3-D earth models 101

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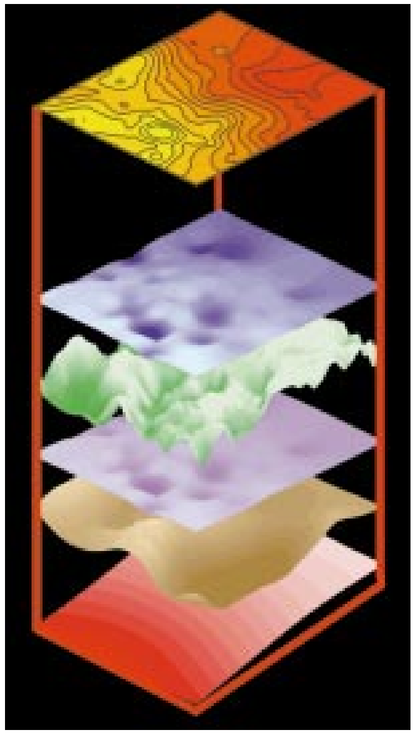
There are 3-D models, and there are 3-D earth models. The geologist describes the 3-D volume as a depth cube, which exhibits structural changes laterally and vertically. This model can be thought of as an endless number of 2-D cross-sections describing geologic formations. In sharp contrast, the geophysicist describes the geologic formations in the 3-D model using geophysical parameters (e.g., velocity, density, magnetic susceptibility, and electrical resistivity).

In the not too distant past, a common 3-D model for depth migration in the Gulf of Mexico was a set of horizontal, constant-velocity layers with velocity increasing with depth down to 3.5 s. Back then, it was considered avant-garde to have dipping layers. The standard model for a depth estimation to the top of a low-density horizon, such as salt and/or geopressured shales, was based on gravity data and consisted of a simple water-bottom layer, and horizontal constant-density layers with density increasing with depth. The density values were based on a nearby FDC log. Our interpretations were based on the assumption that the base of the Louann Salt was flat. We were confined to building these simple structures because of limited computer power, software capability, and data resolution. Generally, our target depths were 5000-10 000 ft, and life was simple.

That was then. Today, we have optimized modeling software, visualization techniques, high-speed computers, and abundant high-resolution data obtained from 3-D surveys or close-sampled 2-D acquisition. There is a comfort zone in using yesterday's tried-and-true methods; however, today's targeted depths for production and the power of technology demand a new level of expertise to effectively utilize multiple data types and techniques.

The optimum 3-D earth model, a geophysical/geological three-dimensional model of the earth, is best described in terms of its exploration objective. This means that when a geologic target is chosen, the model is designed to represent the geologic environment surrounding the prospective zone.

Today's version of the earth model for the Gulf of Mexico is geologically complex. In order to gain any confidence in an interpretation, it must be constrained by the appropriate integration of multiple sciences: seismic, gravity, and magnetics. Using current technologies, we can delineate and constrain deeper horizons over larger areas. As each science utilizes different geophysical (rock) properties (seismic data defines earth-velocities and reflectance horizons, gravity data defines earth-density horizons, magnetic data defines earth-susceptibility horizons), a synergistic impact on the final interpretation is achieved.



An optimum earth model consists of two interrelated parallel models: One is in the time domain, the other is in the depth domain—that is, two volumes, one consisting of velocity layers, the second consisting of density layers. This means that in the time domain, all input, all model layers, from the potential-fields sciences must be converted to time and velocity. Conversely, all input for the space-domain model has to be converted to depth and density. Models will vary widely both in design and emphasis, according to the input and the geologic problem to be solved.

The following descriptions identify typical layers in a 3-D earth model related to oil and gas plays in the Gulf of Mexico:

1) Sea level: The top of the first layer of the earth model is sea level.
2) Bathymetry: The topography of the water bottom forms the top of the second layer, an important layer whose influence is generally underestimated. Coverage and detail required depend on the areal extent of the model. Typical sources of bathymetry are GTOPO30 topographic/bathymetric grid files from the National Geophysical Data Center (NGDC); water-bottom recordings gathered concurrently with a seismic survey; or the latest high-resolution technology, multibeam bathymetry.
3) Sedimentary layers: The thickness and depth of sedimentary layers can be derived from seismic data. The development of comprehensive 3-D velocity databases, which capture the three-dimensional velocity gradients, allows the sedimentary layers to be viable representations of the earth. Effective creation of the 3-D velocity volume depends upon properly calibrating seismic-derived velocities with well data. The process starts with a uniform grid of the best available seismic data. Interpretation of the seismic velocity must abide by essential criteria required to sustain confidence in what the velocity layer represents. Interpreted velocity amplitudes should correspond to coherent reflections in the seismic data. Interval velocities computed from interpreted velocities should not exceed a reasonable range of sedimentary velocities, nor should they oscillate wildly. In the depth domain, the sedimentary layer is a density volume that corresponds to the lithology of the geologic formation. A common source for density information is well control, which can be sufficient if a significant number of wells are evenly distributed over the model area. Pseudo-density layers can be generated from velocity layers. This spatial half of the earth model is commonly designed to interpret a structure based on gravity data, such as the thickness and configuration of salt.

4) Shallow salt/tabular salt: *Allochthonous salt* aka *shallow salt* aka *tabular salt* are all terms used to describe a shallow sheet or sill of displaced salt. These features often play havoc with seismic data because the salt commonly absorbs or distorts seismic energy. While the top of the salt sheet can be interpreted from seismic data with confidence, the interpretation of the base of salt is best left to the integration of various methods using the 3-D earth model. The most common second opinion is from gravity data. Integrated modeling of gravity and seismic data provides a better estimate of the configuration and depth of the base of salt than either technique can delineate alone. If the salt sheet is shallower than 8000 ft, high-resolution aeromagnetic data can effectively delineate salt edges and roots.
5) Deep salt structures: Salt structures were once considered simple autochthonous (in place) diapirs or domes rooted to a "mother salt." New seismic acquisition and processing techniques, together with integrated seismic/gravity interpretation, reveal that deep salt structures have very complex geometries. Again, a common second opinion is from gravity data. Integrated modeling of gravity with seismic data provides a better estimate to the salt shape.
6) Magnetic basement: A reasonably detailed basement surface is an important layer in any geologic or hydrocarbon evaluation effort. This surface identifies critical structural trends, the presence of nonprospective igneous features, the location of the region's prominent structural prospects, and the location/geometry of hydrocarbon generating depocenters. Tools needed to produce such a layer vary from region to region depending on the availability and type of magnetic data.

   Until recently, many explorationists have assumed basement in the Gulf of Mexico Basin is a simple, unstructured erosional contact at the base of the mid-Jurassic Louann Salt formation. Previously, reflection seismic technology has been oriented toward resolution of shallow to moderately deep sedimentary or salt structure, rather than deep presalt structures. Today, deep seismic reflectors on 14-s data may show basement albeit with low confidence. The integration of magnetic data with refraction and deep reflection seismic data has significantly revised the structural interpretation of basement for the Gulf.
7) Moho horizon: Crustal type (i.e., continental, oceanic, or transitional) can be correlated with depth to the Mohorovičič discontinuity (Moho) of the crust/mantle boundary. The Moho is both a density and a seismic velocity discontinuity. Since the Moho represents the surface of the high-density mantle material, it can give an indication of basement rock type and therefore influence the play concept. Both seismic refraction and deep seismic reflection methods can provide discrete Moho depths, but seismic coverage is normally too restricted to permit extensive or detailed mapping of the Moho. Therefore, integrated interpretation of satellite-derived gravity, regional aeromagnetics, and seismic data provides a cost-effective approach to mapping both regional and local detail in offshore areas.

Final comments. Seven layers have been discussed. One cannot overemphasize that the final number and types of layers necessary to build an optimum 3-D earth model are dependent on a number of factors—notably, the type of geologic problem to be resolved, and the quality and type of the input data. Rigorous detail is required to avoid error. The model discussed in this example was primarily designed for the determination of accurate time/depth conversion; simply, a calibrated 3-D velocity model which has integrated results from a 3-D density model and a magnetic basement model, which:

- captures the earth velocities, based on the integration of seismically derived short wavelength and regional velocity gradients correlated with well data
- uses a salt-replacement technique for the shallow and deep salt configuration as interpreted from a parallel density/gravity model, and
- has integrated a magnetic basement depth and configuration interpretation

A "typical" earth model does not exist. Earth models based on judicious integration of multiple sciences have demonstrated capability to:

- produce the highest depth accuracy to the final drill depth
- refine reservoir delineation of prospective targets, and/or
- revise velocities for depth migration.

Today's optimum 3-D earth model is actually a pair of interrelated models which represents the best multidisciplinary technology that can be assembled by skilled interpreters. It is constrained by available, accurate data, and it is processed on the fastest computers utilizing optimized software. Its interpretation is based on integration, and it is visualized in three dimensions. The results achieved today are closer to real in-situ environments, and they are producing solutions to many exploration problems. But we have only begun! A whole new era in 3-D earth modeling will spawn from developing software capability that will allow on-line virtual integration of multiple sciences. It will enable the interpreter to crosscorrelate, integrate, and visualize results in 4-D. In order to maximize tomorrow's technology, the interpreter's critical judgment, insight, intuition, and knowledge of multiple disciplines will become even more crucial to the problem-solving capabilities of any earth model. Are you up to the challenge?

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