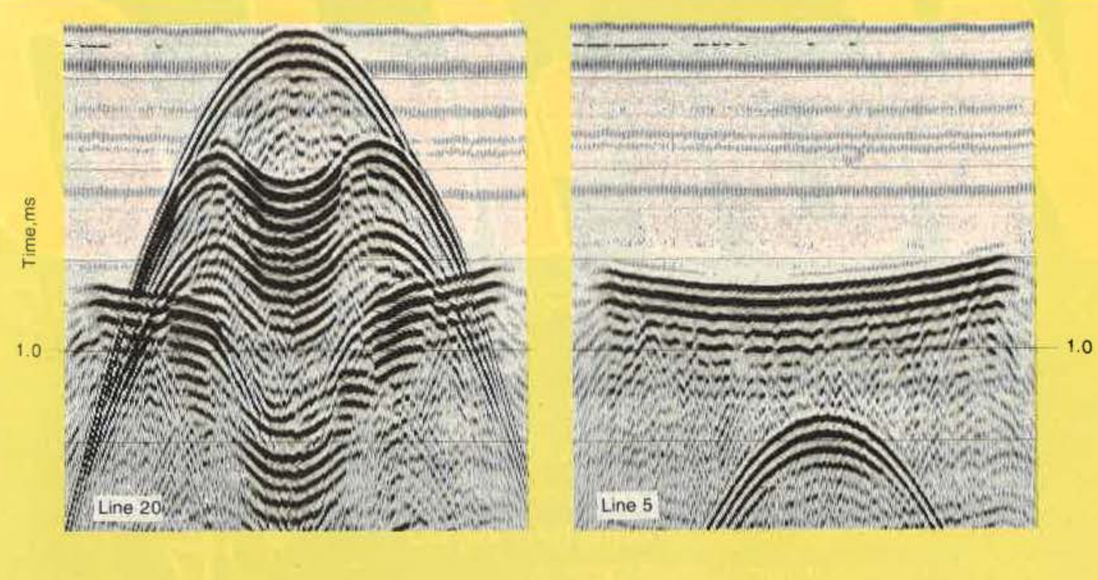
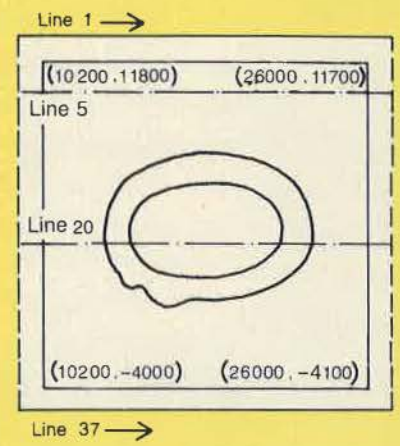


Fig. 11—A map view of the SALHCI model is shown with two seismic lines referenced. Seismic sections for each of the lines are illustrated. Note the sideswipe from the model edge as indicated in the section for Line 5. The velocity push-down from the low velocity (gas) cap is shown in the section from Line 20.



750 ft is a low velocity, 8,000 fps, cap made of silicon rubber. The lower portion of the dome represents a high velocity layer, 21,600 fps, and is made of plexiglass. The surrounding water velocity scales to about 12,000 fps. Fig. 11 shows an example map of 37 lines of single-fold common-offset data. Accompanying are examples of two sections of raw data. Note the sideswipe energy coming in when the line passes about one-half mile from the structure on Line 5. Line 20 is across the center of the model. It shows the velocity push-down due to the low velocity (gas) cap and the velocity pull-up of the plexiglass base on the flanks of the dome. These graphic examples can be very useful in training interpreters to find drillable structures on their seismic sections.

SUMMARY

Physical and theoretical modeling have been used throughout the history of seismic exploration as a tool to understand field-recorded data. As time has passed, these tools have been improved. The modeling techniques described are finding their way out of the research labs and into use by explorationists. It is very helpful for a person developing new algorithms to have a set of data from a known feature on which to test the new programs. Seismic interpreters can use these tools to come to a better understanding of their seismic sections and to explain complex events on field data. As 3D modeling techniques are improved, case histories will be developed that document how field development has been aided by physical and theoretical modeling.

ACKNOWLEDGEMENT

In an article like this, which refers to the historical development of a subject, some significant contributors will certainly have been missed. I apologize in advance. If you, as a reader, have contributions in this area, please forward them to the author's attention.

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LITERATURE CITED

[1]Nelson, H. R., Jr., "3D Seismic Techniques Aid Exploration, Development," *World Oil*, pp. 115–120, December, 1981.
[2]Levin, F. K., Exxon Production Research, personal communication, 1981.
[3]Sherwood, J. W. C., "The Seismoline An Analog Computer of Theoretical Seismograms," *Geophysics*, V. 27, No. 1, pp. 19–34, 1962.
[4]Oliver, J., Press, F., and Ewing, M., "Two-Dimensional Model Seismology," *Geophysics*, V. 19, No. 2, pp. 202–219, 1954.
[5]Woods, J. P., "A Seismic Model Using Sound Waves in Air," *Geophysics*, V. 40, No. 4, pp. 593–607, 1975.
[6]Sherwood, J. W. C., Geophysical Development Corporation, personal communication, 1981.
[7]Trorey, A. W., "A Simple Theory for Seismic Diffractions," *Geophysics*, V. 35, No. 5, pp. 762–784, 1970.
[8]Hilterman, F. J., Geophysical Development Corporation, personal communication, 1981.
[9]Alford, R. M., Kelly, K. R., and Boore, D.M., "Accuracy of Finite-Difference Modeling of the Acoustic Wave Equation," *Geophysics*, V. 39, No. 6, pp. 834–842, 1974.
[10]Kelly, K. R., *et al*, "Synthetic Seismograms: A Finite-Difference Approach," *Geophysics*, V. 41, No. 1, pp. 2–27, 1976.
[11]Kosloff, D. D., and Baysal, E., "Forward Modeling by a Fourier Method," presentation at 51st annual international SEG meeting, Los Angeles, 1981.
[12]Levin, F. K., and Hibbard, H. C., "Three-Dimensional Seismic Modeling Studies," *Geophysics*, V. 20, No. 1, pp. 19–32, 1955.
[13]Hilterman, F. J., "Interpretative Lessons from Three-Dimensional Modeling," preprint of presentation given at 46th annual international SEG meeting, Houston, Texas, 1976 (see also abstract, *Geophysics*, V. 42, No. 1, p. 156, 1977).
[14]Nelson, H. R., Jr., "New vector super computers promote seismic advancements," *World Oil*, January 1982.
[15]Liang, L. C., and Hilterman, F. J., "2D Seismic Migration Effects from 3D Geological Structures," OTC proceedings, paper No. 4096, pp. 263–269, 1981.
[16]Liang, L. C., and Hilterman, F. J., "2D Effects from 3D Structures," SAL Semi-Annual Progress Review, V.7, pp. I.1–74, 1981.
[17]Hilterman, F. J., "Three-Dimensional Seismic Modeling," *Geophysics*, V. 35, No. 6, pp. 1,020–1,037, 1970.
[18]French, W. S., "Two Dimensional and Three-Dimensional Migration of Model Experiment Reflection Profiles," *Geophysics*, V. 39, No. 3, pp. 265–277, 1974.
[19]McDonald, J. A., Gardner, G. H. F., and Kotcher, J. S., "Areal Seismic Methods for Determining the Extent of Acoustic Discontinuities," *Geophysics*, V. 46, No. 1, pp. 2–16, 1981.
[20]Hilterman, F. J., Nelson, H. R., Jr., Gardner, G. H. F., "Physical Modeling: An Aid for Production Geophysicists," OTC proceedings, paper No. 4022, pp. 139–147, 1981.
[21]Physical Model Catalog No. 4, SAL Semi-Annual Progress Review, V. 7, pp. J 46–52, 1981.
[22]Physical Model Catalog No. 4, SAL Semi-Annual Progress Review, V. 7, pp. J 33–37, 1981.
[23]SAL Physical Model Catalog No. 2, pp. 91–99, 1980. ■

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