

Mechanical Earth Model

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A *mechanical earth model* (MEM) is a repository of data—measurements and models—representing the mechanical properties of rocks and fractures as well as the stresses, pressures and temperatures acting on them at depth. Engineers and geoscientists use it to understand how rocks deform, and sometimes fail, in response to drilling, completion and production operations. Each data point in an MEM is referenced to its 3D spatial coordinates and time of sample collection.

Rocks deform in a variety of ways in response to stress. Some rocks, such as granites, are stiff and strong; some, such as mudstones, are soft and weak; and some, such as salts, with sufficient time can flow. An MEM provides information about mechanical behavior and strength by using relationships between rock properties, induced deformations and ambient conditions. Because of the layered fabric of rocks or the presence of fractures, rock properties are frequently *anisotropic*—their properties are not the same in all directions as they would be with *isotropic* media.

An MEM documents the ambient conditions, including the stress, fluid pressure, temperature and fluid content, relevant for a geomechanical analysis. An MEM may represent a snapshot at a time of interest—for instance, the virgin conditions of a reservoir—or it may track how conditions evolve as the reservoir is being produced.

Constructing an MEM

To build and calibrate an MEM, geoscientists characterize the reservoir and overburden and then use monitoring measurements and modeling techniques. Measurements come from a variety of sources such as seismic data, well logs, image data and in situ temperature, pressure and stress measurements. Additional sources are mud logs, cuttings data and laboratory mechanical test data on core samples (Figure 1). Knowledge from external databases, such as the World Stress Map—a compilation of present-day tectonic stresses—can also be included in MEMs.

The data are integrated to derive the various elements of the MEM, including the mechanical properties, pore pressure and magnitude and orientation of the maximum, intermediate and minimum principal stresses (Figure 2). These elements come from direct measurements, such as pore pressure and in situ stress testing, as well as from indirect derivations based on rock physics modeling, such as pore pressure and principal stress models, and empirical correlations between datasets. Pore pressure modeling accounts for the effects of reservoir fluids accumulated over geologic history, cumulative present-day hydrocarbon extraction and fluid injections to stimulate recovery. Principal stress modeling accounts for gravity, the far-field tectonic stresses—distant stresses that result from tectonic plate movements—which are modified by regional, basin and local geologic structures, by human engineering and by the current pore pressure.

| Data Sources Versus MEM Properties | Mechanical Facies and Rock Typing | Structural Geology | Constitutive Properties | Rock-Strength Parameters | Stresses and Pore Pressure |
|------------------------------------|-----------------------------------|--------------------|-------------------------|--------------------------|---|
| Petrophysical logs | X | | | | (P_p) |
| Density logs | X | | | | S_v |
| Cuttings | X | | | | |
| Image logs | (X) | X | | | AzS_{Hr} and (S_H) |
| Sonic logs | X | (X) | X | (X) | AzS_{Hr} , (S_H), (S_H) and (P_p) |
| Stress tests | | | | | S_H and (S_H) |
| Pressure tests | | | | | P_p |
| Drilling mud weight | | | | | (P_p) |
| Core lab tests | X | | X | X | |
| 3D seismic: structural data | X | X | | | |
| 3D seismic: mechanical data | X | | X | | (P_p) |
| Regional database | | | | | AzS_{Hr} |

Figure 1. Main sources of information used to build a mechanical earth model. The properties of MEMs are in columns and the data sources for determining the properties are in rows. The magnitudes of the principal stresses are vertical stress (S_v), minimum horizontal stress (S_H), and maximum horizontal stress (S_{Hr}). The azimuth of the minimum horizontal stress is AzS_{Hr} , the pore pressure is P_p . The items inside parentheses are indirect measurements or available only under certain circumstances. Calibration and validation of the MEM involve a range of monitoring data (not listed here) such as drilling events.

The MEMs are calibrated using laboratory or in situ measurements and by comparing drilling, completion or production observations with their MEM-based geomechanical predictions. If necessary, the MEM data may be refined until they produce a satisfactory match to observations. Many of the Earth's mechanical properties and conditions are interdependent. For example, the pore pressure and state of stress must be consistent with general stability constraints on the geomechanical system. In addition, an MEM needs to be consistent with geologic and reservoir models.

Sizing an MEM

Mechanical earth models encompass various levels of detail. Depending on the application, MEMs may be simple or complex, of high- or low-resolution, at the meter scale in the near-well region or the tens of kilometers scale in a sedimentary basin and in 1D, 2D or 3D. For example, a 3D model will be more appropriate than a 1D model for modeling how structural features, such as salt bodies, affect the in situ stress field. In addition, the data in MEMs may document a single event or a time-lapse record of events. The MEMs are likely to evolve as more data become available or new applications and situations arise.

For geomechanical applications, the region of interest often extends beyond the reservoir. When the challenge is to keep hydraulic fractures contained within a zone, the MEM encompasses the formations expected to act as barriers above and below the zone to be fractured. When the concern

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is the potential for encountering hazards during drilling, the MEM spans from the surface to the reservoir. In addition, the region of mechanical influence may extend beyond the region of interest (Figure 3). For a well drilled near a salt diapir, the state of stress around the well probably includes the mechanical influence of the diapir.

Another practical aspect to consider is the computer run time. During drilling, results are required in near real time. Operational decisions affecting many wells in a field or basin over several years require results less urgently.

Using an MEM

An MEM is the data repository of in situ characteristics for an earth volume. These characteristics may be useful on their own, for example, stress orientation for planning a horizontal well and its completion. Moreover, an MEM contains all available information required to assess how rocks and fractures deform in response to drilling, completion and production operations. Geoscientists conduct these assessments by linking the MEM to other, specialized simulation software such as reservoir, hydraulic fracture,

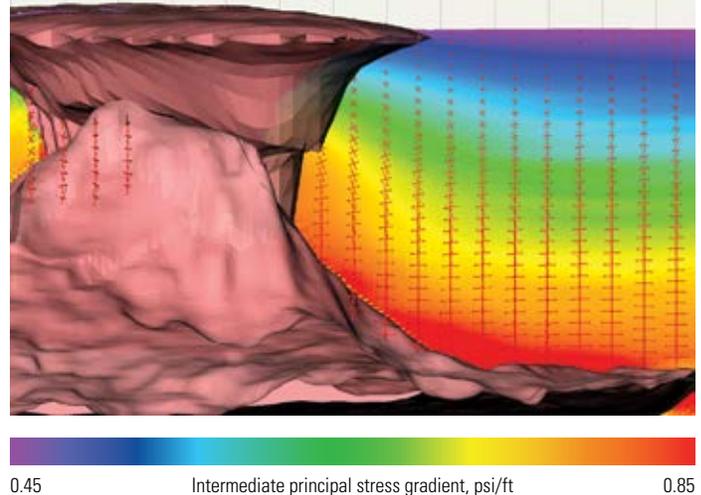


Figure 3. The 3D stress field around a salt diapir. Strong stress direction rotations occur in the vicinity of the salt body (pink). The crossed arrows show the orientation of the maximum (vertical to subvertical) and intermediate (maximum horizontal to subhorizontal) principal effective stresses; the minimum principal stress is perpendicular to the page. The size of the arrows indicate stress magnitude. The distance between crossed arrows is 3,000 ft [914 m] horizontally and 900 ft [274 m] vertically.

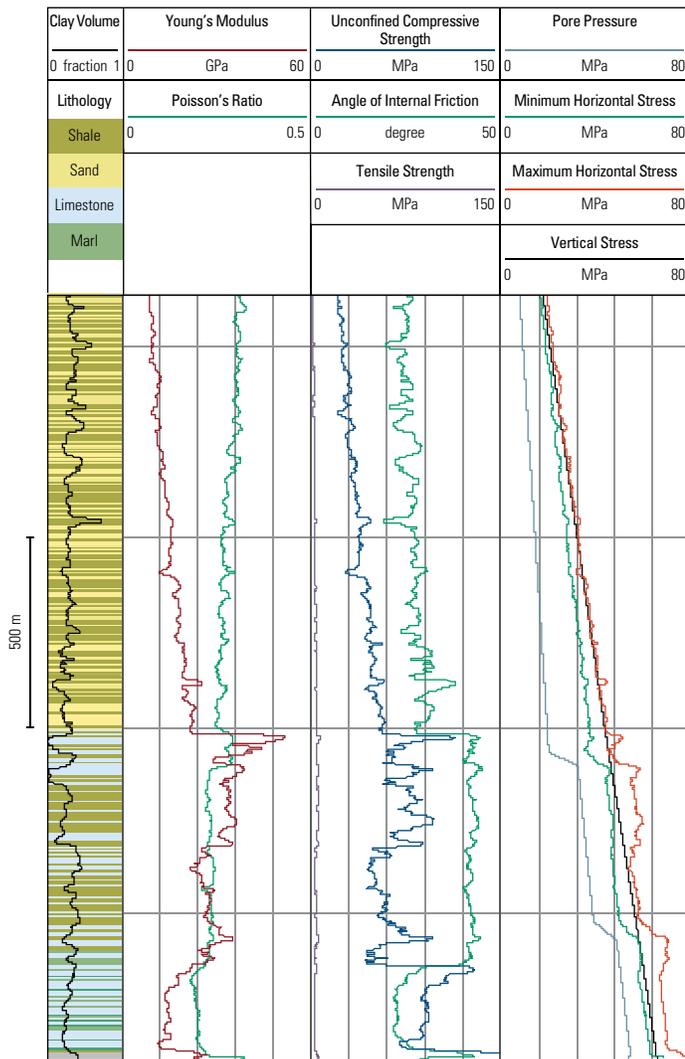


Figure 2. Vertical log display of a 1D MEM. This log presents lithology and the volumetric fraction of clay (Track 1), elastic properties (Track 2), strength properties (Track 3) and the state of stress (Track 4) characterized by stress magnitudes and directions (not shown).

basin and structural geology reconstruction models. In addition, engineering software tools use geomechanical information from MEMs as input to determine how in situ deformation and changes in stress and rock properties affect an operation's performance. For instance, by simultaneously combining reservoir and geomechanical models, engineers can assess how production influences the effective stresses, the opening and closing of natural fractures and the corresponding change in rock mass permeabilities. Such effects are important when engineers assess the reservoir behavior, production rates, recovered volumes and economics of a proposed production schedule.

Engineers use MEMs to understand past experiences and identify the root causes of unexpected events such as early water breakthrough or drilling fluid loss. Drilling and completion engineers can take lessons learned from MEMs to plan future operations that are more efficient and safer than they would be without this information. They can assess the consequences of geomechanical effects for various scenarios of oilfield operations as a function of the development plan or design parameters. Well engineers can conduct wellbore stability analyses to decide well orientation, casing architecture and drilling mud properties such as density. Stimulation engineers can select perforation intervals for hydraulic fracturing based on the stress profile along wellbores to improve reservoir contact and ensure fracture containment.

The integration of mechanical earth models into operators' workflows is important for nearly all aspects of well construction and production. An MEM can be crucial for reducing risk, cutting costs and increasing operational efficiency. Not only are MEMs important during the early exploration and development phases—when little is known about the field—but also late in life when the field requires revitalization through such activities as infill drilling, refracturing and enhanced recovery operations. Geoscientists continue using and updating MEMs as they accumulate and integrate data throughout the life of a field. Mechanical earth models are becoming vital and indispensable repositories of data for many oilfield activities.