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 mostly 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 development of some of modeling techniques, reviews a few examples of lessons that are being learned, and shows how modeling can aid interpreters.

SYNTHETIC SEISMIC TRACE generation has evolved into todays theoretical and physical modeling techniques. Why are synthetic seismic traces of interest to explorationists? The only material information about subsurface geology comes from sparsely spaced well information in the form of cores or logs. This one-dimensional information is then correlated and interpreted 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 expands the well information along a line or over an area.

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 interpretation possible 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 of the 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 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 impuse 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 computers is the Seismoline. This device was built by John Sherwood at Chevron, and 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 5000 to 22000 feet per second. 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 monitored by an analog oscilloscope.[3] The response can thus be evaluated in real time. Back in the early 1960's 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 seismology problems using ultrasonic pulses propagating in small scale models. Thin discs (1/16 inch thick and 20 inches in diameter) were used as a medium for studing 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 two-dimensional 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 transduceres 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 of the major oil companies. The author is aware that there has also 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 really used widely today, but they are very good for illustration purposes.

Another related physical model experiment was carried out by John 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 of 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 directly related 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 only varied in elevation along along the cross-section axis. The depth along the strike axis was constant. Extensive spark gap modeling studies were also 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 have 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 figure 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 termination 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 this type of modeling, the boundary is mathematically defined as a 2D strip that goes into and out of the plane described by the cross-section in figure 1. The boundary is made very short into a strip.

Then a series of these strips are put together used 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. Figure 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 approximately 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 differance approach is simple and may be readily implemented. 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 proceedure is that the wave front can be stopped in time. This allows a "snapshot" of the position of the wave front at any specified time to be plotted. Kelly, et al described this capability for finite difference modeling.[10] This capability is very 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 back and forth, events that could not otherwise be interpreted can be followed from the time they are recorded back to the time when they are generated. This is shown in the sequence of wavefront "snapshots" in figure 3. This is from an animation of some 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 expaining a "mystery" event from a 2D wedge physical model experiment. It turns out that this is a diffraction from the top of the wedge. The physical model, a physical model section, and the theoretical model are shown in the sequence of pictures in figure 4.

Dan Kosloff's **Fourier forward modeling** is a hybrid technique that calculates the derivatives in the frequency domain. The major benefit here is that there only have to be 2 samples per wavelength in order to approximate the derivative of the waveform.[11] This is a savings of a factor of 5 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 for whether multilayered, multivelocity 3D models can be run using a realistic amount of computer time.

Three-Dimensional Modeling

Frank Levin was also involved in some of the early 3D physical model studies. In one project, a two-bed model consisted of three inches of cement over a one inch 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 these approaches is that once the models are built you have to start from scratch 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. This is the method that the Geoquest AIMS modeling package is based on. 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 get the expected seismic response.[13] The source and receiver can be arbitrarily placed in three 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 working 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 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 make 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. The basin results are a good example of their work.[16] Figure 5 illustrates this problem with three pictures that show the triangular representation of a symmetric basin, and isometric drawing of an oblong basin, and the location of 8 synthetic sections overlain on a 100-foot contour map of the oblong basin. The scaled radii of curvature in the two principal planes of this oblong basin are 4000 and 7000 feet respectively. The scaled velocity down to the modeled interface is 12,000 ft/sec. The basin is 750 feet deep and the square edge of the isometric drawing scales to 12,000 feet on a side. Figure 6 shows the raw sections generated for a source-receiver placed 5500 feet above the model. One 3D effect is shown on line 4. Here a focused events from the far flank of the structure are not connected to the upper horizon. Figure 7 shows 2D migrations of the sections in figure 6. Note that there appears to be a fault on line 6, and a graben on lines 5 and 7. Much of the ringyness 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 can not 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 to do 3D physical modeling. This was built for Gulf Research and Development in Pittsburg, Pennsylvania. A paper in 1974 describes how the system was used to collect data over 3D models. This data was used to study 2D and 3D migration techniques.[18] A more recent example of work done with this system is the article by John McDonald, et al in 1981.[19] This 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 similiarly processed field data to 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 x 6 ft x 5 ft deep. Everything is scaled so that 1 inch equals 1000 feet, 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 ft/sec) or different silicon rubbers (scaled velocity around 8,000 ft/sec). The models are normally smaller than 24 in x 24 in x 5 in (scaled 4 miles x 4 miles x 1 mile 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 interpreters contour maps. Figure 8 shows a simple example of two contour maps that were converted to the two layer faulted anticline physical model SALFAN.[21] This model was built by cutting the contours out of clay as shown in figure 9. The contours were then filled in with clay and a plaster cast 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 shown in figure 10. This model is 16 inches square, or about 3 miles on a side scaled.

These models are placed on a wire mesh in the center of the water tank, and then data collected over the models similar to how it is done in the field. The source and reciever 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. If fact, the physical modeling tank can be used to collect data that is not practical in the field, like tape sequencial CMP (common midpoint) gathers. The plotters move to the nearest 10 feet in x and y and to the nearest foot in the z-axis under computer control. The data is recorded in tape sequencial format on standard magnetic tapes.

It takes an average of one and a half seconds for the plotters to move to the next shot point position, to fire the transducers and 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 miles (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 having to even change 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 that much trouble.

Figure 11 is an example of a simple model, 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] The two sections shown in figure 12 show two single fold sections across this model. Note the differance in the reflection as the discs gets 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 2000 feet 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 figure 13. This geologic model is an asymmetrical double plunging anticline with scaled relief of 1750 feet. The upper 750 feet is a low velocity, 8000 ft/sec, cap made of silicon rubber. The lower portion of the dome represents a high velocity layer, 21,600 ft/sec, and is made of plexiglass. The surrounding water velocity scales to about 12,000 ft/sec. Figure 14 shows an example map of 37 lines of single-fold common-offset data. Figure 15 is an example of two sections of raw data. Note the sideswipe energy coming in when the line passes about a half a 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 the 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 useful for a person developing new algorithms to have a set of data from a known feature to test the programs on. Seismic interpreters can use these tools to come to a better understanding of what is on their seismic sections, and to explain complex events on field data. As 3D modeling techniques are improved, there will be case histories develop showing how field development has been aided using physical and theoretical modeling.

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When writing an article like this, that refers to the historical development of a subject, there is bound to be significant contributers that have been missed. I apoligize in advance. The historical development is of sufficient interest to me that it might make the subject for a book someday. If you, as a reader, have contributions in this area, please forward them.

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