The Northern Gulf of Mexico Basin

by Doris M. Curtis

In Mesozoic and Cenozoic times a passive margin developed on the Ouachita fold belt described in the preceding article. In this review the author outlines the geological development of this hydrocarbon-rich province, which is characterized by extensional and gravity tectonics involving arcuate rifting and salt doming. Triassic to Lower Jurassic red beds as graben fill are overlain by Middle Jurassic salt, and covered in turn by Upper Jurassic and Cretaceous carbonates and terrigenous clastics. During the Cenozoic subsidence increased, and thick deltaic sequences prograded to the deep Gulf of Mexico.

The Region

The U.S. Gulf Coast province is the northern half of the Gulf of Mexico basin and includes the coastal plain portion of the states bordering on the Gulf and the northern continental shelf and slope (Fig. 1). The rocks of the coastal plain form a homocline that dips gently toward the Gulf, interrupted by salt diapirs and faults, some of which have surface expression. The coastal plain is a relatively flat, almost featureless, gently dissected area rising from sea level to less than 150 m. In addition to the Mississippi River and the Rio Grande, several major rivers that originate in the coastal plain constitute the major drainage.

The shore line is characterized by barrier islands and small bays, except for the Holocene delta of the Mississippi, which extends to the continental shelf edge. The continental shelf is 200 to 300 km wide and relatively featureless, sloping gently to an average depth of about 150 m at the shelf edge. The latter is marked by a gradual change from a gentle to a slightly steeper slope, except off Florida where the shelf is bounded by a steep escarpment. Topographic irregularities represent piercement salt domes, igneous plugs, and reef-like banks or mounds. The DeSoto and Mississippi canyons cut deeply into the slope, the topography of which is very irregular because of salt features, slumps, and intraslope basins. The Mississippi fan extends over the slope out to the deep Gulf.

The Tectonic Setting

The northern Gulf basin developed as a post-Paleozoic passive margin on the Paleozoic Ouachita fold belt (see article by J. Rodgers, this issue). Late Paleozoic sediments, which appear to be relatively undeformed, underlie the province on the Gulf side of this belt. The Appalachian fold belt extends southwestward beneath the eastern part of the coastal plain, and continental crust underlies the province from the peripheral Paleozoic fold belts to the central Gulf, which is itself underlain by oceanic crust. The precise boundary between transitional and oceanic crust is controversial, but it appears to be close to the Early Cretaceous shelf margin.

Subsidence of the Gulf basin took place along an arcuate zone of faults overlying the Ouachita orogenic belt and extending southeastward across Mississippi and Alabama (Fig. 1). Several parts of this subsiding basin persisted from Paleozoic time. The principal positive elements (uplifts) are the San Marcos arch, Sabine uplift, Monroe uplift, and Wiggins arch, and between these are negative areas - the interior salt basins (Fig. 1). Within the broad area of subsidence are areas of greater depression, Rio Grande and

Mississippi embayments, and areas of thicker salt accumulation, the Gulf Coast salt basin and Texas-Louisiana slope salt basin.

Fault Systems

The province is characterized by structures resulting from extensional and gravity tectonics (Fig. 2). Arcuate systems of en echelon extensional faults and grabens form a strike-oriented zone of parallel, partly syndepositional faults around the periphery of the basin. This zone forms the updip (landward) boundary of the Mesozoic-Cenozoic northern Gulf basin, and determines the regional structural and depositional strike. This zone contains pre-Jurassic rocks as graben fill, and it forms the approximate limit updip of the Jurassic salt that underlies the province. Several similar but discontinuous and less extensive fault systems occur within the basin; these faults were active during Mesozoic and later deposition.

From the Cretaceous shelf margin to the continental slope, the structural style is dominated by closely spaced syndepositional (growth) systems that are strike-oriented, and generally down-to-the-basin. These are listric normal faults that had their greatest growth in their early history and that die out upward. Most are buried, but some come to the surface, and they flatten and merge into décollement surfaces at the top of thick shale sections. This type of faulting is fundamental to the extensional and gravity tectonics of subsiding passive margins. The faults are a result of gravity imbalance due to sediment loading together with a strong horizontal stress component.

The fault systems are progressively younger basinward, beginning with Late Cretaceous faults along the Cretaceous shelf margin trend. Each fault system is closely inter-related in time and space with the progressively younger

Figure 1: Tectonic map, northern Gulf basin (modified from Martin, 1978). 1 - inner margin of outcropping Cretaceous strata; 2 - boundary faults for Gulf basin; 3 - San Marcos arch; 4 - Sabine uplift; 5 - Monroe uplift; 6 - Wiggins arch. Salt basins: 7 - East Texas; 8 - North Louisiana; 9 - Mississippi; 10 - South Texas; 11 - Gulf Coast; 12 - Texas-Louisiana Slope.

Cenozoic sequences that make up the basin fill. Growth on each fault begins at the shelf edge of progressively younger strata gulfward and continues through several depositional intervals. Each depositional sequence thickens downdip in a series of separate fault blocks, with the furthest downdip fault block of each stratigraphic unit having the thickest section. Rollover (reverse drag) anticlines are characteristically developed in downthrown blocks in the thicker sections.

Gravity Tectonics

The other dominant structural feature of the northern Gulf basin results from salt or shale movements, gravity tectonic phenomena due to density contrast between salt or under-compacted shale and overlying denser sediments. Salt structures grew from the Jurassic source layer at times and places of rapid deposition of the overlying sequences, with growth intermittent or continuous depending on salt thickness and sedimentation rates.

These structures are described and classified in a number of ways, depending on shape of the salt structure, continuity of strata across the top of the structure, and depth to the top of the salt. There are domes, anticlines, ridges and salt massifs, as piercement and non-piercement features, and at all depths from surface to 5 or 6 km beneath. Some deep-seated low-relief structures are believed to be salt related, even where no evidence of salt has been found.

Rim synclines surround domes or clusters of domes as a result of salt withdrawal, which may also leave residual anticlines. The domes may have irregular shapes and overhangs, and the surrounding sediments are uplifted on their flanks thinning towards and over the crests, or they are truncated against and over the domes. A complex pattern of radial and tangential crestal and peripheral faults is characteristic, except on the relatively simple low-relief deep-seated structures.

The salt is thickest under the slope basin and thinner under the continental shelf and onshore in the Gulf Coast and interior salt basins. The shape and distribution of the salt structures are related to the salt thickness. In the interior

Figure 2: Cross-section along line A-A' on Fig. 1 (modified from Martin, 1978, and Murray et al., 1985). 1 - Paleozoic rocks; 2 - Triassic (?); 3 - Jurassic; 3a - Jurassic salt; 4 - Lower Cretaceous; 5 - Upper Cretaceous; 6 - Paleocene and Eocene; 7 - Oligocene; 8 - Miocene; 9 - Plio-Pleistocene.

salt basins and the onshore portion of the Gulf Coast salt basin, the structures occur as isolated diapirs and deep-seated anticlines, but under most of the continental shelf the structures are larger diapiric domes and broad anticlinal swells. Under the continental slope, there are broad, semi-continuous diapiric salt uplifts and associated shale masses, and broad continuous ridge-like salt massifs.

Low-density shale is diapiric in several settings. There are shale domes and anticlines in south Texas outside of the salt basins, and shale domes or anticlines associated with the "toes" of syndepositional faults and slumps or with salt diapirism. There are also "sheaths" around many of the salt stocks, consisting of low-density shale older than the adjacent layered sediments. The "mudlumps" at the mouths of the Mississippi River are also diapiric shale structures.

Figure 3: Generalized columnar section with conventional lithologic symbols.

Stratigraphy: The Mesozoic

The rocks of the basin (Fig. 3) are Mesozoic and Cenozoic terrigenous clastics, carbonates, evaporites, and minor intrusive and extrusive volcanics. Paleozoic "basement" underlies the province and crops out in the orogenic belts that border the basin. These rocks are recognized in the subsurface in positive elements and in some buried high blocks.

The oldest coastal province rocks, Upper Triassic-Lower Jurassic red beds and basalt (Eagle Mills), occur as fill in grabens, half-grabens, and rift basins in the peripheral fault belts. Evaporites (Louann salt and underlying Werner anhydrite) deposited during late Middle Jurassic (Callovian?) time extend from the rim of the province to the central Gulf, but are thin or absent under the south Texas coastal plain and continental shelf. The original thickness of the evaporites is not known, except near their updip edge where they unconformably overlie the Triassic red beds, but it has been estimated as high as 4000 m. Salt tongues protrude

into the deep Gulf, and the salt forms a mobile substrate that is responsible for many aspects of Gulf Coast tectonics, as outlined above.

Overlying the salt is an Upper Jurassic (Oxfordian) sequence of sandstone (Norphlet) and limestone (Smackover). These are conformably overlain by Upper Jurassic (Kimmeridgian) evaporites and red beds (Buckner, not shown on Fig. 3) followed by deltaic and marine shelf sandstones, shales, and carbonates (Haynesville). These are succeeded in turn by a thick sequence of deltaic and non-marine to near-shore marine deposits that extends into earliest Cretaceous (Cotton Valley). The total thickness of Upper Jurassic beds reaches about 3000 m.

Lower Cretaceous (Hauterivian through Lower Cenomanian) rocks overlap older beds unconformably, forming a transgressive sequence over the Early Cretaceous unconformity and extending landward to rest on Paleozoic rocks beyond the peripheral boundary faults of the province. The oldest Lower Cretaceous rocks throughout the province are terrigenous clastics (Hosston), which are overlain in south and central Texas by carbonates (Sligo, Trinity, Fredericksburg, Washita) of Aptian, Albian and Early Cenomanian age. The section becomes more terrigenous and contains an evaporite section from northeast Texas eastward to Alabama and northwest Florida, and in south Florida the Lower Cretaceous rocks are almost entirely carbonates.

Figure 4: Schematic dip section illustrating deltaic sedimentation in a paralic basin. From Curtis, 1970.

A composite series of carbonate shelf-margin reef buildups forms the "Lower Cretaceous Reef Trend" or Early Cretaceous shelf edge (Edwards or Stuart City reef trend) from the Rio Grande across Texas and Louisiana, extending as a submarine scarp southeastward to form the edge of the Florida platform. Slope and rise sediments were deposited on the gulfside of this trend, and the maximum thickness of known Lower Cretaceous rocks is on the order of 4000 m.

A mid-Cenomanian unconformity separates rocks of Lower from those of Upper Cretaceous (Late Cenomanian through Maastrichtian) age. The latter overlap the older rocks except in central and northern Texas where they are in fault or erosional contact with Lower Cretaceous carbonates. The Late Cretaceous transgression extended up the Mississippi embayment and over the continental interior to join with the western interior seaway.

The oldest Upper Cretaceous unit (Woodbine-Eagleford-Tuscaloosa) is a terrigenous clastic fluviodeltaic and near-shore marine sequence that extends across the Early Cretaceous shelf edge, expanding in thickness across a series of growth faults that are the oldest expression of "Tertiary style" tectonics. Rocks of the conformably overlying Austin Group are generally chalky and marly, becoming more sandy eastward, whereas the overlying Taylor and Navarro groups

are terrigenous clastics that become increasingly calcareous eastward. Downdip from the Lower Cretaceous shelf edge, the Upper Cretaceous rocks are slope shales, except for Tuscaloosa turbidites and some Woodbine slump blocks. The thickness of the Upper Cretaceous rocks is on the order of 1000 m on the shelf, expanding to more than 3500 m down-dip from the shelf edge.

Cenozoic Strata

The Cenozoic sediments are almost entirely terrigenous clastics, which prograded as much as 400 km beyond the Early Cretaceous shelf margin to the present continental slope. Regressive, basin-filling sequences that are progressively younger gulfward comprise the sedimentary prism. These sequences consist of a fluvial - inner deltaic massive sand facies, a delta plain - delta fringe interbedded sand and shale facies, and a marine pro-delta - outer shelf to continental slope shale facies, which may contain turbidite, submarine channel and fan sands. Transgressive marine shales separate the regressive sequences. The resulting lithologic sequence is composite and diachronous and has a massive sand facies at the top, underlain by a sand-shale facies and in turn by a marine shale facies. Each becomes progressively younger down-dip, with the transgressive shales marking approximate time planes (Fig. 4).

The basin began to fill in the Rio Grande area and proceeded in a series of deltaic depocenters that are progressively younger to the east and towards the Gulf. Thick regressive sequences, deposited during Late Paleocene-Early Eocene (Wilcox), mid to Late Oligocene (Frio), Miocene, and Pliocene-Pleistocene times, represent major progradational pulses that constitute the regressive phase of a megacycle, (Fig. 4). At other times, sedimentation was less progradational (the transgressive phase of a megacycle). Such changes result from variations in relative rates of sediment supply and subsidence, and sea level change. Growth faults developed at the progradational limit of each regressive unit and extended upward in the section as deposition continued. Thus the faults, like the regressive sequences with which they are associated, are progressively younger towards the Gulf.

The aggregate thickness of Cenozoic strata exceeds 15 km. A distinctive and characteristic aspect is the presence of overpressuring (abnormal formation pressures). This occurs at a depth in the section where formation pressures exceed hydrostatic gradients. The top of the geopressed section is generally in the marine shale facies, a short distance below the sand-shale facies. The undercompacted, low-density geopressed shales form a mobile substrate that is involved in growth faulting and shale diapirism. Both the stratigraphic position and the depth of the top of the geopressed section change across growth faults. Undercompaction, clay mineral diagenesis, hydrocarbon generation and aquathermal pressuring are among the mechanisms that have been proposed as causes of overpressuring.

Summary of Geological History

Triassic rifting and faulting initiated the subsidence of the modern Gulf basin, and the fault-bounded depressions were filled by Triassic and Lower Jurassic red beds intruded by basalt. The zones of faulting mark the inland boundary of subsidence of the northern Gulf basin. After an erosional interval of about 20 Ma, a widespread Middle Jurassic evaporite sequence was deposited, followed during the next approximately 20 Ma by Late Jurassic marine and paralic sedimentation.

Terrigenous clastics and carbonates were deposited during an overall advance and retreat of the sea that ended in earliest Cretaceous time. After another 10-12 Ma interval of erosion and non-deposition, fluviodeltaic and near-shore marine sedimentation began a new transgression. Carbonate

shelf deposits over a wide area graded eastward into terrigenous clastics derived from the Appalachians. Sedimentation kept pace with subsidence, a broad shelf was built over subsiding continental crust, and a series of banks and reefs developed along the arcuate shelf margin from south Texas to Florida.

During the Late Cretaceous, the proportion of terrigenous clastics increased. Thicker sections accumulated in interior salt basins and salt domes grew from the underlying Jurassic salt. There was active intrusive and extrusive volcanism throughout the province. Extensive inundation of the continental interior connected the Gulf basin with the western interior seaway, and advances and retreats of the sea can be correlated with coastal onlap curves related to eustatic sea level changes.

Beginning in Late Paleocene time the rate of subsidence in the basin increased, and the supply of sediment from the Rocky Mountain area, resulting from the Laramide orogeny, exceeded the rate of subsidence. Extensive progradation of deltaic sequences began in south Texas in a series of shifting depocenters that advanced into the deep Gulf. Extrusive volcanism was common during Oligocene and Miocene time.

By Middle Miocene time, the principal drainage had shifted to the Mississippi embayment. Composite Cenozoic sedimentation constituted three diachronous megafacies with undercompacted, low-density, overpressured shale at the base. Listric growth faults developed in the shale at each newly constructed shelf edge and continued during several depositional intervals. Rollover anticlines developed simultaneously in downthrown fault blocks, and salt domes and shale diapirs grew as sedimentation advanced, with salt walls and ridges developing under the continental slope.

Figure 5: Seismic line across growth faults with rollover anticline.

Hydrocarbon and Other Resources

Oil and gas are the most important mineral resource of the northern Gulf basin (see also Masters and Mast, this issue). Commercial volumes of hydrocarbons have been produced from every state in the province and from reservoirs of every age from Late Jurassic to Pleistocene. The oldest production is along the inner margin of the province, with producing trends progressively younger towards the Gulf, extending to Pleistocene production on the lower continental slope in water depths of 3000 m. Hydrocarbons occur from very shallow depths on salt domes, down to depths greater than 7000 m below sea level.

According to some estimates, ultimate recoverable reserves of 68 billion barrels (BB) of oil and 300 trillion cubic feet of gas have been discovered, with about 25% of these reserves remaining to be produced. Some 75% of the oil and gas is

from Cenozoic terrigenous clastic reservoirs. Traps are mostly structural on salt domes, deep-seated anticlines and rollover anticlines (Fig. 5), and seals are provided by transgressive shales and faults. The source rocks have not yet been identified for Cenozoic hydrocarbons, but geochemical considerations indicate that they are in older deep geopressed marine shale facies beneath the reservoir section. Hydrocarbons expelled from deeply buried sources migrated through the shale facies, possibly through micro-fractures, into growth faults that form migration paths to the younger reservoir facies.

The oil and gas in Mesozoic rocks occur in terrigenous sandstone and carbonate reservoirs, trapped by faults, anticlines, permeability and truncation traps, and salt domes, among other structures. The great East Texas Field, which has an estimated ultimate recovery of 6 BB of oil from Upper Cretaceous sandstone, is a stratigraphic trap resulting from onlap and truncation of Upper Cretaceous sandstone and shale on the Sabine uplift. The source rocks for Mesozoic accumulations have been identified in Jurassic and Cretaceous sequences, and the seals are shales and anhydrite.

Other important mineral resources of the basin include lignite and bituminous coal, phosphorites in Florida, salt, and gypsum and sulphur in salt dome cap rock. Significant deposits of uranium are present in Tertiary rocks. Carbon dioxide and hydrogen sulphide are produced in conjunction with deep gas from Jurassic deposits.

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