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Geological Controls and Variability in Pore Pressure in the Deep-Water Gulf of Mexico

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ABSTRACT

In most areas of the world, pressure-related drilling problems are the leading cause for abandoning a deep-water well or else requiring expensive remedial changes in the drilling and casing programs to reach its targeted reservoir depths. This chapter discusses geological controls and trends in the onset of geopressure in the deep-water Gulf of Mexico, shallow water flow from overpressured sands in the top-hole section, and other pressure-related problems unique to deep water. Pore-pressure prediction has become a subject of intense current interest with several joint industry projects and predictive models now available for government and company participation.

INTRODUCTION

As exploration moves into deeper water in the Gulf of Mexico, pore-pressure prediction and the correct anticipation of overpressured sands becomes more and more critical to the effective evaluation of federal outer continental shelf (OCS) lease blocks. Since 1992, the growth in deep-water activity has been reflected in numerous leasing, drilling, and production statistics. The number of exploratory wells drilled and the number of Exploration Plans filed for deep-water lease blocks have increased by about a factor of 5 since 1994, but many of these leases will expire without being drilled. In addition, many deep-water blocks, initially leased after the OCS Deep Water Royalty Relief (DWRR) Act in 1996 provided economic incentives to develop deep-water fields, will be available by 2006. During the last eight years of the 1990s, the number of deep-water active leases increased from about 1500 to nearly 3900 (Figure 1), about half of the active present-day OCS blocks, including a record number of lease blocks since 1996 in ultradeep water (>5000 ft [1524 m]). Baud et al. (2000) noted that, in the 1990s, the average Gulf of Mexico field size in more than 1500 ft (457 m) of water was 60 million BOE, 12 times the average shallow-water discovery. Deep-water oil now provides more than half of the region's production, and increases in gas production have also offset the shallow-water decline in recent years, with much of new volume coming from subsea completions.

In this chapter, we look at the occurrence of geopressure in about 100 wells in deep water from Viosca Knoll to Alaminos Canyon, most of them drilled in more than 2000 ft (610 m) of water during the last five years. We also analyze shallow water-flow encounters and trends in these areas. As exploratory drilling begins in previously untested geological trends in ultradeep water, new technology and equipment will be needed to control unique pressure-related drilling problems encountered in the exploration and development of hydrocarbon resources in this emerging province.

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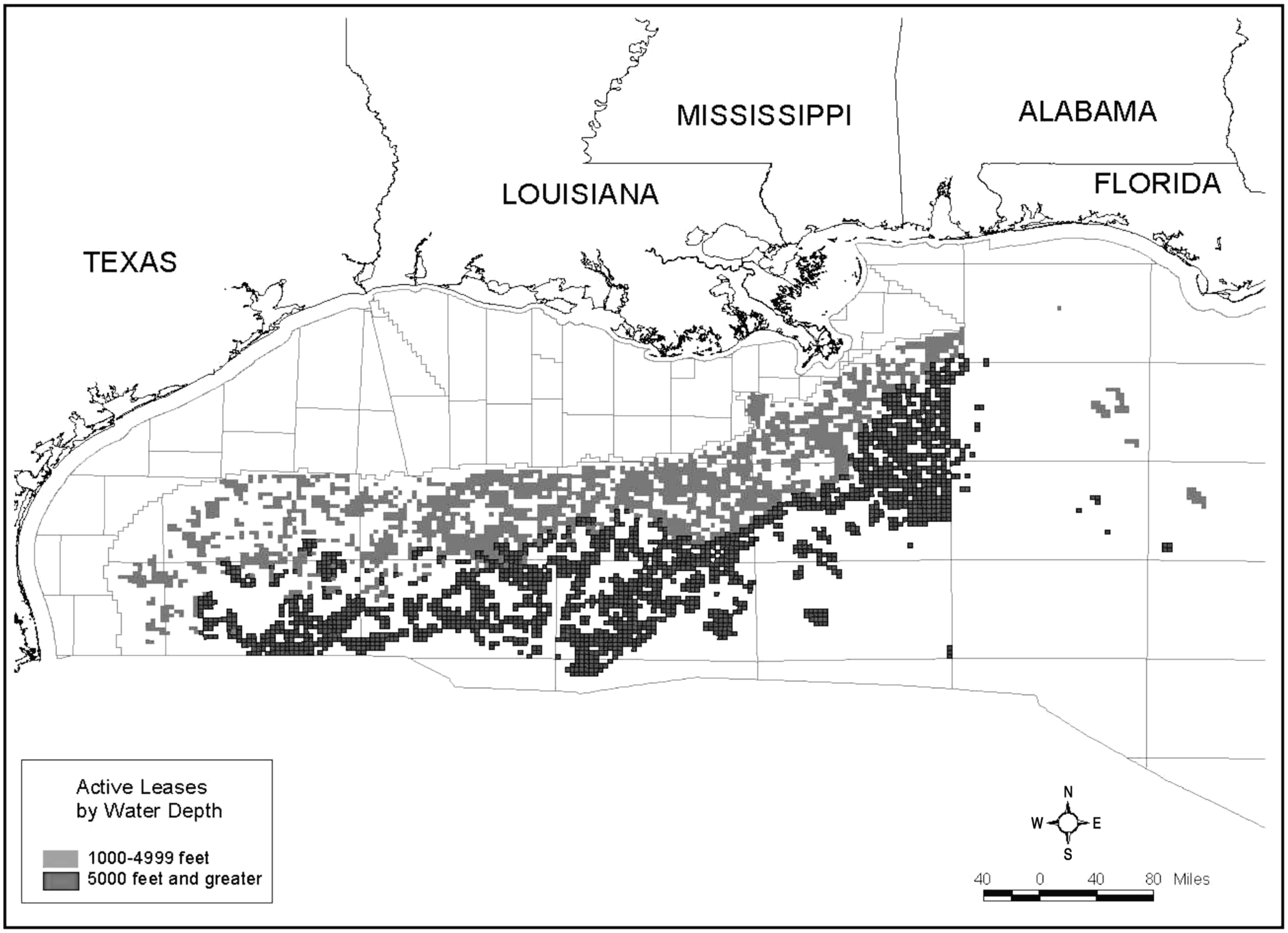

Figure 1. Deep-water (>1000 ft [305 m]) and ultradeep-water (>5000 ft [1524 m]) active leases in the Gulf of Mexico.

PORE-PRESSURE GRADIENTS

Minerals Management Service (MMS) geological reviews of exploration and development plans and applications for permit to drill on Gulf of Mexico OCS leases include a discussion of possible abnormal pressure zones. Geopressure is defined as the situation where pore fluid pressure exceeds normal hydrostatic pressure (Fertl, 1976; Dutta, 1987). This onset of moderate overpressure in continental shelf deltaic sediment occurs where pore pressures are equivalent to 12.5 pound per gallon (ppg) mud weights. In deep water, however, the fracture gradient and shallow casing shoe tests are lower, and the onset of even mild overpressures of 9.5 to 12.0 ppg contributes to many drilling problems such as shallow water flow. Burial rates, geothermal gradients, compaction, and diagenetic reactions are the primary factors affecting the occurrence of geopressure (Law et al., 1998). In deep-water wells, the large seawater column also results in greater depths to abnormal pressure, so depths below the mud line (bml) or sea floor were used in this study in place of vertical subsea depths. Geological factors that control the deposition of turbidite systems, sequence stratigraphy, major faults, unconformities, and salt also affect pore pressure. In complexly faulted structures, formation pressures may be compartmentalized and may vary between different sands.

We analyzed predicted and actual pore pressures, sedimentation rates, and formation temperatures in the deep-water Gulf of Mexico and prepared trend maps of the occurrence of geopressure for this province. The top of geopressure was defined as the depth at which pore-pressure equivalent mud weights, referenced to kelly bushing elevation, exceeded 12.5 ppg. The wells in this study are located in four deep-water sections that include, from east to west, Viosca Knoll/Mississippi Canyon/Atwater Valley, Green Canyon, Garden Banks, and East Breaks/Alaminos Canyon. The upper slope (less than 1000 m of water) in Mississippi Canyon has a thicker Pliocene section with a shallower top of geopressure, an average of about 6950 ft (2118 m) bml, than the deeper water parts of this area. In deeper water, the average top of geopressure occurs in the Miocene at about 10,700 ft (3261 m) bml. In the younger Pliocene–Pleistocene section to the west in Green Canyon, Garden Banks, and East Breaks, the average top of geopressure occurs at about 8700 ft (2652 m) bml. In the deeper water sections in Green Canyon, Garden Banks, and Alaminos Canyon to the south and southeast, however, the top of geopressure occurs in the Miocene at an average depth of about 11,200 ft (3414 m) bml. Throughout the deep-water Gulf of Mexico, as shown in Figure 2, it appears that older and more compacted strata have a deeper top of geopressure than occurs in younger strata.

Except for the northeastern corner of Mississippi Canyon, the thermal gradient in the eastern study area is lower than that of deep-water areas to the west, generally about 1.05°F/100 ft (0.58°C/30.5 m). The thermal gradient falls from an average of 1.25°F/100 ft (0.69°C/30.5 m) in East Breaks to about 1.0°F/100 ft (0.555°C/30.5 m) in Garden Banks, and in Green Canyon the temperature gradient appears to decrease from 1.3 to 0.8°F/100 ft (from 0.72 to 0.44°C/30.5 m) to the southeast with greater water depths. These observations suggest that lower thermal gradients may correspond to a deeper top of geopressure.

Salt domes and ridges that form the boundaries of salt-withdrawal minibasins cause increased pore pressure in the surrounding sediment. This fact results in anomalously high pore pressures in wells drilled on the flanks of a salt dome relative to wells drilled through equivalent strata toward the center of the basin. Pore-pressure ramps or steep increases also occur adjacent to salt masses, and some deep-water exploratory wells have had to be abandoned during attempts to drill through overpressured fractured shale associated with a salt diapir before the reservoir interval was reached. Below tabular salt sheets, formations can be

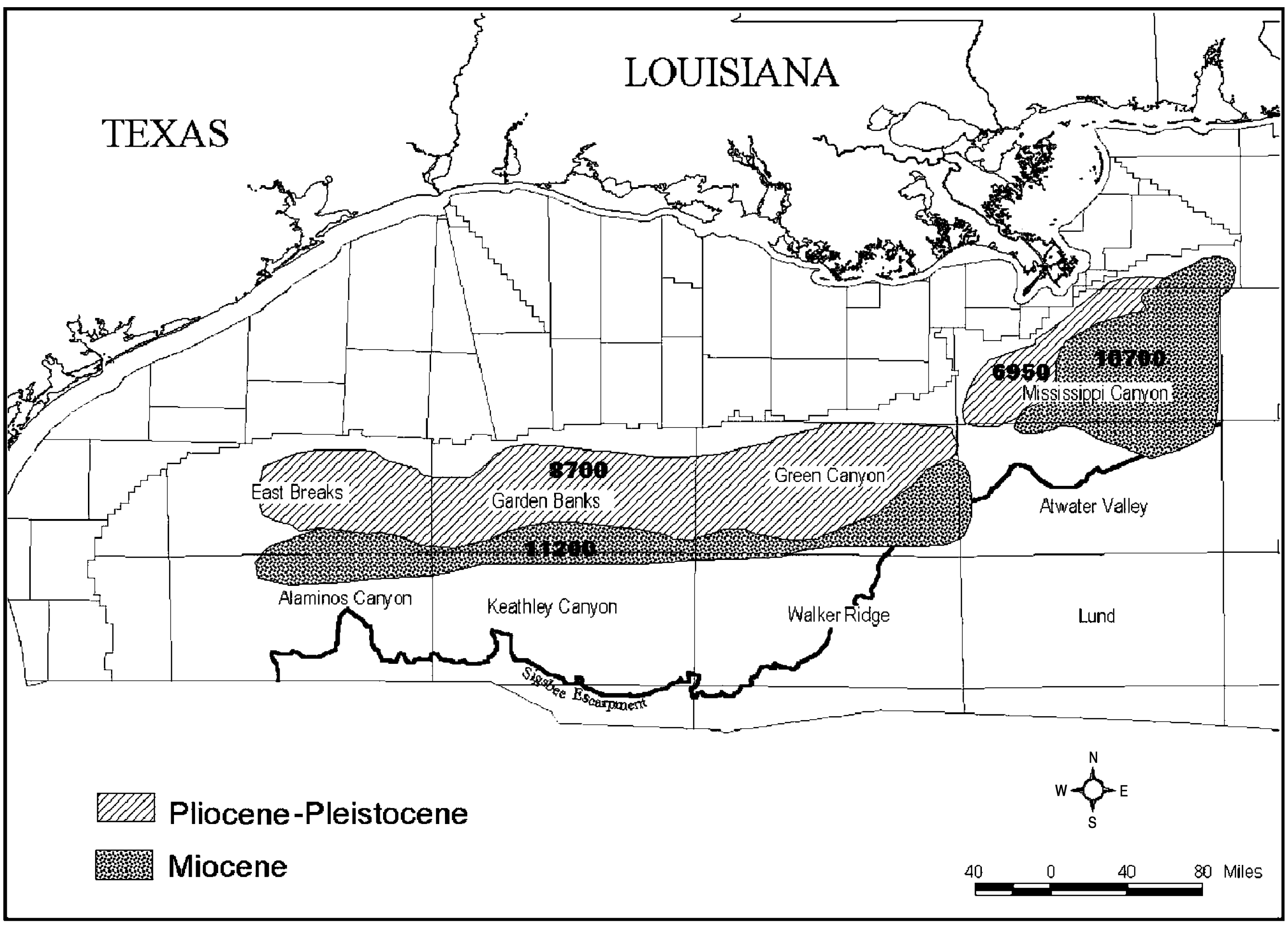

Figure 2. Average depth and stratigraphic interval for the occurrence of moderate overpressures (12.5 ppg pore pressure), deep-water Gulf of Mexico.

overpressured because of an effective seal, and in some subsalt wells a pressure kick has been encountered in the rubble zone below salt. In general, however, the top of subsalt geopressure occurs at greater depths and deeper in the stratigraphic section than in wells without salt.

SHALLOW WATER-FLOW SANDS

Water flow from an overpressured shallow aquifer occurring above the first pressure-containing casing string can significantly impact drilling and cementing practices in addition to the setting depth and number of shallow casing points. This shallow subsurface geohazard may even cause an operator to change a surface location or lose a well. Shallow water-flow sands were deposited as continental slope/fan sequences during upper Pleistocene progradation, the building out of prodelta sandy zones. Since 1984, shallow water-flow occurrences have been reported in about 70 Gulf of Mexico lease blocks covering 55 oil and gas fields or prospects. With a few exceptions, water-flow incidents occur at water depths exceeding 1700 ft (518 m) with a mean value at about 3000 ft (914 m) of water. Water-flow problem sands also typically occur from 950 to 2000 ft (290–610 m) bml but have been reported from 450 to 3500 ft (137–1067 m) below the sea floor. Individual channel-sand units display slumping zones or debris flows with a chaotic seismic character and, in some cases, tilted and rotated slump blocks. In the Mississippi Canyon and southern Viosca Knoll areas, some of the shallowest channel sands can be identified as part of a particular distributary system such as the old Timbalier Channel, Southwest Pass Canyon, or Einstein levee/channel system. High-sedimentation rates and an impermeable mud or clay seal from a condensed section are the main factors contributing to overpressures in shallow water-flow sands (Alberty et al., 1997). These sands occur in several depositional subbasins that are generally bounded by salt ridges or walls. No significant water-flow occurrence, however, is found over tabular salt sills that are 1000 to 10,000 ft (305–3048 m) below the sea floor in some areas. This fact may suggest that communication with the deeper stratigraphic section contributes to abnormal pressures in shallow sands or that the salt forms a positive sea floor topographic feature, preventing sediment loading that might contribute to the generation of overpressures.

The integration of high-resolution multichannel and reprocessed conventional two-dimensional (2-D) and three-dimensional (3-D) seismic data for the top-hole section, further refined by seismic facies analysis, can identify sand bodies with moderate or high shallow water-flow potential. In assessing shallow water-flow risk, information from surrounding wells and shallow borehole tests also provides important data for drilling program design. The MMS Notice to Lessees and Operators (NTL) on shallow hazards requirements for the Gulf of Mexico OCS, NTL 98–20, is currently undergoing extensive revisions (Stauffer et al., 1999). The updated NTL will accommodate the shifting focus of drilling into deeper water and the improved technology and data now available to mitigate deep-water geohazards such as shallow water flow.

Mitigating approaches that have been used in the drilling of shallow water-flow areas include measurement while drilling (MWD) logging plus an annular pressure measurement while drilling (PWD) tool, monitoring and confirming shallow water-flow occurrences with remotely operated vehicles (ROV), and drilling the shallow section as a pilot hole. Additional casing strings and quick-setting foam cements, borehole tests to 1500 to 5000 ft (457–1524 m) bml before development drilling, and other geophysical and engineering techniques that are currently under development have also been employed. The loss of integrity plus buckling or collapse of shallow casing strings in development wells has caused serious economic loss in several cases. Establishing a database of known shallow water-flow occurrences and the most effective methods for controlling them will greatly advance the partnership between the MMS and offshore operators in containing this critical deep-water hazard (Smith, 1999).

OVERPRESSURED SANDS IN ULTRADEEP WATER

In low-margin deep-water drilling areas with abruptly increasing pore pressures and weak fracture gradients, extra casing strings are needed to maintain control in the shallower part of the well. A conventional single-gradient mud system and marine riser maintain bottom-hole pressure with a single mud density from the rig to the bottom of the well, which may require extra casing strings to prevent weaker formations from fracturing. In addition, loop currents or other strong deep-water currents might limit drilling at times because of high riser loads. With a dual-gradient system, however, mud is diverted to separate riser return lines with the effect of replacing the mud from the drilling riser with seawater and referencing pressure gradients relative to the sea floor (Smith and Gault, 2002). The larger hole size maintained at total depth with this technology also allows more completion and production options for deep-water reservoirs.

The northern Gulf of Mexico Basin can be divided into various arcuate tectonic provinces that parallel the shelf/slope break (Diegel et al., 1995; Karlo and Shoup, 1999). Salt-withdrawal minibasins on the continental slope, such as those in the Green Canyon and Garden Banks areas, are bounded by salt walls and filled with the ponded turbidite sands that provide reservoirs for most of the earlier deep-water Gulf of Mexico discoveries. A tabular salt canopy tectonic province occurs in a basinward direction in Walker Ridge and Keathley Canyon, and the Sigsbee Escarpment defines its extent. The middle to lower continental slope contains fold/thrust belts with large prospective geological structures that are the focus of current deep-water drilling and include several recent discoveries (Peel, 1999; Rowan et al., 2000). Figure 3 shows the distribution of hydrocarbon plays in the deep-water Gulf of Mexico, including untested plays in ultradeep water.

In the centroid concept, pore pressure in a reservoir sand at the crest of a high-relief overpressured structure can exceed pore pressure in the bounding shale. Deep-water areas with extensive shallow faulting are particularly vulnerable to low-margin drilling conditions that require extra casing strings. The top of a large, high-relief fold or anticlinal structure at various depths in an exploratory well may contain fluid pressures that approach the fracture gradient in adjacent shale (Traugott, 1997). The mud log from a 1996 ultradeep-water well (Figure 4) provides an example of substantial pore-pressure increases that required closely spaced additional casing strings in the shallow section. This exploratory well was abandoned less than

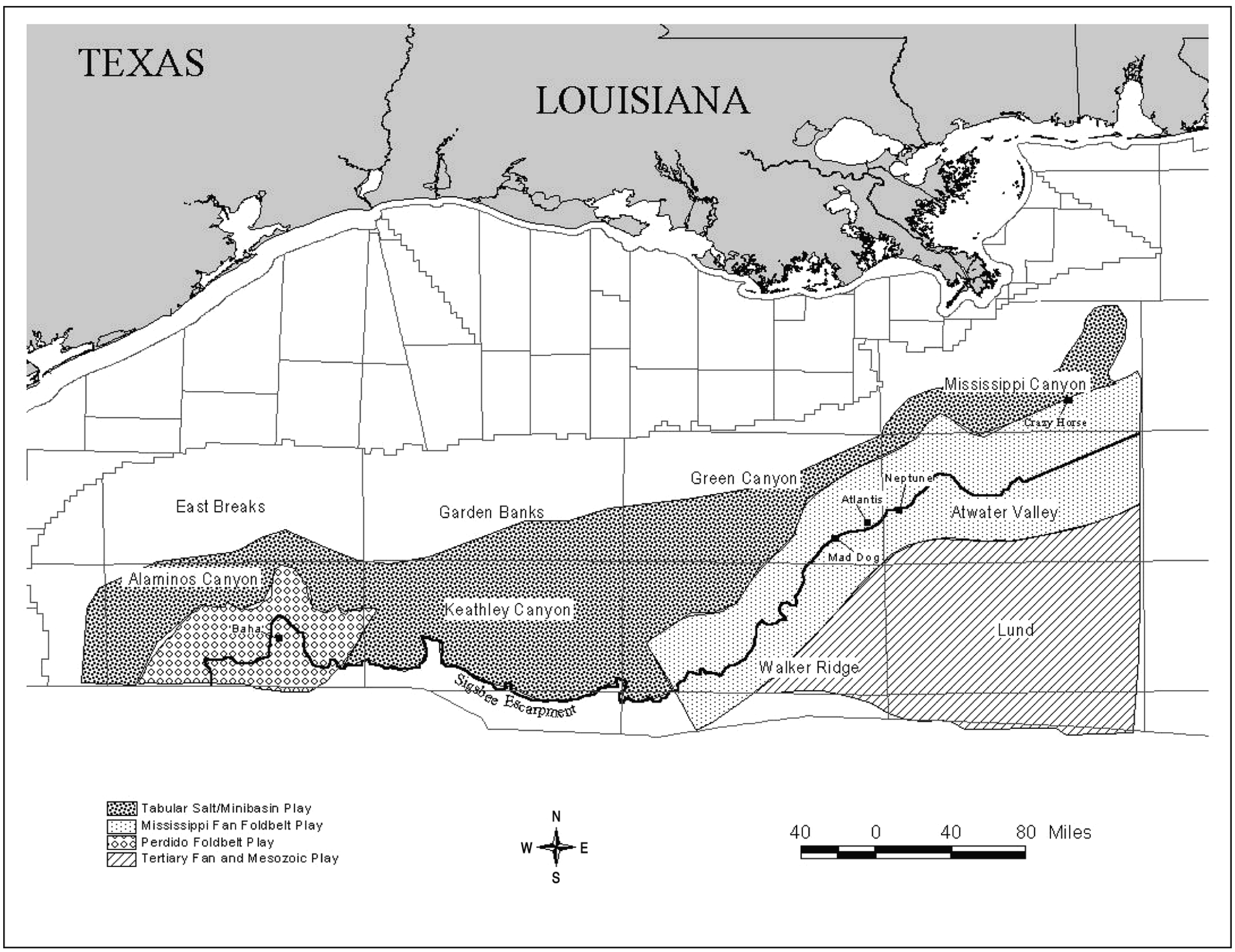

Figure 3. Established and frontier deep-water Gulf of Mexico hydrocarbon plays.

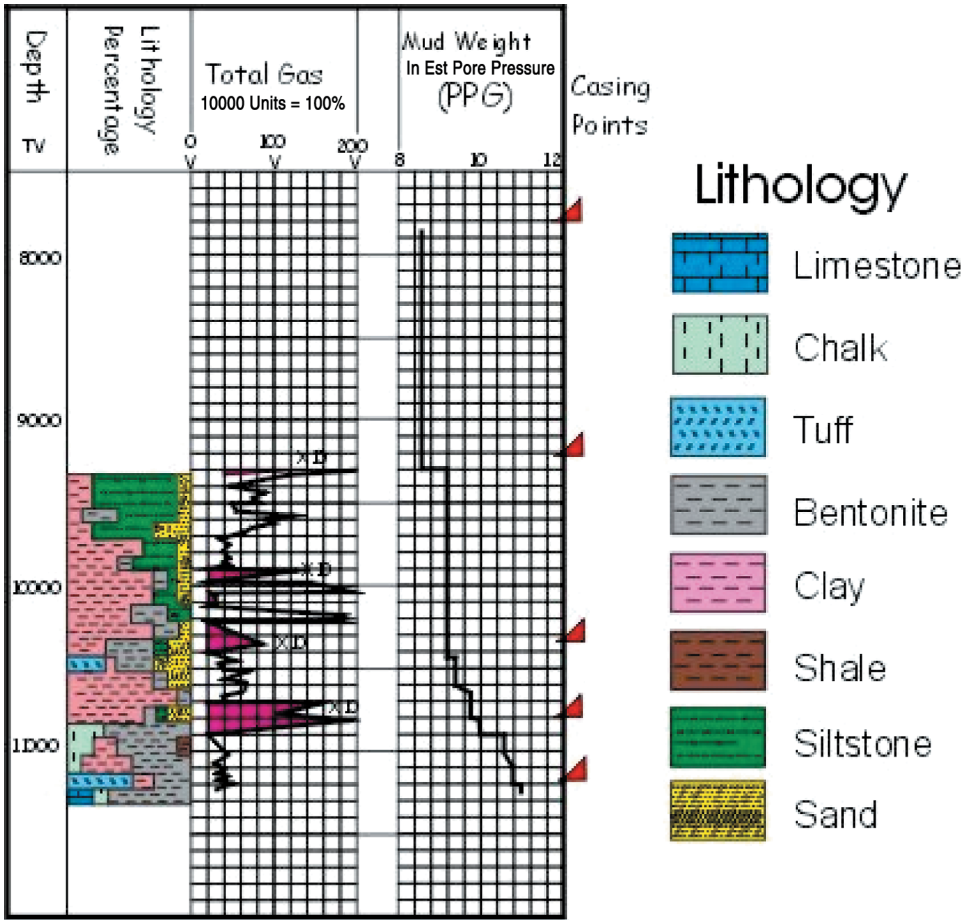

Figure 4. Ultradeep-water exploratory well that encountered rapid pore-pressure buildup requiring extra shallow casing strings. Higher values in the Total Gas track are marked with an x.

3000 ft (914 m) bml because of the narrow margin between pore-pressure and fracture gradient in addition to its small hole size well above the prospective target interval. The use of a dual-gradient/riserless drilling approach and other innovative casing and diverter systems that are under development, however, may contribute the new technologies required for successful exploration in the deepest Gulf of Mexico leases.

CONCLUSIONS

Many of the serious and costly drilling problems in deep water are related to the pore-pressure/fracture-gradient relationship. Other pressure-related hazards, such as shallow water flow, require better predrill identification and quantification of overpressured problem sands. In many Gulf of Mexico frontier deep-water areas, a lack of offset wells mandates better pressure models that incorporate all available geological data. Operations geologists and geophysicists in the MMS are working with deep-water operators to establish databases and methodologies that will improve industry's success in dealing with deep-water geohazards well into the new millennium.

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