The Prize Beneath the Salt

Exploration and production activities in the deep and ultradeep waters of the northern Gulf of Mexico have led the way to the latest subsalt play. Lessons learned from this play may, in turn, open the way for subsalt exploration in other basins around the world.
Successes in deep- and ultradeepwater prospects are spurring a resurgence in exploration in the Gulf of Mexico. Announcements of significant discoveries or record-setting achievements have piqued interest in the activities of deepwater operators, as evidenced by bidding competition at recent offshore lease sales. Exploratory drilling has also confirmed the presence of reservoir-quality sands that are much farther from shore than expected. The discovery of hydrocarbons in several of these sands is fueling speculation about the tantalizing potential that might lie beneath deep Gulf waters.

Speculation is in large supply. Offshore operators diligently safeguard their expensive and hard-won secrets of the deep and release only the data required by governmental mandate. Press releases are carefully constructed to avoid revealing the full extent of discoveries in this highly competitive arena, where choice blocks of offshore real estate can lease for more than US $100 million for a 10-year lease. But secrecy and competition are not the only impediments to exploration in this area.

Perhaps the greatest challenge is posed by thick layers of salt in the subsurface. Several deepwater prospects lie beneath sheets of salt—some up to 20,000 ft [6,100 m] thick. Like an undulating and tattered canopy, coalesced salt sheets extend from the US Continental Shelf to the deepwater Continental Slope off the coasts of Texas and Louisiana. A similar subsalt province lies well to the south, in less-explored waters off Mexico’s Yucatan Peninsula.

In their pursuit of new exploration targets, many offshore operators have had to drill through hundreds or even thousands of feet of salt to discover pay sands. Their efforts have led to notable subsalt discoveries on the Shelf, such as Mahogany; or in deeper waters, such as Gemini, Atlantis, Tahiti, Mad Dog and Pony; or in ultradeep waters, such as Thunder Horse, St. Malo, Jack and Kaskida. Salt is a particular challenge for drillers, who must contend with high-pressure sediment

2. The concept of deep water has evolved considerably throughout the years. The US Department of Interior Minerals Management Service (MMS) originally defined deep water as 200 m [656 ft]. This mark was later eclipsed by industry drilling trends, and now the deepwater standard is set at 1,000 ft [305 m]. The MMS has designated depths greater than 5,000 ft [1,524 m] as ultradeep water. In the Gulf of Mexico, the deepest waters are found in the Sigsbee Deep, whose estimated depths range from 12,303 ft [3,750 m] to 14,383 ft [4,384 m].
inclusions or rubble zones as they drill through salt bodies (see “Meeting the Subsalt Challenge,” page 32). It also poses substantial difficulties for geophysicists as they attempt to image deep structures beneath irregularly shaped salt bodies. In salt, seismic waves can reach velocities of 14,500 to 15,100 ft/s [4,400 to 4,600 m/s]—in some cases roughly twice the velocity they would travel in surrounding sediments. This velocity contrast causes geophysical imaging problems that can mask underlying structures and prevent geoscientists from determining the location or extent of potential reservoirs. However, advances in seismic acquisition and processing techniques are helping geophysicists resolve problems that previously prevented imaging beneath the salt (see “Shooting Seismic Surveys in Circles,” page 18).

The process of drilling and producing a subsalt well requires significant planning, operational skill and investment. Given the difficulties associated with drilling in deep waters, the decision to take on the additional challenge of drilling through salt must be justified by potential for payouts and returns worthy of the additional expense and risk involved. One frequently cited article, written in 1997, noted that potential subsalt reserves from 25 or more significant fields located primarily on the Continental Shelf of the northern Gulf had been estimated at 1.2 billion bbl [190 million m³] of oil and 15 Tcf [435 billion m³] of gas. These estimates do not include additional reserves that have since been discovered in the deepwater Miocene play—including Mad Dog, Pony, Tahiti and others—nor do they include ultradeepwater subsalt discoveries such as Jack, Kaskida, St. Malo and Thunder Horse.

This article describes the evolving subsalt play in the northern Gulf of Mexico. We briefly review the geologic processes that led to deposition of the Louann Salt and the transport of reservoir-quality sands into deeper reaches of the basin. We examine the role of salt mobilization and its effect on overlying sediment in the formation of traps and migration pathways necessary to complete an effective petroleum system in the Gulf of Mexico. We also discuss how sands that were originally deposited on top of salt have come to lie beneath it. Although this article focuses primarily on the intensively explored US waters of the northern Gulf of Mexico, some of the principles described are also relevant to other basins around the world.

Evolution of the Gulf of Mexico Basin

Discoveries in the Gulf of Mexico have challenged previous thinking regarding the occurrence of hydrocarbon-bearing sands that lie beneath great thicknesses of salt. This salt is actually older than the sands that lie beneath it. However, the salt has moved and in some cases created seals capable of trapping oil and gas. Understanding the geological complexities of these discoveries requires a step back in time.

The evolving subsalt play in the Gulf of Mexico is inextricably tied to the geologic history of the Gulf itself. This history goes back eons, before the Gulf of Mexico existed, to a time after most of the world’s continental plates had converged into a supercontinent known as Pangea (left). The tectonic activity that followed would mold the Gulf basin and influence the distribution of sediments that subsequently filled it.

In addition to unremittingly gradual tectonic and depositional processes in this basin, other forces were at work. The early history of the Gulf of Mexico was at times abruptly punctuated by catastrophic events that not only influenced the formation of the Gulf, but also changed the world. These events were remarkable in their scale, but were certainly not unique; one such cataclysm occurred just before the Gulf began to open. Approximately 250 million years ago, much of life on Earth was extinguished. On land, insect biodiversity plummeted, while plant and animal losses were even more severe, as 70% of land species vanished. In the seas, trilobites, tabulate and rugose corals, and nearly all crinoids became extinct, along with roughly 90% of all marine species. Atmospheric oxygen levels dropped from 30% to less than 15%.

6. A graben is a downthrown fault block that is bounded on either side by opposing upthrown normal fault blocks. Grabens occur in areas of rifting or extension, where the Earth’s crust is being pulled apart. Red beds are reddish sedimentary strata, such as sandstone, siltstone or shale, which have accumulated under oxidizing conditions. The red color results from specks of iron oxide minerals in the sediments. Oxidizing conditions are common in hot, arid environments and therefore imply that the sediments have been exposed to these conditions through surface weathering as a result of uplift or erosion of overlying sediment. Red beds are commonly associated with rocks of the Permian and Triassic periods.
7. Salvador, reference 5.
This was the great Permian-Triassic extinction event (above). The cause of this mass extinction is subject to debate. While recent discoveries point to an asteroid impact, other evidence supports a variety of theories including massive volcanic activity, falling sea levels brought on by the formation of continental ice sheets, anoxia caused by sluggish ocean circulation, a massive release of methane from seafloor hydrates, or some combination of these events. Regardless of the cause, this extinction established a prominent geological benchmark in outcrops around the world, providing a gauge by which to establish the timing of subsequent processes that led to the formation of features such as the Gulf of Mexico.

After this extinction, Pangea began to drift apart as a precursor to the development of the Gulf of Mexico basin. In the Late Triassic, as the North American plate pulled away from the South American and African plates, deep rifts began to form. These rifts were associated with stretching of the continental crust.1 Still part of the North American plate, the area that would eventually become the Gulf of Mexico was cut by grabens, which gradually subsided as they filled with volcanic deposits and nonmarine red beds derived from sediments eroded from adjacent elevated areas.2 These red beds, which provide some of the earliest records of Gulf of Mexico rifting, make up part of the Eagle Mills formation.

Subduction-related tectonism along the western margin of the North American plate permitted sporadic encroachment of the Pacific Ocean. During the Middle Jurassic, Pacific storm surges reached eastward across Mexico to fill shallow depressions in the proto-Gulf—the surface expressions of continually subsiding grabens activated during the Late Triassic. Between surges, the connection with the Pacific Ocean would close, leaving behind isolated bodies of salt water.

Throughout countless cycles of replenishment and evaporation, salinity in these bodies of water steadily increased. This resulted in halite precipitation in the center of the hypersaline basins and anhydrite precipitation along parts of the periphery. Local subsidence accommodated the pace of halite precipitation, as evidenced by evaporite deposits that are thousands of feet thick. In the northern Gulf of Mexico basin, these extensive salt deposits came to be called the Louann Salt, of late Middle Jurassic age.

In the Late Jurassic, during what is inferred to be the final stages of rifting, continued stretching of the continental crust caused the Yucatan platform to separate from the North American plate, taking a portion of the salt body along with it. A connection between the early Gulf of Mexico and the Atlantic Ocean probably opened late in the Jurassic, when a passageway between the Florida and Yucatan platforms was established, and the connection to the Pacific Ocean became restricted.3 The Yucatan rotated counterclockwise as it continued to drift southward.4 It finally came to rest on the northern edge of the South American plate during the Early Cretaceous (below).

Tectonics beyond the basin greatly influenced the sequence and areal extent of sedimentary deposits that began filling the Gulf and burying the thick layers of Louann Salt. Some of these sediments would later become hydrocarbon sources, while others would become possible hydrocarbon reservoirs that today are being targeted for exploration.

Jurassic uplift of the Appalachian Mountains was accompanied by erosion of granitic mountain materials. As they weathered, the feldspar and mica minerals within these granites broke down to produce clastic deposits rich in...
clay, known as feldspathic sandstone. Locally, arid winds transported some of the clastic sediments, winnowing the clays away from the quartzo-feldspathic fraction, resulting inolian deposits of the Upper Jurassic Norphlet sandstone.9 Meanwhile, the Florida Shelf and Yucatan Shelf became starved of clastic sediments and were dominated by the deposition of massive layers of chemical carbonates.

Following Norphlet deposition, a rise in sea level produced a transgressive period during which localized deposition of evaporites, shallow marine clastics and organic-rich carbonates occurred. The organic matter, derived from algae, plankton and other materials in the marine environment, was mixed and buried within layers of carbonates and shales. As the sediments were buried deeper over time, heat and pressure resulting from the accumulating overburden transformed the organic matter into Type I and Type II kerogens, essential precursors to the generation of hydrocarbons.10

During the Cretaceous, thick deposits of interbedded carbonates, marls and organic-rich marine shales were laid down during another series of marine transgressions. Like their deeper Jurassic equivalents, these organic-rich deposits would become important source rocks when buried deep enough to generate hydrocarbons. The end of the Cretaceous—about 65 million years ago—was marked by the arrival of a large asteroid, which heralded a new era in the geologic history of the Earth.

This asteroid, 5 to 6 mi [8 to 10 km] in diameter, impacted near the present-day town of Chicxulub Puerto, on Mexico's Yucatan Peninsula (above). Upon impact, the asteroid excavated a crater in the Yucatan carbonate shelf that spans more than 112 mi [180 km] in diameter and melted the Earth's crust to a depth of about 18 mi [29 km].11 The energy released on impact exceeded that released from 100 million megatons of TNT.12 In the Gulf basin, massive earthquakes induced slumping of coastal sediments, while 330-ft [100-m] tsunamis radiated across the Gulf of Mexico and the proto-Caribbean and Atlantic basins.13

Attesting to the physical effect of the impact is a layer of melt spherules found across Haiti, as well as in the United States, Canada, Spain and New Zealand. These spherules were produced as tons of molten ejecta blasted out of the crater, forming a red-hot plume that circled the globe and rained molten glass for days, sparking fires across parts of North and South America, central Africa, India and Southeast Asia. As a consequence, a deposit of ash and soot is preserved in the sediments of Europe and the western USA.

During this time, greenhouse gases increased more than a hundredfold, atmospheric sulfur content increased by a factor of a thousand, and chlorine gas destroyed the ozone, creating an environment that ended the age of the dinosaurs and extinguished 75% of the Earth's species.14

Following the Cretaceous-Tertiary cataclysm, sediments shed from mountain-building events on the western margin of the Gulf began to fill the subsiding basin. At the beginning of the Paleocene, clastic detritus from the west accumulated in the basin, while 330-ft [100-m] tsunamis stripped the seabed of clastics. These turbidite sandstones are reported to have permeabilities from 1 to 10 mD and porosities between 14% and 18%.15

As basin fill continued during the Early Eocene, amalgamated deepwater channel-levée sequences buried the basin-floor fan complex. These Upper Wilcox sediments were deposited under higher energy conditions than those of the Lower Wilcox and are better sorted than their basin-floor counterparts. Consequently, these amalgamated sequences have fewer rock fragments, less clay and better reservoir properties, as evidenced by reported values of 50- to 200-mD permeability and 20% to 28% porosity.

10. Following burial to depths of 0.8 to 1.2 mi [1 to 2 km] and heating to temperatures of 140°F [60°C], the kerogens serve as primary feedstock for the generation of hydrocarbons.
16. Some authors have proposed that a collision of the Cuban Arc against the Yucatan and Florida blocks during the Paleocene and Eocene may have isolated the Gulf of Mexico, prompting a dramatic short-term regressive lowering of sea level through evaporation. This would have allowed reworking of previously deposited Wilcox sands. As the sea level dropped, these sands would have been redeposited onto the deep basin floor in a series of proximal basin-floor fans. For more on this scenario: Rosenfeld JH and Blickwede JF: “Extreme Evaporative Drawdown of the Gulf of Mexico at the Paleocene-Eocene Boundary,” presented at the AAPG Annual Convention, Houston (April 9–12, 2006), http://www.searchanddiscovery.com/documents/2006/06065_rosenfeld/index.htm (accessed September 30, 2008).
Major canyon systems cut through Cenozoic Shelf margins and channeled the Wilcox clastics far from shore. These clastics were carried out to the deepwater basin floor (above). The resulting thick deposits of clastic reservoir rock are now being targeted for exploration, and offshore operators have announced discoveries containing significant oil accumulations in areas of the Perdido and Mississippi Canyon fold belts, as well as beneath the salt canopy at the Jack, Kaskida and St. Malo prospects.

The Upper Wilcox deposits were buried beneath thick layers of deepwater marine shale during the Late Eocene. During the Oligocene, another influx of clastic sediment was delivered by a series of deltas sourced from uplift of the

Moving sands to deeper waters. When a river meets the ocean, water velocity dictates where it will deposit the sediments it carries in suspension. Heavier materials—typically coarse- to medium-grained sands—drop out first. Then, as velocity decreases with distance from shore, finer sands and silts are deposited, followed by very fine particles that make up clays. Such a depositional progression is seen in the formation of river deltas on the continental shelf (map view and cross section, top left). However, water levels rise and fall—the result of glacial activity and cycles of tectonic plate dispersion or collision—and this variance has an impact on sedimentary processes. Thus, during periods of glaciation, water becomes locked up in continental ice sheets, which can dramatically lower sea levels. The ensuing regression draws water away from existing coastlines and deltas until it reaches a maximum fall of sea level, or lowstand. As they become exposed to weather, these coastlines and deltas erode and successively reveal deposits of sand, silt and clay when the sea recedes. As they are eroded, these sediments are redeposited downbasin—farther from their original source—and some rest temporarily on the steeper continental slope, away from the gentler dipping shelf that they were originally deposited on (top right). As deposition on the slope continues, these water-laden, shelf-edge deposits become steeper and more unstable (bottom left). An earthquake, loop current or major hurricane may eventually trigger the release of these sediments. When they give way, turbidity currents carry the sediments toward the abyssal plain, to be deposited in basin-floor fans (bottom right). In other cases, entire fault blocks can also be transported downdip intact or with varying degrees of mass translation. With changing glacial or tectonic conditions, sea level will eventually encroach upon the land in what is termed as a transgression. During this hightstand, a new delta may form where the river meets the sea. (Used with permission of John R. Dribus.)
Sierra Madre range, to the west. Ensuing erosional processes led to sequences of interbedded deltaic arkosic clastic sediments, marine shales and volcaniclastics.

By the Early to Middle Miocene, deepwater clastics entering the Gulf of Mexico basin were increasingly sourced from the northern Mississippi River system as uplift and erosion of the Rocky Mountains continued, and sediment input from the Sierra Madres in the west began to decline. As these western-sourced systems diminished, clastic deposits in the Gulf became more quartzose and less arkosic, thereby creating reservoir rock with less clay and better reservoir potential. In the Middle Miocene, sand-rich turbidites, fed almost entirely from the Mississippi River system, formed sheet deposits across the Gulf basin floor, and by Late Miocene, contributions from western river systems became negligible (above).

Throughout transgressive and regressive depositional cycles spanning the Jurassic and Miocene, the Louann Salt has been responding to basin tectonics, as well as to clastic loading processes from deltas and turbidite fans that continue to this day. Depositional loading has had profound effects on the salt and the potential for viable prospects throughout much of the Gulf of Mexico.

Salt Tectonics

A basic knowledge of salt tectonics is helpful in understanding how hydrocarbon traps formed above deposits of salt, and how these same traps later became covered by thick layers of tectonically emplaced salt. Thick layers of salt, when buried and deformed, result in continental margin stratigraphy and structures that are utterly different from those in margins lacking salt. These tectonic effects are a product of the distinctive properties of salt.

Pure rock salt is composed of sodium and chloride, forming a mineral known as halite. Other minerals formed by evaporating seawater, such as gypsum and anhydrite, are commonly interlayered with halite, and the entire accumulation of evaporite minerals is referred to simply as “salt.” As these minerals precipitate from brine, they form a crystalline rock.

One of the more important properties of rock salt is that it is much weaker than surrounding sedimentary rocks, such as sandstone or shale. Its strength diminishes with decreasing crystal size and increasing temperature, or when thin films of original seawater remain between salt grains. Failure in salt often leads to ductile flow. Even at ambient temperatures and pressures, salt can flow at a rate of meters per year, as has been measured in the salt glaciers of Iran (next page, top).

Salt is also distinctive for its low density. Freshly deposited mud and sand are less dense than salt. However, these sediments expel their interstitial fluids and compact during burial, eventually becoming denser than salt. The salt consequently becomes more buoyant by comparison. In the Gulf of Mexico, the average density of a sedimentary column does not usually exceed that of salt until the overburden thickness reaches 1 to 2 mi [2 to 3 km]. Another important property of salt is its permeability. It is so low that salt acts as a seal to liquids and gases, and thus can stop fluid migration and trap hydrocarbons.

Salt is mechanically stable if compressed equally from all sides during burial. However, salt’s low viscosity allows it to flow under unbalanced forces or loads, which occur in nature primarily under two conditions. Gravitational loading results when overlying...
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Sediments vary laterally in thickness or density, causing the underlying salt to flow laterally toward thinner or less-dense overburden. Displacement loading is the second form of instability. It is driven by tectonic forces and typically acts horizontally. If the sediments flanking a salt body pull away laterally, the salt can stretch and sag into the resulting gap. Conversely, if the flanking sediments press together, any intervening salt body will be squeezed, tending to rise like toothpaste extruded from a tube.

However, even if unbalanced forces are imposed on weak salt, it may not deform. Two important forces resist salt flow. First is the strength of overlying sediment layers. For salt to rise, it must penetrate or lift the sediments above it. If the overlying sediments are thick enough, they will be too heavy to be lifted and too strong to be pierced by the salt, despite its buoyancy. Second is boundary drag, caused by friction against the top and bottom of the salt layer. Where a salt layer feeds a growing salt structure nearby, it becomes exponentially more difficult for this feeder layer to flow laterally as the salt source depletes and the layer grows thinner.

Salt is originally deposited in flat layers. The forces described above transform these layers into underground mountain ranges of salt—some hundreds of miles long—that can grow taller than the greatest mountains on Earth. Because it was originally thought that such salt masses push through overlying sediments, they are called diapirs, from the Greek word *diapeirein*, to pierce.

Diapirs are unquestionably the tallest and most spectacular of the various salt bodies (left). Horizontal salt layers may transform into subsurface mountainous diapirs in three ways. First, where a sedimentary basin is stretched, *reactive* diapirs can rise to create sharp-crested ridges below strata that are thinned by extensional faulting. Second, *active* diapirs can break through arch-like folds whose crests have been thinned by erosion, especially in areas where tectonic squeezing has pressurized the salt. Third, *passive* diapirs can grow like “islands” of salt, exposed on the Earth’s land surface or seafloor, while the base of the diapir and surrounding sediments sink as the sedimentary basin fills.

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^ Allochthonous salt spreading subaerially. Kuh-e-Namak (Mountain of Salt in the Farsi language) is the most famous salt diapir in Iran. This salt glacier (light gray) emerges from an anticline, its summit towering 1,400 m [4,593 ft] above the surrounding plain. Note the vehicle (circled) in the foreground for scale. Here, the Infra-Cambrian Hormuz salt spreads over much younger Jurassic-Cretaceous strata (tan), which form the anticline. The main body of this salt glacier advances at an average rate of about a meter a year. A collision between the Arabian and Iranian microplates created the Zagros Mountains and enhanced the rise and extrusion of the salt. (Photograph courtesy of Martin Jackson.)
Where the original source layer of salt is thick enough, the crests of the largest diapirs can begin to spread laterally at or below the seafloor, forming a shallow sheet of salt. The source layer of salt is said to be autochthonous, or formed in place (above). Autochthonous salt overlies older rocks and is, in turn, overlain by younger strata. By contrast, the shallower sheets of salt that spread out from the diapir are said to be allochthonous, or formed out of place and away from their original source. Allochthonous salt sheets overlie younger strata. Thus, while the autochthonous Louann Salt dates back about 160 million years to the Jurassic period, the shallow sheets of allochthonous salt derived from the Louann Salt may overlie strata as young as 1 million years of age.

These fundamental processes of salt tectonics combine to create continental margins of great complexity, and no divergent margin is more complex than the Gulf of Mexico. One way to better understand this margin is to divide the region into provinces, each of which has a dominant structure or distinctive geologic history. This approach has become more refined with improvements in seismic acquisition and processing that allow better visualization of the geometries of the deep salt.

Geoscientists initially investigated this region using well data linked by a grid of 2D seismic surveys. However, the subsalt regions tended to be poorly imaged, so the structural provinces were based mostly on mapping of shallow salt structures. The advent of widespread 3D seismic coverage during the 1990s enabled geoscientists to start defining structural provinces on the basis of deep autochthonous salt and related structures. These refinements helped shape the following summary of key processes and events, roughly in chronological order, which shows how salt tectonics influenced basin evolution of the Gulf.

Seismic data reveal that the Louann Salt varied in thickness from almost zero to perhaps as much as 2.5 mi [4 km] as it accumulated on a surface made uneven by faulting, erosion or volcanism. Countless cycles of seawater influx and evaporation resulted in this massive thickness of salt. Many of the crustal structures controlling original salt thickness are oriented along a northwest-southeast trend. Vertically connected by salt, these deep structures appear to have influenced much shallower structures, causing them to trend along a similar direction.

Crustal stretching and basin-center rifting severed the Louann Salt basin into northern (USA) and southern (Mexico) parts. This was followed by cooling of newly formed oceanic crust and exhumed upper mantle in the center of the opening Gulf, which created a density increase that caused the basin floor to sink. The resulting basinward tilt sent the severed salt flowing toward the center of the Gulf. At the same time, sediments began to pile up on the new oceanic crust, ahead of the spreading salt. This sedimentation caused the base of the spreading salt to climb over the accumulating strata, building a seaward-climbing wedge of allochthonous salt during the Jurassic and Early Cretaceous. The wedge formed a fringe of salt at least 19 to 25 mi [30 to 40 km] wide beneath the Sigsbee Escarpment between the Mississippi Canyon and Keathley Canyon areas, marking the first of several salt-sheet emplacements in the Gulf of Mexico.

During the Late Jurassic to Miocene periods, folding of strata above the salt began in the Walker Ridge area, along the eastern edge of the Sigsbee Escarpment. This folding was partly a result of loading caused by uneven clastic sedimentation from deltaic systems, which forced the salt to flow away from thick depocenters and into areas below thinner layers of sediment. In addition, lateral compression induced by tilted strata caused the salt overburden to buckle.

Some areas, such as the eastern Mississippi Canyon, originally contained thin layers of autochthonous salt and yielded only a few scattered tall diapirs. However, in other places, such as the Green Canyon and Atwater Valley areas, thin deposits of salt were subsequently thickened by salt inflation, beginning in the Late Jurassic. Inflation occurred as sediments shed off the North American continent were deposited into the thick salt basin and displaced underlying autochthonous salt ahead of the advancing sedimentary load. The displaced salt flowed horizontally into peripheral regions, where thinner layers of salt had been deposited. As displaced salt built up these deposits on the periphery, salt inflation enabled growth of much larger diapirs and folds than would otherwise have been possible.

During the Cenozoic, folding and thrusting began in earnest on the lower Continental Slope. This folding was driven by gravitationally induced compression caused by the basinward slope of the seafloor. The Perdido fold belt, in the Alaminos Canyon area, formed on a thick cushion
of autochthonous salt in the Late Oligocene and Early Miocene. To the east, the Mississippi Fan fold belt formed on the deep wedge of allochthonous salt in the Atwater Valley area during the Late Miocene. Across a broad area between these fold belts extending from Keathley Canyon to west Walker Ridge, deep fold belts have not been recognized because they are below the deepest part of the basin, which has been poorly imaged by seismic surveys.

Concurrent with this folding was the most remarkable process of all. From the Miocene to the present, vast salt sheets spread laterally like pancake batter wherever salt supplies from depth were sufficient to feed their expansion. These sheets then coalesced to form shallow salt canopies. Some shallow salt sheets were fed by massive salt diapirs sourced from the deep autochthonous layer below. Other sheets were fed by overlying, yet deeply emplaced allochthonous canopies.

This massive spreading of salt was highly variable. In the eastern Mississippi Canyon area, where autochthonous salt was thin, only scattered, small salt sheets formed. To the west, in the Green Canyon area, where deep salt was thicker, most diapirs merged into canopies. Even farther west, from the Walker Ridge to Alaminos Canyon areas, where autochthonous salt was thickest, massive diapiric walls of salt fed a single giant canopy that spread southward for many tens of kilometers.

Allochthonous salt spread throughout the Cenozoic, and its lateral extent increased over time. The main driver for the Neogene spreading of canopies was a mid-Miocene switch in continental sediment sources, which moved from the west and northwest to the northern rim of the Gulf. This switch increased the sedimentary load in areas where autochthonous salt was still thick. As the shallow salt sheets surged southward, they either pushed and smeared smaller salt sheets ahead of them or overrode small diapirs that were locally sourced from thin, autochthonous salt.

Clues to how the salt canopies spread are found along the Sigsbee Escarpment, where a veneer of Pleistocene sediment covers the leading edge of the shallow spreading salt (above). The Sigsbee Escarpment is the largest deformation structure affecting the seafloor in the Gulf of Mexico and is the largest exposed salt structure in the world. The escarpment reaches a height of approximately 4,100 ft [1,250 m]. It has a great-circle length of about 350 mi [560 km] and a sinuous and buried length of more than 620 mi [1,000 km]. The salt canopies continue to advance today over about 60% of the escarpment, gradually obscuring much of the subsalt geology.

Initially, salt sheets extrude across the seafloor as salt glaciers, and much of the soluble salt dissolves into the seawater. However, the spreading salt is partly protected by deep-marine clay that has settled as a muddy veneer. Moreover, as the most-soluble salt minerals dissolve, a mushy layer of less-soluble minerals remains as a thickening protective blanket. Today, sediments bury almost all of the Sigsbee Escarpment, hindering salt extrusion. Thus, salt and its roof must advance together over the abyssal plain, causing thrusting along the base of the escarpment. Either the compressed sediments ahead of the advancing salt break cleanly as a single thrust fault, or they are bulldozed into a tapering prism of thrust slices.

The youngest salt sheets are now found in pristine form along the Sigsbee Escarpment, at the foot of the Continental Slope. Progressing landward up the Slope, the covering sediments thicken. This increasing sedimentary load on the sheets causes the salt within them to be expelled inexcorably seaward.

Sedimentation is highly irregular and typically creates minibasins in the top of the salt’s surface. Some minibasins begin as mere dimples in the top of the salt sheets, then deepen into sediment-filled dishes 6 to 25 mi [10 to 40 km] wide. Once the minibasins become greater than 1 or 2 mi thick, their compacted density is enough to make them sink, causing diapiric salt to well up around them. Other minibasins form in a different manner entirely.

On the lower Slope, gravitationally induced compression wrinkles the sedimentary veneer and initiates minibasins. On the middle Slope, several other mechanisms have been proposed. The pattern of sedimentation controls where subsidence is greatest and thus molds the top of the salt canopies. This structural relief, in turn, creates the local bathymetry, which is the main influence on where sediment moves and where it amasses. Here, cause and effect blur because salt tectonics and sedimentation affect each other.

Sediment works its way down the Continental Slope, following a sinuous path created by partly merged minibasins, while avoiding bulges on top of salt structures. Some pathways end in temporary or permanent cul-de-sacs, where sediment is trapped in minibasins. The minibasins continue to subside until all underlying salt is expelled laterally. At this point, a salt weld is formed as sediments that were formerly above and below the salt are brought together during its expulsion. Like a boat grounding at low tide, a minibasin comes to rest on unyielding sediment instead of on displaced mobile salt.
The patterns of minibasin subsidence, salt thinning and welding are complex but are generally viewed as combinations of three end members: salt-stock canopy systems, roho systems and stepped counter-regional systems.

- **Salt-stock canopy systems** are characterized by evacuated clusters of funnel-shaped salt diapirs that have coalesced.
- **Roho systems** are characterized by stretched sediments that are spread on long smears of welded allochthonous salt. A roho system consists of a group of listric basinward-dipping growth faults that sole, or bottom out, onto an allochthonous salt sheet or weld. (Listric faults are curved, normal faults that exhibit decreasing dip with depth.) Sediment wedges in the fault blocks dip and thicken landward, but become younger seaward.
- **Stepped counter-regional systems** are distinguished by sagging sediments on short welded allochthonous salt sheets. A stepped counter-regional system consists of a major listric landward-dipping growth “fault” or leaning salt diapir. This fault is actually a landward-dipping salt weld that passes downward into a flat salt weld and, even more deeply, into another landward-dipping salt weld that roots into the flat source layer. Sediment wedges dip and thicken seaward.

In these varied ways, thick salt sheets can be transformed into a three-dimensional network of irregular salt bodies partly connected by thin smears of salt and arrays of faults.

The Petroleum System

The earlier discussions on tectonics and deposition touched upon key elements required for creation and accumulation of hydrocarbons. These elements, long recognized by the oil and gas industry, have been codified into a single concept known as the petroleum system. An effective petroleum system comprises the following elements:

- **source rock** containing organic material of sufficient quality and quantity for the generation of hydrocarbons
- **temperature and pressure envelope** (achieved through burial) suitable for converting organic material into hydrocarbons
- **hydrocarbon migration process and pathway**
- **reservoir rock with enough porosity to accumulate and store hydrocarbons and sufficient permeability to eventually produce the hydrocarbons**
- **trap and seal** to stop the migration process and provide containment within the reservoir
- **preservation to preclude destruction through erosion, tectonics or temperature.**

The absence of any one of these elements will condemn the viability of a prospect. Until the mid 1980s, the search for reservoir, trap and seal in the Gulf of Mexico basin was focused on strata lying above the salt canopy. Although an effective petroleum system had been confirmed with each discovery made above the salt, there was no evidence that requisite conditions existed beneath it.

This mindset was challenged in 1983, when Placid Oil Company drilled a well through two thin salt sheets before being forced to plug and abandon it in the third salt body it encountered. Although the borehole penetrated only 295 ft (90 m) of subsalt sediment, with no indication of pay, this well drilled completely through two sheets—rather than diapirs. This spurred interest from other operators that helped set the stage for further subsalt drilling. Then, in 1986, Diamond Shamrock penetrated 990 ft (302 m) of salt before drilling out into a 1,000-ft (305 m) reservoir-quality sand section. No hydrocarbons were encountered in this South Marsh Island Block 200 well, but drilling results confirmed that sandstone of sufficient porosity and permeability could be found beneath salt. Four years later, Exxon drilled a commercial discovery in 4,350 ft (1,326 m) of water at its Mica prospect, in Mississippi Canyon Block 211. Exxon drilled this deepwater well through 3,300 ft (1,021 m) of salt before discovering a reservoir estimated to contain 100 to 200 million bbl (15.9 to 31.8 million m³) of oil equivalent—proving that an effective petroleum system could indeed exist beneath the salt.

Today, E&P companies have a much better understanding of the subsalt region, thanks largely to data and experience gained through deepwater and subsalt drilling, along with improved seismic acquisition, processing and imaging techniques. There is no longer any doubt that all elements of the petroleum system can be found above and below the salt. By exploring the subsalt region, E&P companies are learning how salt affects structure and deposition and how interactions between salt and overburden influenced the development of petroleum systems in the Gulf of Mexico basin.

Geoscientists have come to understand that, as the basin evolved and continued to subside, burial and subsequent heating of organic-rich source rocks of Jurassic—and perhaps Cretaceous—age created an excellent system for generating hydrocarbons. The deformation of the autochthonous Louann Salt on the floor of the basin below the source rocks, and subsequent deformation of the salt into pillows, diapirs and allochthonous salt bodies, resulted in numerous structural traps. Faults created during extension of the salt and overlying sediments would, in many cases, provide conduits for hydrocarbon migration to potential reservoir rocks above. In some cases, faulting juxtaposed permeable sands.
Subsalt wells. Noteworthy wells that were drilled beneath the allochthonous salt show a range of water depths and targets. Compiled from press basis of a few lines of 2D seismic data. Moreover, uncommon for wildcats to be drilled solely on the seismic coverage was often sparse, and it was not salt. These encounters were not predictable— For the first 40 years of drilling in the Gulf of Revolution in the Gulf and 1990s also found salt while aiming for DHIs. Several other subsalt wells drilled in the 1980s were reluctant to drill ahead. One supposed DHI target helped to launch the subsalt trend in the northern Gulf of Mexico. The Placid Oil Company No. 2 well at Ship Shoal Protraction Area Remarks

<table>
<thead>
<tr>
<th>Block Number</th>
<th>Total Depth (feet)</th>
<th>Water Depth (feet)</th>
<th>Year Drilled</th>
<th>Field Name</th>
<th>Remarks</th>
</tr>
</thead>
<tbody>
<tr>
<td>366</td>
<td>8,203</td>
<td>2,500</td>
<td>1983</td>
<td>—</td>
<td>Dry hole. Targeted a direct hydrocarbon indicator (DHI); drilled through salt.</td>
</tr>
<tr>
<td>200</td>
<td>13,500</td>
<td>4,115</td>
<td>1986</td>
<td>—</td>
<td>Dry hole. DHI target proved to be salt; however, 1,000 ft [305 m] of wet, reservoir-quality sand lay beneath it.</td>
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</tbody>
</table>

<table>
<thead>
<tr>
<th>Name</th>
<th>Field</th>
<th>Water Depth</th>
<th>Date</th>
<th>Depth</th>
<th>Type</th>
</tr>
</thead>
<tbody>
<tr>
<td>Mica</td>
<td>Mahogany</td>
<td>Put on line before Mica. Became the first commercial development in the Gulf of Mexico subsalt play.</td>
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<tr>
<td>Enchilada</td>
<td>Chimichanga</td>
<td>Second commercial subsalt discovery, drilled 1,300 ft [396 m] of salt, tested at 2,100 bbl/d [334 m³/d] of oil and 20 MMcf/d [566,337 m³/d] of gas.</td>
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<tr>
<td>Gemini</td>
<td>Atlantis</td>
<td>Third commercial discovery of the play, in Pliocene-Miocene sands. Deepest mounded floating oil and gas production facility in the world and also one of the largest.</td>
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</tr>
<tr>
<td>Hickory</td>
<td>—</td>
<td>Penetrated 8,000 ft [2,438 m] of salt.</td>
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</tr>
<tr>
<td>Tanzanite</td>
<td>—</td>
<td>First well tested 1,917 bbl/d [305 m³/d] of oil and 29.7 MMcf/d [841,100 m³/d] of gas, one of the highest rates in the shallow-water Gulf of Mexico.</td>
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<tr>
<td>Thunder Horse</td>
<td>—</td>
<td>Largest field in the Gulf of Mexico.</td>
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<tr>
<td>Magnolia</td>
<td>—</td>
<td>Tension leg platform (TLP) installed in record water depth for TLPS.</td>
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<tr>
<td>K2</td>
<td>—</td>
<td>Drilled through 10,000 ft [3,048 m] salt canopy of the Miocene fold trend.</td>
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<tr>
<td>Mad Dog</td>
<td>—</td>
<td>300 ft [91 m] of net pay discovered in Mississippi Fan fold belt.</td>
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<tr>
<td>Fedhawk</td>
<td>—</td>
<td>Produced from the world’s first truss spar facility.</td>
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<tr>
<td>Tahiti</td>
<td>—</td>
<td>Middle Miocene trap beneath 11,000 ft [3,353 m] salt canopy.</td>
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<tr>
<td>St. Malo</td>
<td>—</td>
<td>First subsalt well of the Wilcox trend, drilled through 10,000 ft [3,048 m] of Sigbee salt canopy, with 450 ft [137 m] of net pay.</td>
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<tr>
<td>Jack</td>
<td>—</td>
<td>Wilcox test: deepest extended drillstem test in deepwater Gulf of Mexico history.</td>
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<tr>
<td>Kaskida</td>
<td>—</td>
<td>First Wilcox subsalt wildcard located significantly inboard of the Sigbee Escarpment, northern frontier of Wilcox prospects. Found 880 ft [244 m] of net pay.</td>
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</tr>
<tr>
<td>West Tonga</td>
<td>—</td>
<td>Discovered 350 ft [107 m] of net oil in three Miocene sands.</td>
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</tbody>
</table>

Subsalt wells. Noteworthy wells that were drilled beneath the allochthonous salt show a range of water depths and targets. (Compiled from press releases and US Department of Interior Minerals Management Service, reference 31.)

against impermeable shales to create traps and seals. Thick deltaic and turbidite clastic sediments created potential reservoir rocks of varying quality throughout the Tertiary, from high-permeability and high-porosity quartzose sandstones in younger rocks to less-permeable arkosic sandstones in older rocks. Studies of basin history have also indicated favorable timing of fluid expulsion and hydrocarbon migration. Thus the northern Gulf’s subsalt play appears to have all the elements necessary for an effective petroleum system.

**Revolution in the Gulf**

For the first 40 years of drilling in the Gulf of Mexico, it was not unusual for drillers to stop short of targeted depth once they encountered salt. These encounters were not predictable— seismic coverage was often sparse, and it was not uncommon for wildcats to be drilled solely on the basis of a few lines of 2D seismic data. Moreover, sparse coverage and early processing techniques sometimes led operators to target poorly resolved seismic structures or seismic bright-spot anomalies known as direct hydrocarbon indicators (DHIs). However, these seismic targets sometimes turned out to be the top of salt. Having drilled to targeted depth without striking pay, but rather finding their bit in salt, most operators were reluctant to drill ahead.

One supposed DHI target helped to launch the subsalt trend in the northern Gulf of Mexico. The Placid Oil Company No. 2 well at Ship Shoal Block 366, mentioned previously, was drilled to a DHI target that instead encountered three salt bodies before being plugged and abandoned. Several other subsalt wells drilled in the 1980s and 1990s also found salt while aiming for DHIs.

In the 20 years following the dry hole at Ship Shoal, more than 140 subsalt wells have been drilled in the Gulf of Mexico. Although some were not commercial, several of these wells were notable for extending the trend or setting records in their day (above).

Of these wells, only 50 were drilled in relatively shallow waters of the Outer Continental Shelf, their water depths ranging from 93 to 560 ft [28 to 171 m]. The rest were drilled on the Continental Slope, in water depths ranging from 630 to 7,416 ft [192 to 2,260 m]. There was no gradual and deliberate move from shallow to deeper waters; in the year following its Ship Shoal Block 366 dry hole, Placid drilled another subsalt well in 2,004 ft [610 m] of water.

32. MMS, reference 31.
The subsalt drilling campaigns of the 1980s and 1990s primarily targeted turbidite deposits of Pliocene age, with some Pleistocene and Miocene sands. Today, however, in a basin where 99% of proven oil reserves are produced from formations of Miocene age or younger, the Gulf of Mexico subsalt trend is being rejuvenated from deepwater and ultradeepwater discoveries in much older Eocene and Paleocene sands (above). Discovered in turbidite channel and fan systems, the deep-basin equivalent of onshore deposits of the Wilcox formation in Texas and Louisiana, are helping to extend the subsalt play.

These turbidite reservoirs have been discovered more than 250 mi [400 km] downdip from Wilcox delta systems. This deepwater Wilcox trend lies in 4,000 to 10,000 ft [1,200 to 3,050 m] of water and is thought to cover some 30,000 mi² [77,670 km²]. Some prospects lie beneath salt canopies that are 7,000 to 20,000 ft [2,130 to 6,100 m] thick. Interestingly, however, the early discoveries in this trend never penetrated salt. At first, operators tried to avoid the salt by moving to deeper waters to drill outboard of the salt. There, seismic imaging was not distorted by salt, and drillers had to contend only with familiar challenges associated with drilling in deep waters. However, once they established the viability of this deepwater Wilcox trend, exploration teams began chasing their prospects updip, beneath the salt, resulting in discoveries such as St. Malo and Jack.

The Lower Tertiary Wilcox play was initiated by the second Baha well drilled at Alaminos Canyon Block 557, a prospect that originally targeted fractured carbonates of Mesozoic age. In 1996, drilling problems forced the No. 1 well to be abandoned before reaching total depth, but it did encounter 15 ft [4.6 m] of pay in an Upper Eocene sand, thereby suggesting that a viable petroleum system and perhaps a commercial discovery might exist deeper within the structure. In 2001, the Baha No. 2 well was successfully drilled to 19,164 ft [5,841 m] and showed the original Mesozoic carbonates to be nonporous. Though this dry hole found only 12 ft [3.7 m] of oil in an Eocene sand, it also identified possible reservoir-quality sands contained in more than 4,000 ft [1,219 m] of a Wilcox turbidite section.

Shortly thereafter, wells located south of Baha, such as the Trident prospect (Alaminos Canyon Block 903), and Great White prospect (Alaminos Canyon Block 857), discovered Wilcox pay sands in the Perdido fold belt of the western Gulf of Mexico. Subsequent drilling ventures to the east resulted in Wilcox discoveries at the Cascade, Chinook, St. Malo and Jack prospects located in the Walker Ridge area. The Kaskida discovery and the noncommercial Sardinia and Hadrian wells in Keathley Canyon helped bridge the gap between west and east. Data from these wells allowed geologists to infer that Wilcox sands extend more than 300 mi [480 km] across the Gulf of Mexico basin. By 2007, at least 20 wildcat wells had been drilled in this trend, resulting in 12 discoveries. Estimated recoverable reserves for each discovery ranged from 40 to 500 million bbl [6.4 to 79.5 million m³] of oil.

The St. Malo discovery at Walker Ridge Block 678 is distinguished as the first well to reach Wilcox sands beneath allochthonous salt. Another subsalt Wilcox well was drilled at Walker Ridge Block 759—the much-heralded Jack discovery. A second well was drilled to appraise the structure. This well—the only well in the subsalt Wilcox to be tested—produced encouraging results: it was announced that the Jack well flowed for 23 days, sustaining a rate of 6,000 bbl/d [953 m³/d] of oil, while testing 40% of the total net pay interval (next page). To the northwest, the Kaskida well marks the northernmost frontier for Wilcox subsalt discoveries to date and lies farther from the edge of the Sigsbee Escarpment than others of this trend.

How many more trends and fields will eventually be discovered beneath the expanse of the Sigsbee salt canopy? Once hampered by poor imaging, subsalt exploration has benefitted from revolutionary approaches to measuring properties of deep formations. New seismic acquisition techniques, together with more accurate velocity models and migration algorithms, are helping to meet the challenge of imaging beneath salt. In particular, wide-azimuth and rich-azimuth seismic survey techniques obtain improved signal-to-noise ratios in complex subsalt geology and provide natural attenuation of certain types of signals that cause multiple reflections. The Q-Marine system capitalizes on less-attenuated low frequencies to better image the subsurface. It also provides large, steerable, calibrated source arrays for better subsalt energy, single-sensor recording to improve noise sampling and attenuation, and the capability to record while the vessel turns to a different heading.

With the aid of complementary nonseismic technologies that measure different properties of the subsurface terrain, geoscientists and engineers are building more comprehensive models to help E&P companies better determine the viability of a prospect and identify drilling risks before moving a rig onto location. In addition to seismic data, geoscientists are turning to marine magnetotelluric, gravimetric and electromagnetic surveys. These surveys have advanced well beyond first or second generation, and all are acquired by marine survey vessels.

Complementary technologies have been used to improve delineation of prospects located above
Preparing to test. The Jack 2 well, drilled by the Discoverer Deep Seas drillship, was cased and suspended before the Cajun Express semisubmersible rig moved in for an extended well test. Barges were also brought in to collect fluids produced by the test.

Driven by Salt

Technologies developed for exploring the subsalt province of the deepwater Gulf, along with the experience gained in the process, will prove helpful in developing future subsalt plays. The Gulf of Mexico is, after all, just one of 55 basins around the world that contain allochthonous salt bodies. These salt bodies can be found offshore Angola, Brazil, Canada, Madagascar, Mexico, Morocco and Yemen. Some basins share remarkable similarities with others around the world.

For instance, a close analog of the Sigsbee Escarpment is seen in the ultradepth-water Kwanza basin off the coast of Angola. The Angola Escarpment is roughly 665 mi [1,100 km] long and marks the seaward limit of an allochthonous salt fringe, although the fringe is typically less than 12 mi [20 km] wide. The Scotian basin off the coast of Nova Scotia, Canada, also has similarities such as Cretaceous and Tertiary turbidite deposition, along with traps controlled by lateral and vertical motion of Triassic-Jurassic salt.

Not all salt bodies are found in offshore waters; some are in orogenic belts that mark episodes of mountain-building, or are otherwise landlocked. These salt bodies can be found in Algeria, Canada, Colombia, Germany, Iran, Kazakhstan, Peru, Spain and Ukraine. So although salt in the Gulf of Mexico basin has been explored by drill bit and seismic boat, salt in mountain ranges has been studied extensively in outcrop and explored hands-on. Geoscientists are recognizing similarities in each, and studies of salt structures in the field yield insights into those found beneath the sea.

Comparisons have been made between the Gulf of Mexico basin and the Precaspian basin of Kazakhstan and Russia. The Precaspian basin was formed in Permian times as a result of the Uralian orogeny. Beyond age differences, both basins experienced rapid salt deposition and were dominated by a major source of sedimentation (the Mississippi and Volga rivers). Both also display salt overhangs that spread into allochthonous salt sheets. Recognizing differences between basins is also helpful, as in the pre salt play of Brazil. In the Santos basin, different processes are at work. There, large discoveries within carbonate reservoirs are located beneath autochthonous salt and are structurally and stratigraphically unaffected by salt tectonics.

Identifying such similarities or differences helps E&P companies recognize the presence of characteristics in one basin that may point to corresponding, yet previously undiscovered features in analogous basins. Thus, intensely explored outcrops—such as the salt glaciers of Iran—or extensively explored basins—such as those of the Gulf of Mexico, the Precaspian or West Africa—complement each other in helping to unlock hydrocarbon potential in other basins around the world.

—MV