Introduction to this special section: Seismic modeling

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Seismic modeling plays an important role in data acquisition, processing, interpretation, and reservoir characterization, making the results more effective and reliable. The simplest form of seismic modeling is the generation of synthetic seismograms from well logs (forward modeling) and its subsequent comparison with seismic data. Another common process is the generation of pseudologs from seismic data (inverse modeling) and using the results in those parts of the seismic volume where there is not enough well control. Seismic modeling is important, therefore, for both forward and inverse problems. One straightforward application of seismic forward modeling is the development of models to address problems of structure and stratigraphy during the interpretation of seismic data. This helps an interpreter relate the modeled seismic response generated from a hypothesized geologic model with the seismic data being interpreted. Another application is in the design of seismic acquisition geometries and the simulation of the seismic response that would occur if the target objectives were met.

Besides these, there are other applications that are designed for testing seismic processing and imaging methods. Since the seismic method as such is an inverse approach, the formation of subsurface images from seismic data involves the application of inversion principles. The process of migration, for example, is an inverse method in this context.

The forward-modeling methods have developed from simple 1D convolution through ray tracing to full 3D elastic wave-equation descriptions of the total wavefield. In general, seismic-wave propagation through the subsurface could be very complex, and the different methods used employ simplistic assumptions to make the problem tractable. Some of the methods in use include the finite-difference, finite-element, boundary integral, pseudo-spectral and spectral-element methods, as well as the Gaussian beam and Kirchhoff modeling methods. Each method comes with its own set of assumptions, its suitability to the problem, and the associated mathematical rigor. With computing costs coming down over the last decade, and the computational speeds increasing several fold, some of the methods involving rigorous computation have now become cost-effective. There may not be a single fast approach that is applicable for all purposes, and the interpreter needs to be aware of the strengths and limitations of the different methods to make a judicious choice for the problem at hand.

The importance of seismic modeling in oil and gas exploration can also be gauged from the SEAM project put in place a couple of years ago by SEG. With collaboration from the oil and gas industry, this project aims to improve 3D seismic modeling and imaging wherein 3D elastic models will be generated for concerted modeling efforts as well as 3D-imaging methods.

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An important ingredient for realistic seismic modeling are rock physics relations that allow the variations in density, elastic moduli, anisotropy, and attenuation to be determined from variations in mineralogy, microstructure, porosity, pore shape, pore fluids, pore pressure, stress, permeability, viscosity, and features such as laminations, fractures, and faults within the rock. Based on rock physics models and reservoir simulation, time-lapse modeling is also being attempted to evaluate its feasibility and to extract seismic attributes to identify changes in the reservoir. An interesting application in this area is the modeling of CO_2 rock physics under reservoir conditions and generating modeled data over a range of properties. These enable the evaluation of changes in the reservoir properties such as pore pressure and CO_2 saturation by using the modeled data in a multiparameter inversion of time-lapse data.

The papers submitted for this special issue on seismic modeling have been grouped into three sections: applications, methods, and rock physics relations.

Applications

Brice, in his paper, "Seismic acquisition design for the SEG advanced modeling (SEAM) project," describes the work carried out by the acquisition design committee of the SEAM project to define modeling parameters. SEAM is a cooperative industry effort focused on the construction of subsurface models and generation of synthetic data sets. Acoustic and elastic synthetic data sets will be some of the ultimate products from this project, and these are expected to be used by geophysicists for many years to come.

In "Seismic wave modeling for seismic imaging," Virieux et al. focus on seismic modeling as a tool for seismic imaging by full-waveform inversion (FWI) where recorded and modeled seismograms should fit. Various 2D and 3D time-domain and frequency-domain forward-modeling tools have been designed for 2D and 3D frequency-domain FWI, and the authors review the advantages and drawbacks of the various modeling strategies that have been suggested.

Seitchik et al., in their paper, "The Tempest Project—Addressing challenges in deepwater Gulf of Mexico depth imaging through geologic models and numerical simulation," describe the process and results of a simulation project that was executed for evaluating the industry ability to correctly image deepwater Gulf of Mexico (GOM) subsalt structures. This was achieved by creating a realistic GOM model and using it as a basis for generating synthetic 3D seismic data. These data were subsequently imaged using a known velocity model and by participating groups who developed the velocity model using the seismic data. Comparison of the depth-imaging results not only highlights the algorithm's positive and negative attributes, but also allowed documentation of variations in results produced by the participating groups, as well as their level of accuracy.

Modeling of seismic waves in volcanoes is critical for the proper interpretation of underlying volcanic processes. In "Observation and modeling of source effects in coda wave interferometry at Pavlof volcano," Haney et al. apply coda wave interferometry to repeating explosions at the Pavlof volcano and conclude that the measured changes reflect subtle variations within the magma conduit. This conclusion is supported by 3D seismic modeling of a changing volcanic conduit at Pavlof that incorporates rugged topography and high-contrast interfaces such as the conduit-rock interface.

Methods

Several versions of the finite-element method (FEM) have been proposed for seismic modeling. De Basabe and Sen, in their paper, "New developments in the finite element method for seismic modeling," discuss recent developments in this field and review three FEM methods (the spectral-element method, the mixed FEM, and the discontinuous Galerkin method) that provide more accuracy than the finite-difference method by carefully selecting the polynomial degree of the approximations and aligning the element edges with the media discontinuities and topography.

Luo et al., in their paper, "Seismic modeling and imaging based upon spectral-element and adjoint methods," explore the connections between finite-frequency seismic tomography, adjoint methods, and time-reversal mirrors in the context of exploration seismology, with a particular emphasis on imaging. The authors show that Claerbout's "imaging principle" is closely related to the density sensitivity kernel that arises in adjoint tomography. In seismic modeling, based upon the elastic wave equation, a better choice from an imaging perspective is to use the "impedance" kernel, which is the sum of the density, shear modulus, and bulk modulus kernels. Unlike the density kernel, the impedance kernel clearly delineates reflectors.

In "Modeling primaries of acoustic/elastic waves by one-return approximation," Wu and Xie summarize the development of the primary-only modeling method using the one-return approximation and examine its features and advantages using numerical examples. The ability of this method to model only the primary waves enables applications in modeling, imaging, data processing, and interpretation. The method can be used to provide extended one-way propagators for migration/imaging using unconventional waves, such as turning waves, reflected waves, or duplex waves for difficult targets.

Ayzenberg et al., in their paper, "Tip-wave superposition method with effective reflection and transmission coefficients: A new 3D Kirchhoff-based approach to synthetic seismic modeling," summarize their experience with seismic modeling using the tip-wave superposition method. In this method, the Kirchhoff integral is treated as a propagation operator acting on the reflected and transmitted wavefield at the reflector. This results in the propagation inside smoothly heterogeneous layers being independent of the reflection and transmission at internal reflectors, and to be treated separately in the numerical simulations.

Rock physics relations

Dutta et al., in their paper, "Compaction trends for shale and clean sandstone in shallow sediments, Gulf of Mexico," provide normal compaction depth trends of porosity, seismic velocities, and V_P/V_S ratio for shallow sediments in the Gulf of Mexico. The results obtained can be used to establish normal compaction trends in the shallow subsurface, where log data are usually not available or are of poor quality. Establishing such trends may find application in detecting drilling hazards and distinguishing shallow resource potential prior to drilling in deep-water environments.

In "Relationship between velocity and anisotropy perturbations and anomalous stress field around salt bodies," Sengupta et al. apply 3D geomechanical modeling to a real and complex salt structure and its surrounding sedimentary rock, using a real 3D salt model obtained from a wide-azimuth survey in the Gulf of Mexico. The authors show that presence of a complex salt body within a sedimentary basin can cause large stress perturbations in the surrounding rock, which in turn can lead to large velocity reductions below salt and significant velocity anisotropy adjacent to the salt flanks. Updating the seismic velocity using geomechanics is important for imaging and pore-pressure prediction once the methods used are calibrated using available subsalt data from offset wells along with wide-azimuth seismic data.

We thank the authors for their valuable contributions to this special section, and we hope *TLE* readers find the articles both informative and interesting. TLE