Environment and Intrusion of Gulf Coast Salt and Its Probable Relationship to Plate Tectonics

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ABSTRACT

The depositional environment and tectonics of Gulf Coast salt deposits seem generally favorable toward the concept of Mesozoic spreading-apart of North and South America, but neither really disproves the permanent-basin concept, thus, suggesting the existence of a proto-gulf. Because some of the disagreement over the environment of the origin of salt is caused by differences in terminology, a provisional classification based on depth and environment is presented.

Gulf Coast salt formed in a restricted, but expanding and sinking, linear Jurassic basin with the characteristics of a newly formed rift between continents. Continental masses shed redbed sediments onto the borders of the basin which has since subsided 10,000 to 60,000 feet (3-20 km) and has been filled with sediments from the sides. Salt occurs in the basal portions. By Cretaceous time the basin was wide and open enough to allow permanent seas and carbonate deposition.

The tectonics of Cenozoic geosynclinal sedimentation produced a series of shoreline-parallel sedimentary wedges laid out one in front of another. The line of maximum deposition was near the advancing continental shelf/slope boundary. The sediments caused isostatic sinking of the basin, triggering a phase change at the Moho discontinuity. The weight of the sediments forced diapiric rise of the salt in favorable areas and propelled the rest of the salt forward toward areas of eventual high-rise diapirism. The northern domes formed first, the complex coastal domes later, and the continental slope domes are still rising. The continental material of the central Louisiana domeless area is best explained as a horst left during rifting and drifting.

The northern diapirs are simple, relatively impure, and have risen only relatively short distances through the sediments. They are of the basin-margin type. Maximum movement probably occurred in the Cretaceous and Eocene and had essentially ended by the Miocene. The southern (coastal) diapirs rose, first forming broad arches or massifs, and then in the Miocene forming the distinctive, nearly-cylindrical salt domes. The still more southerly salt of the outer shelf and continental slope has only recently been buried to any great depth; its diapirs are still more arch-like than dome-like, and very active. Salt on the original floor of the Sigsbee Deep has, through very prolonged exposure to very slow sedimentation, received a significant thickness of overlying sediment and is now moving; but like the salt on the adjacent slope, the degree of diapirism is minor and the salt shapes are subdued rounded arches rather than high and vertical-walled stocks.

The Gulf Coast salt deposits formed in a late Triassic and Jurassic environment that suggests a spreading apart of North America from the combined continents of South America, Africa, and Europe; followed by the Cretaceous carbonate sedimentation and Cenozoic geosynclinal clastic deposition.

INTRODUCTION

This paper has been prepared as a summary of the various geological factors that have influenced salt tectonism and diapirism in the Gulf Coast. It is intended to serve as an introduction to the Gulf Coast for the visitors from outside the area to the Fourth Symposium on Salt, which is being held at Houston, Texas, in the heart of the Gulf Coast. Most of the ideas expressed are those of others, and insofar as possible credit is given. Many ideas, however, are difficult to identify as to their sources, and come from numerous conversations and discussions with a great variety of people. In particular I would like to acknowledge a very deep gratitude to C. O. Durham who first introduced me to Gulf Coast geology and has, through the years, been my advisor, sounding board, and chief source of new ideas. All of the ideas expressed in this article have been strongly influenced by my discussions with him, even though in some cases we may actually have diverging or opposing opinions. Others who have had a considerable influence on my ideas include my friends and co-workers such as G. E. Murray, G. A. Atwater, J. D. Martinez, and J. P. Morgan; and fellow scientists such as S. W. Carey, B. N. Cooper, G. C. Kennedy and many others.

SALT DEPOSITION

Classification

Most of the major salt deposits of the world, including those of the Gulf Coast of America, have been precipitated from the sea. The major problem of how to accumulate a thick deposit without the need for an astronomically deep ocean basin was solved in 1888 by the Ochsenius "bar theory." Many variations have been suggested since, but all involve the dynamic movement of sea water into some sort of restricted environment of evaporation. One group (cf. Kinsman, 1969; Delwig, 1968) have emphasized that this environment is at the shoreline, can be very shallow, and even supratidal (sabkha-like). Another group favors larger and deeper basins (Borchert and Muir, 1964; Schmalz, 1966 and 1969; Richter-Bernburg, 1955 and 1957). These environments are transitional and what is shallow to one person may be deep to another. For example, Richter-Bernburg calls the shallower of his two horizons a "flachschelf-salinar" (1955, p. 4–6) which means a shallow shelf, and yet implies a depth of up to 300 meters. In contrast, commonly the shallow horizon is said to be a sabkha, which model "implies brine depths above the salt of a few centimeters to a few tens of meters." (Schmalz, 1969, p. 809). Yet when Richter-Bernburg coined the name "megasebkha" (1970, p. 181) for his shallow basin (1972, Fig. 6), Kinsman stated (1969, p. 839): "There is no sound basis for distinguishing a megasabkha from a sabkha." Dellwig and Evans (1969) state that the Michigan salt basin is of the shallow sabkha-type at the edges and that the center was deep water.

Deep water is also a very relative term. The deeper of Richter-Bernburg's two "deep" basins is 300–500 meters (1957, p. 91–92). Yet in the early stages of the finding of hot brines at 2000 meters depth in the Red Sea, comparable basins were suggested for the origin of some salt and these were called "deep," and by contrast the 500-meter deposits "shallow." Now it is rather generally recognized that the Red Sea brines are secondary solutions of older salt deposits.

It is clear that the words "shallow" and "deep" without qualification, can be misleading. In an attempt to set some

TABLE I

Depth Classification of Salt Basins
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Depths of water in feet (Meters)

#.	Name	Average Depth	Depth Range (?)	Comments	Possible Examples
a.	Land	Plus (+)	0 to 1000 (0 to 300)	On land, generally interior, nonmarine	Playas, Bonneville, Dead Sea (Today), Salton Sea
b.	Sebkha	0 (0)	0-20 (0-6)	Flat coast at sea level	Trucial Coast, Gulf of California margins
c.	Bay	100 (30)	0-300 (0-100)	Embayed coast (flat or rocky)	Gulf of California (upper end)
d.	Shelf	500 (200)	0-1000 (0-350)	Continental Shelf (stable or dynamic)	Michigan Basin, Gulf Coast, Zechstein
e.	Slope	1000 (300)	300-2500 (100-750)	Continental slope or graben	Red Sea, lower part of Gulf of California
f.	Abyssal	5000 (1500)	1,500-10,000 (400-3000)	Oceanic depths	The Mediterranean
g.	Trench	<15,000 (<5,000)		Oceanic trenches	No known examples

NOTE: This is a depth classification. Whether examples of salt basins can be found for each type is problematical. The environments and examples are suggestions; neither definitive nor limiting.

TABLE II

ENVIRONMENT CLASSIFICATION OF SALT BASINS

Environment and/or Isolation

Donald H. Kupfer, L.S.U., 1973

A. **Land**

1. *Playa*, small, arid basin. Subtypes: *Open* (to groundwater egress; a clay pan). *Closed* (no groundwater drainage; a salt pan). *Isolated Marine* (tectonically cut-off; most will be only carbonate and/or sulfate).
   Examples from San Bernardino County, California playas: Amboy (open, now); Bristol (closed); Danby (isolated marine, evaporites at 1000 feet below surface).
2. *Internal* drainage basin (large, nonarid).
   Examples: Lake Bonneville—Great Salt Lake; Lake Lahontan, Lake Baikal, Caspian Sea ?.

B. **Coastal**

3. *Highly Restricted* basin. Small basin with shallow sill, essentially landlocked.
   Examples: Gulf of Kara Bogaz, Salton Sea.
4. *Restricted Coastal* basin. Large but definite basin with wide, low sill; probably formed by subsidence. Also a graben or downwarp. Subtypes: *Extension* and *subduction.*
   Examples: Red Sea, Gulf of California.

C. **Marine**

5. *Restricted Marine.* Surrounded by continents, probably an early stage of sea-floor spreading. If the Gulf Coast Louann Salt is an example of this environment, then its characteristics are: A large body of water with good circulation and moderate, but fluctuating floor-depths. The restricted opening is probably not a sill, but tectonic; but reef growth aids restriction. Basin has dynamic pycnoclines, multiple salts precipitated, many local environments (reef, coal, sulfate, salt, sabkha).
   Modern example: The Mediterranean.
6. *Subductive.* Island-arc bounded, geosynclinal, probably elongate.
   Examples: restricted seas along the eastern margin of Asia.
7. *Shelf* or epicontinental sea. Wide, shallow continental shelf in a low latitude; reef growth strong, especially at outer edge of basin (restriction); epeirogenic, stable.
   Probably no present examples; the shelf seas of southeast Asia are similar. Hudson Bay might also be if it were at a lower latitude.

sort of standards for discussion, Table I is proposed. And because many other genetic differences are also hidden in the "depth" discussion, such as shape, location, and tectonic environment of the evaporite basin, the environments of Table II are suggested as representative. One very controversial element of this proposed classification is the attempt to relate some of the basins to plate tectonics (Fig. 1). The "Restricted Marine" environment is considered to be most representative of the spreading phase and some of the others are related to subduction. The continental shelf deposits are related to the more stable interior parts of plates. Eventually the classification of Table II will need to be further subdivided by shape and location on the one hand and a separate classification by tectonic environment on the other.

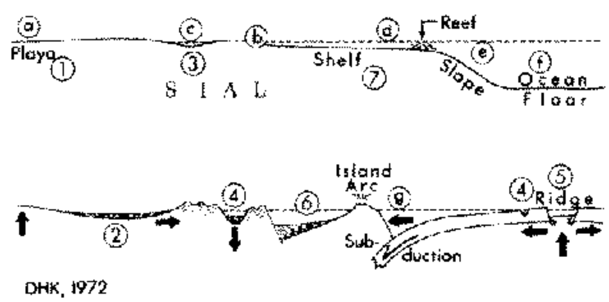

Figure 1. Diagrammatic cross sections to show typical environments of deposition of salt as related to plate tectonics. Letters refer to depth classification and numbers to environmental classification as given in Tables I and II.

It will be up to the experts for each individual salt deposit to put that salt deposit into its proper categories, but to illustrate the method, I have suggested some examples. The German Zechstein is probably class 5d, and the Nova Scotian deposits, class 4c; but agreement is not to be expected, and Paul Schenk (1967) calls the Nova Scotian deposits supratidal or class 7b. Two categories can also be combined, and thus the Silurian mid-continent basins of the United States are probably class 7b at the edges and 7d at the center.

Gulf Coast salt environment

All of the major salt deposits of the world originated in large, subsiding basins of limited marine access and dynamic marine recharge. The basins had to be in an area of excess evaporation over water influx (negative annual water budget), which does not necessarily mean an arid climate. Sabkha environments are generally indicated for the basin edges. Even if the center of the basin is moderately deep, which seems probable, significant subsidence must occur to accommodate the thick sequences of evaporites and associated sediments. All of these conditions are met by most of the generally-accepted models for the Gulf Coast geosyncline, including the one proposed herein.

At the present time the tendency in the Gulf Coast is to group all of the salt deposits (Fig. 2) together and call them all part of the Louann Salt of Jurassic age (Kirkland and Gerhard, 1971). This is particularly true of the northern Gulf Coast where the salt is mostly beyond the reach of the drill. This is an oversimplification that will have to change (Viniegra, 1971). For example, in the far better known north German salt basin, ten periods of salt deposition have been recognized (Richter-Bernburg, 1972, p. 275) ranging in age from lower Permian to upper Jurassic (the Tertiary example is a special case). Even the famous Zechstein is subdivided into four cycles, some present in one area, some in another, but all generally confined to the same basinal area. In the Gulf Coast, it now appears that salt deposition started in the north and progressed southward, but Cuba is somewhat of an exception.

The pre-salt story can best be recognized at the basin edges north and south of the Gulf Coast Geosyncline. Here, both salt and sediments rest in great angular unconformity on Paleozoic and older metamorphic rocks. In the center of the geosyncline the only evidence is geophysical, and this suggests that salt and/or sediments rest on oceanic-type basement. One of the major present-day tectonic problems is the origin of this oceanic crust. Has it been generated by sea-floor spreading (Freeland and Dietz, 1971; and Walper and Rowett, 1972), or has it merely subsided during the Mesozoic and Cenozoic under the weight of the sediments of the Gulf Coast Geosyncline (Paine and Meyerhoff, 1967) or both (Wilhelm and Ewing, 1972)? These are just a representative sampling of the suggestions that have been made on this crucial subject.

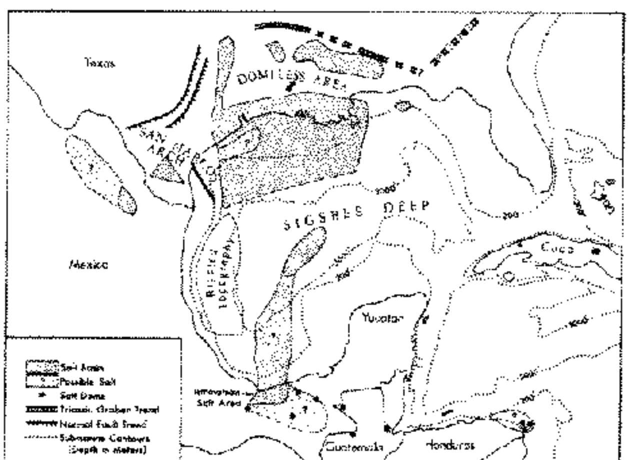

Figure 2. Salt distribution in the Gulf Coast as taken from many sources. Dotted areas probably received a thick layer of salt in Jurassic time. Question marks indicate areas in which the presence of salt has not been proved. Circles mark isolated known occurrences of salt, but the shape of the depositional basin is unknown. The 200 and 3000 meter depth contours are shown by dotted lines.

To understand this problem properly, one must consider the general geologic setting. The story in the northern Gulf Coast is related to events at the end of the Appalachian and Ouachita orogenies. It appears that the north-northeast trending Appalachian Mountains were active mainly during the Mississippian and had ceased activity by late Pennsylvanian (Rodgers, 1967, p. 418); whereas the west-northwest trending Ouachita Mountains cut across the Appalachian trend in the Pennsylvanian (Erlich, 1965), thus forming a right-angle bend in the backbone of the future Atlantic-Gulf Geosyncline (Murray, 1961, Figs. 2.23, 2.36 and 2.42). Whether or not the Appalachian trend continues southward under the Ouachita trend and into Louisiana, as has sometimes been suggested, is beyond the scope of this paper; but, as will be described later, there is a wedge of crustal material under southern Mississippi that can and has been interpreted this way. (Warren et al., 1966). However, I prefer to interpret this high-velocity zone under the Wiggins arch of southern Mississippi (Eargle and Herbst, 1970, Fig. 12) as continuous with the domeless area of central Louisiana (Fig. 2), and as a "horst" of continental crust left between the interior salt province (including the Mississippi salt basin) and the larger salt basin of the coast and offshore. As has been pointed out to me by C. O. Durham (personal communications, 1970–73), the general structural configuration of this part of the Gulf Coast is on a west to west-northwest trend.

Because of this right-angled bend, the equivalent of the prominent north-northeast trending Triassic Graben of the Appalachian Highlands is a series of west-northwest trending Triassic grabens now buried under several thousand feet of sediments along the northern margin of the Gulf Coast (Fig. 2). To the west, in Texas, the grabens probably swing southward again along the normal fault zone bounding the western side of the Gulf Coast Geosyncline. If present at all to the south of this, they are lost in the syn-depositional Laramide orogenies of Mexico (Durham and Murray, 1967).

It was into this structural environment that the redbeds of Triassic and Jurassic age were deposited as subaerial alluvial aprons spreading southward from the Paleozoic mountains (Fig. 3), and grading southward into sabkhas and marine deposits (Tyrell, 1973). As indicated by Tyrell and many others before him, the Louann Salt is interfingered with these redbeds and extends for 1000 miles (1500 km) southward.

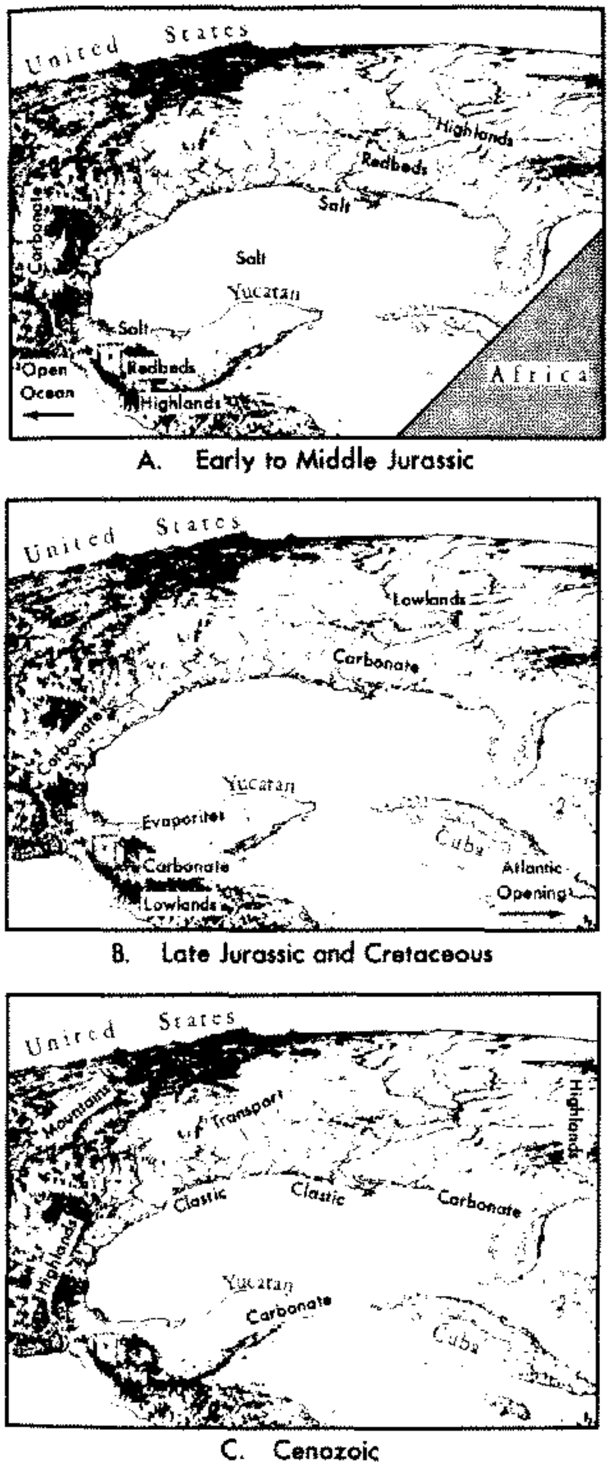

Figure 3. Schematic maps showing generalized location of clastic, carbonate, and salt deposition in the Gulf of Mexico region. Base map from the National Atlas of the United States, U.S. Geological Survey, 1970.

Redbeds

In the northern Gulf Coast the first unit above the orogenically deformed rocks of the Appalachian-Ouachita mountain system is a group of diverse beds, generally of continental origin, called the Eagle Mills and/or the Moorehouse. The poorly exposed and widespread Eagle Mills may well include units that are not everywhere correlative. Imlay (1940) placed the Eagle Mills under the Moorehouse and most later workers (Hazzard, Spooner, and Blanpied, 1945) have reversed this. The Moorehouse is generally conceded to be middle to upper Pennsylvanian (Andrews, 1960, and others). The Eagle Mills, which probably represents the first episode of Triassic rifting, is poorly dated as late Triassic (Scott, 1961).

This sequence is angularly overlain by a sequence of beds that although representing a variety of environments (marine, evaporite, coal (?), eolian, sabkha, and subaerial fan) are generally considered to intergrade with each other laterally (facies) and vertically (virtual conformity, but local unconformities) and to represent a reasonable homogeneous tectonic unit. The salt is the Louann Salt (more later) and in some areas it is underlain by the Werner Anhydrite and in others overlain by the Norphlet beds. All three of these are underlain and overlain and grade laterally into a series of redbeds. Where the redbeds are low in the series they may be called Werner or even Eagle Mills; if higher they are generally called Norphlet. The Norphlet also includes an eolian sandstone (Denkman sandstone), black shales (carbonaceous?), and magnesite (Tyrell, 1972). The age of this Werner-Norphlet sequence is generally conceded to be middle Jurassic (Murray, 1957; Andrews, 1960), but early Jurassic is also a good possibility for some parts of the unit. In the central Mississippi area these and the immediately overlying parts of the Smackover carbonates are supratidal or sabkha-like (Badon, 1973).

The above described formations suggest exactly the environment one would expect in the waning stages of orogeny, as continental relief is subdued, and tensional release occurs; they have classically been interpreted that way. But these also are the conditions that one would expect in the initial stages of continental breakup (see Kinsman, this symposium), and are considered by some as strong evidence of sea-floor spreading.

Equivalent beds are found in Mexico (Viniegra, 1971) and Guatemala (Anderson et al., 1973) and Honduras (Mills et al., 1967). Here, as with redbeds the world over, some beds of very different ages (Paleozoic to Tertiary) have formerly been miscorrelated. Most of these problems have now been worked out, and here, as in the northern area, these and related or lithologically similar rocks probably represent all ages from the late Triassic to at least Cretaceous.

In Cuba (Meyerhoff and Hatten, 1968), the redbeds are known only from drilling and constitute a very minor part of the evaporite sequence, which is itself little known. Thus its origin is extremely problematical.

Summarizing, during the Permian the Gulf Basin, on the north and south, was surrounded by low mountains from the waning stages of the Pennsylvanian orogeny. These mountains were uplifted to maximum elevation by epeirogeny in the Triassic and Jurassic (Fig. 3A). The resulting flood of clastics near the mountain front has been subdivided into many formations separated by angular unconformities and disconformities, and representing several environments. By Upper Jurassic, however, marine carbonates (Fig. 3B) dominated all the area except that immediately next to the now subdued mountains, and by the Cretaceous this whole region was one of very subdued relief.

LOUANN SALT

Distribution

The Louann Salt is a formation known only from the subsurface, and the type locality is in southern Arkansas. Because most drilling stops at the top of the salt, little is known of its true stratigraphy and thickness, and almost nothing of the formations that underlie it. In 1960, Andrews listed all of the wells that had penetrated the salt, estimated its thickness at 5000 feet (1500 m.), and gave its known distribution over southern Arkansas, northern Louisiana and the adjacent parts of Texas and Mississippi. Considerable information has been added to this since (Fig. 2). The deposits of Mexico, Cuba, and even the new discovery off Honduras (Pinet, 1972) are now considered to be part of the Louann Salt (Fig. 2). Of particular interest are the various areas where salt domes have not been found and salt is thus considered to be either absent, thin, or removed. The oldest and best known is the domeless area of central Louisiana. Another dome-free area may be present on the continental shelf in the Texas offshore, but this may be the result of insufficient exploration. Others are the San Marcos arch and the equivalent coastal shelf area offshore, the salt-free areas on the floor of the Sigsbee Deep, and much if not most of the more southerly limits of the area.

A series of very low topographic swells (rippled topography of Fig. 2) of north-south trend have been described off the eastern coast of Mexico by Jones, Antoine and Bryant (1967) and attributed by them to salt mobility. When drawn at true scale, these are very low broad ripples and are more like the topography caused by submarine slumping than salt diapirs. Until such time as salt is actually proved to be present by drilling or other means, it seems advisable to consider all of that part of Mexico and the continental slope and adjacent ocean floor as salt free (Fig. 2).

Age

As has already been indicated, there are two schools of thought on the age of the salt deposits of the Gulf Coast. Some would consider them all as originally deposited in a simple, large, contiguous, and synchronous basin (Feeley and Kulp, 1957; Murray, 1961; Jux, 1961; and Kirkland and Gerhard, 1961). But a careful compilation of the evidence (Fig. 4), and a comparison with the Zechstein of Germany would strongly suggest otherwise. Viniegra (1971), in the southern Gulf Coast where the salt is shallow over a much greater area shows that the salt basin gradually migrates from the Isthmian area in pre-Kimeridgian times (middle Jurassic) eastward and stratigraphically upward into northern Guatemala in the lower Cretaceous. He also gives evidence to suggest (p. 482) that salt may have been present in the middle and even late Cretaceous and that evaporites continue in the Yucatan area into the Paleocene (op cit., Fig. 7). Farther to the east, in Cuba, the salt is pre-Callovian (Meyerhoff and Hatten, 1968) and thus earlier than any of the Central America salt.

In the northern Gulf Coast, the only accurate information comes from the Arkansas-Mississippi area where the pre-Smackover age of the salt is generally conceded to be middle Jurassic or older (Murray, 1957; Andrew, 1960). For the more southerly diapirs Jux (1961) suggested a slightly older age of middle to lower Jurassic or even Triassic based on sparse, broken, and poorly identified palynmorphs. This pioneer work has been muchly criticized informally (many personal communications) and

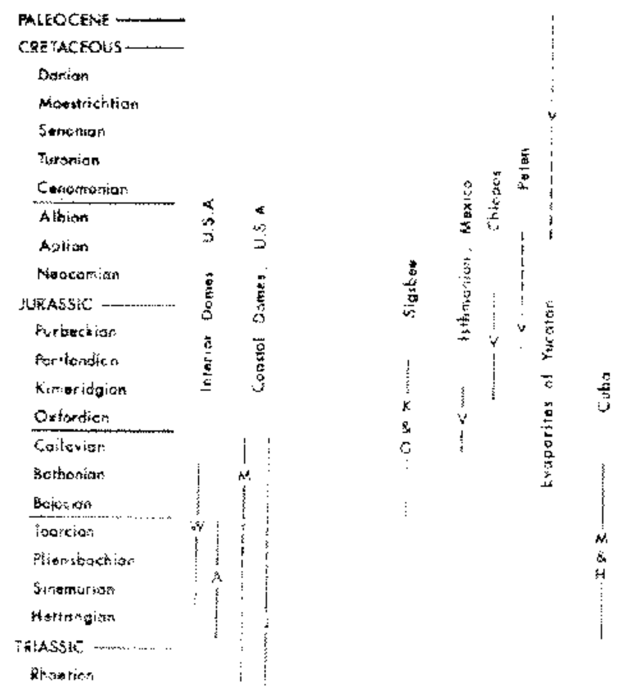

Figure 4. Chart showing present knowledge of the age of the Mesozoic salt deposits from Louisiana (left) to Mexico, Guatemala and Cuba (right). W = Woods, 1956; A = Andrews, 1960; M = Murray, 1957, 1961, J = Jux, 1961; K&G = Kirkland and Gerhard, 1971; V = Viniegra, 1971; M&H = Meyerhoff and Hatten, 1968.

formally (Kirkland and Gerhard, 1961), but must remain undisputed until such time as the work is repeated. The only check made so far is that by Pflug (1963) who concluded the salt must be at least as old as indicated by Jux, but could possibly be even older. Andrews (1960) suggests a younging of the salt southward.

Higher in the section, still younger evaporites are well known, such as the Haynesville salt and Buckner anhydrite of late Jurassic and the mid-Cretaceous Ferry Lake Anhydrite. The Permian evaporites of west Texas are distinctly older than the type Louann deposits.

Thus the salt deposits of the Gulf Coast formed in a large and subsiding basin in about Jurassic times. That this basin and the basin of the Atlantic seaboard were related is the theme of Grover Murray's book (1961) published before the present emphasis on plate tectonics. In this case, what can we learn from the depositional environments of this elongate belt? In the Gulf Coast a sabkha shoreline (Badon, 1973) was to the north, but continental masses and redbeds were also present in Central America (Viniegra, 1971). The strongly continental character of the Triassic grabens of the Atlantic seaboard has long been established even if the details have not been completely worked out to everyone's satisfaction. Thus if an opening to the sea existed, it would probably have to be from the west and this seems to be the case (Viniegra, 1971, p. 484; Wilhelm and Ewing, 1972, p. 595). Thus a consistent story can be made using sea-floor spreading. The continent fractured in the late Triassic and salt deposition began in the north (Arkansas-Mississippi) and south (Cuba) in early Jurassic (Fig. 3A). As spreading continued salt covered a wider (southern Louisiana, Isthmian of Mexico, and Sigsbee knolls) and wider (northern Guatemala, scattered deposits of the northern Gulf Coast) area. By middle Cretaceous the sea was so widespread that carbonate deposition predominated almost everywhere (Fig. 3B), but local areas of anhydrite deposition persisted in a few isolated patches. By the end of the Cretaceous the North American lowlands became highlands and the vast influx of Tertiary clastic sedimentation into the Gulf Coast geosyncline began (Fig. 3C). By this time the Gulf of Mexico had attained essentially its present dimensions.

Character

In examining the various diapirs of the Gulf Coast, it becomes clear that within any one diapir there are various packets (spines) of salt that have intruded separately (Kupfer, 1963, p. 119–122 and in another paper in the present symposium). Also, the salt in each diapir is somewhat different from that in an adjacent one (Atwater, 1968, p. 38; Kupfer, 1963, p. 107–109). This can best be explained by assuming that each packet of salt came from a different stratigraphic horizon within the Louann Salt. But considering the regional picture as already described (also: Atwater, 1968), it appears that the Gulf Coast salt, like the salt of the Zechstein area of Germany, belongs to several different ages. Most of it is Louann and probably closely related in time, but like the Zechstein it will eventually be subdivided into several parts. A lesser amount of it is actually of different ages ranging over most of the Mesozoic.

Moreover, even for the Louann Salt itself (restricted), it is quite possible that packets (sedimentary units) of salt with significant sediment content have been selectively left behind (Kupfer, 1970, p. 55–56) and only the purer and thicker layers of salt have moved up the necessary 30,000–60,000 feet (10–20 km) to be exposed near the surface today. The 3000–5000 feet (1–1½ km) of salt in the Louann could easily be interbedded with 3000 to 10,000 feet (1–3 km) of associated sediments. Thus the Louann Salt appears to be a sequence of evaporites and associated sediments of 5,000–15,000 feet (2–5 km) thickness of middle to late Jurassic age.

GULF COAST TECTONICS

A very concise and up-to-date summary of the principal stratigraphic and structural features of the Gulf Coast geosynclinal story as it is now recognized by the petroleum geologists of the area is given in the Gulf Coast section of "Natural Gases of North America (A.A.P.G., Memoir 9, 1968). As the summary article on south Louisiana was written through the combined efforts of the geologists of both the Lafayette and New Orleans Geological Societies (1968), their views are current, authentic, and representative. The article includes a description of such routine things as stratigraphy and structure, but emphasizes all of the newer concepts, many of which are not otherwise well described in the published literature. Anyone interested in a brief and comprehensive summary of the Gulf Coast would do well to read the first 40 pages which are profusely illustrated with excellent maps, sections and diagrams.

In the synthesis of the Gulf Coast that follows, most of the description is confined to the northern Gulf Coast, particularly southern Louisiana and the immediate offshore, as this is the area with which I am most familiar. As nearly as I have been able to determine, the same processes operate all around the Gulf Coast and at approximately the same times. I will, however, leave it to those more acquainted with the local geology of these other areas to determine how well and when.

Sedimentation

In the Gulf Coast, the early Mesozoic evaporite sedimentation and concurrent redbed deposition was followed in the later Jurassic and Cretaceous by carbonate deposition (Fig. 3B). But in the Tertiary, with the rise of the Cordilleran mountains in the west, vast quantities of sediment were brought to the Gulf of Mexico (Fig. 3C). Everywhere except in Florida and Yucatan, this carbonate deposition of the Mesozoic gave way to clastic deposition in the Cenozoic. According to some authors (cf. Durham and Murray, 1967), the beginning of true geosynclinal conditions begins with these thick clastic Cenozoic sequences. In the northern Gulf Coast, for any time-unit (Fig. 5A), the zone of thicker clastic deposition is a belt trending generally east-west and thinning rapidly to the north (Fig. 5B). To the south the unit is thickening as it plunges under the younger sediments, and this appears to

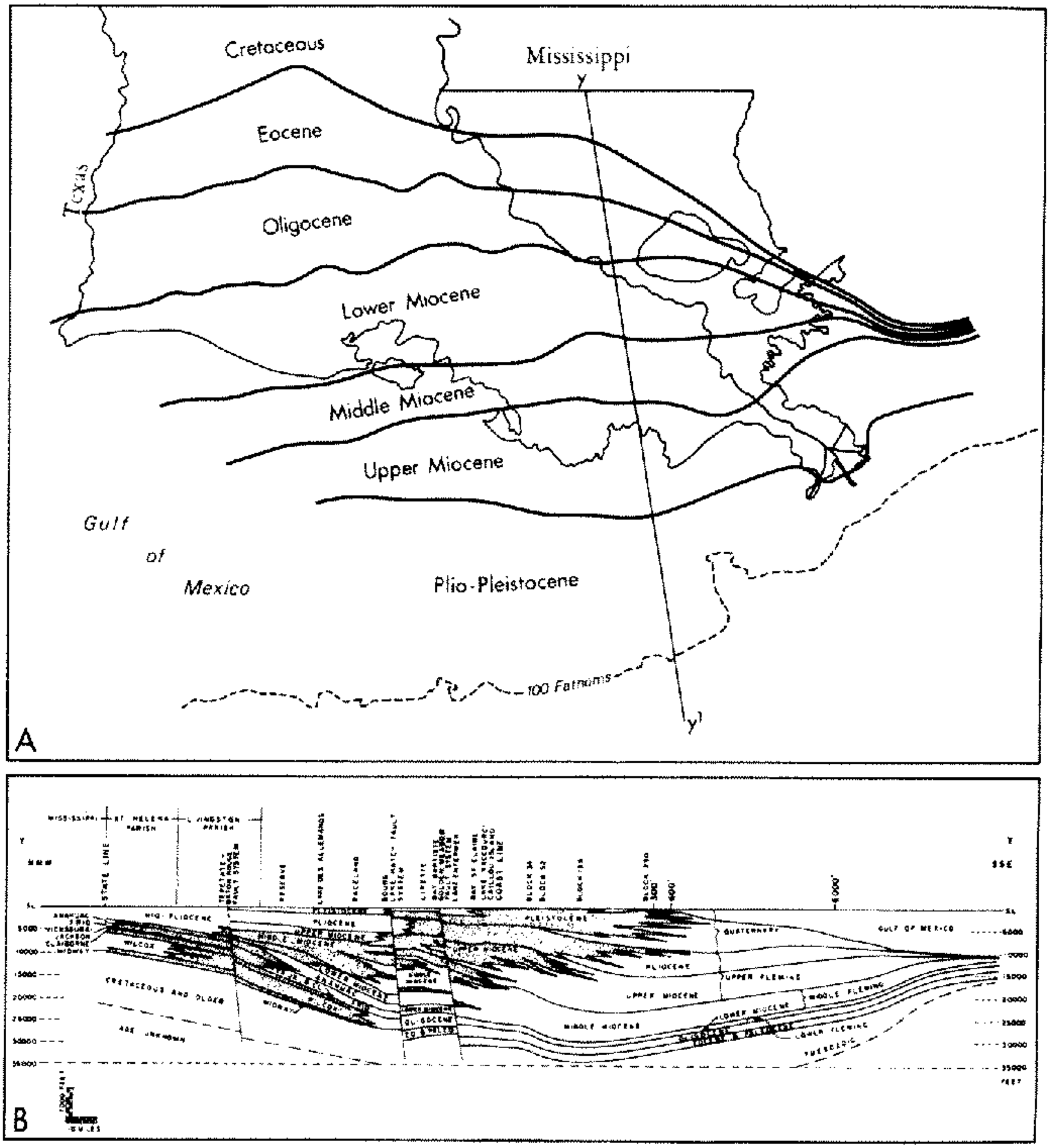

Figure 5. Cenozoic sediment distribution in southern Louisiana (Adacted from Figures 1 and 4 of Lafayette-New Orleans Geol. Soc., 1968).
A. Index to age of major producting trends of south Louisiana (approximate index of greatest sediment thickness).
B. Cross-section Y-Y' from A. Stippled pattern is principal sand facies and center of producing trend. Shale facies to south are generally unexplored and diagrammatic.

continue to the depth of observation, but it is assumed to thin and feather out still farther south (Fig. 5B).

For any single time-unit of deposition (Fig. 6A), the zone of thicker sedimentation is a belt corresponding to the continental shelf-slope zone of that time. Along this belt are local centers of maximum sedimentation corresponding to local areas of compaction or isostatic sinking. In north-south cross-section (Fig. 6B) each depositional unit consists of a lens of sediments. Starting from the north, the thin non-marine fluvial and paludal deposits thicken southward and interfinger with the predominantly sandy deposits of the beach and near-shelf environment. To the south these clastics thicken markedly and interfinger with sands and silts of the outer continental shelf. Continuing southward, these interbedded sediments change into continental-slope clays and then into the dark, deeper-marine clays and turbidites. Within the transition zone and just to the south of it, the clays can be quite thick, but they thin farther south and become the clays and turbidites of the abyssal plain (Fig. 6B).

In time (vertical) sequence, these depositional environments migrate back and forth forming a series of well-established marine transgressions and regressions (Fig. 5B), but the overall picture is one of continued regression of the sea as the deposition moves southward. Thus maximum Jurassic sedimentation (Bishop, 1973) centered in Arkansas and northern Mississippi, and the Cretaceous farther south. Maxima of early Tertiary sedimentation extended in a belt from coastal east Texas, through central Louisiana, and into southern Mississippi-Alabama (Durham and Murray, 1967). Miocene depocenters are farther south near the present shorelines, and Pleistocene depocenters roughly correspond to the present continental shelf. A very good summary of the current state of knowledge of Gulf Coast sedimentation processes is contained in the symposium on the *Future Petroleum Provinces of the Gulf Coast* (Cram, 1971, Regions 6 and 11), parts of which were given in a Gulf Coast Association of Geological Societies symposium at Shreveport, Louisiana, in 1970.

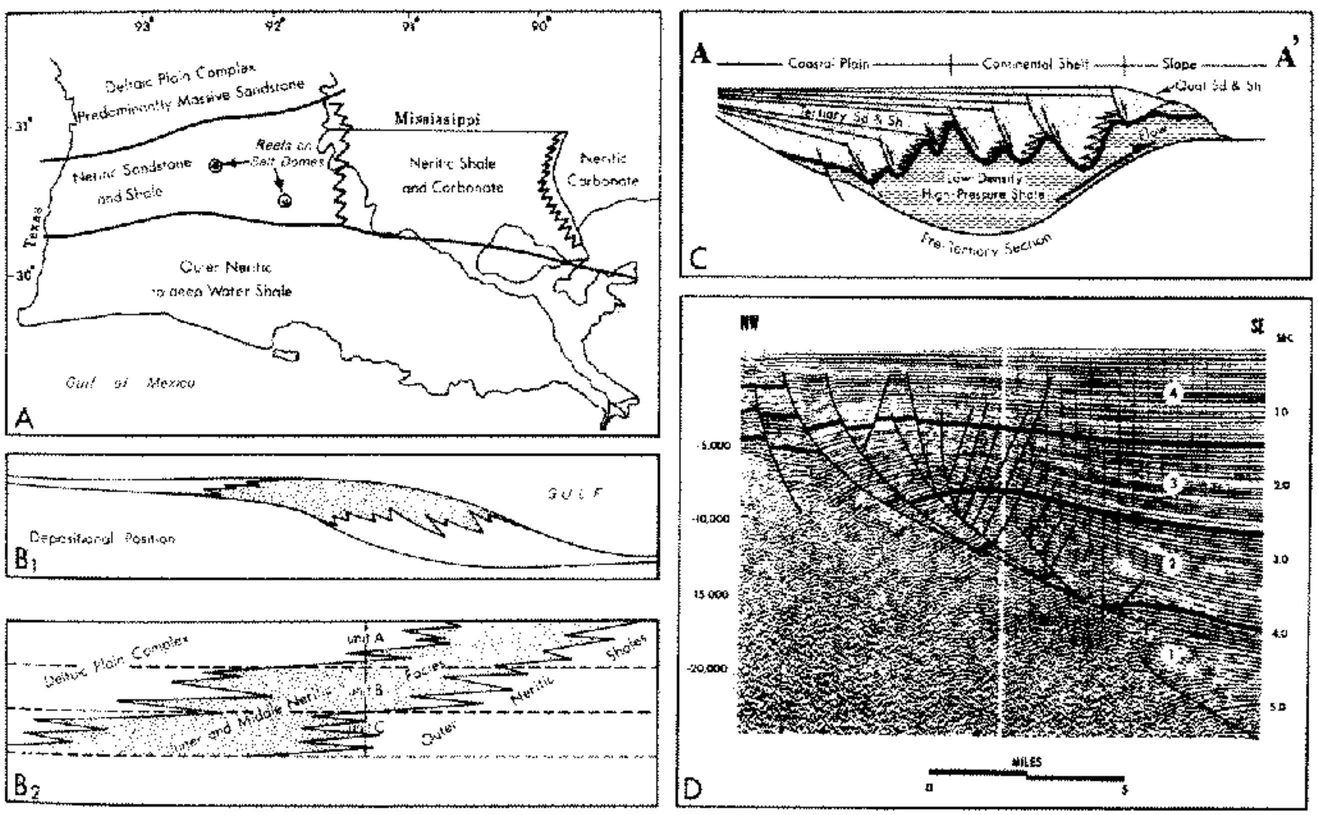

Figure 6. A. Generalized facies-environmental map of south Louisiana in the middle Eocene showing three environments from onshore (north) to offshore. Map also shows principal facies changes from east to west in the neritic-shelf environment. Adapted from Lafayette-New Orleans Geol. Soc., Figure 23, 1968.

B. Idealized schematic cross-sections to illustrate regressive character of Gulf Coast Tertiary deposits; vertical scales greatly exaggerated. Adapted from Figure 13, Lafayette-New Orleans Geol. Soc., 1968.

C. Diagrammatic cross-section, with vertical scale exaggerated, across southeast Texas and the Gulf of Mexico to show the effect of loading of Tertiary sands on overpressured shales (Bruce, 1973, Fig. 1).

D. Seismic illustration to show rollover on a typical Gulf Coast growth fault. Note flattening of fault with depth and how the upper horizons maintain unchanged their approximate stratigraphic slope outside of the fault zone; vertical scale = 2X. (Bruce, 1972, Fig. 8).

These Cenozoic (and Mesozoic?) deposits form the Gulf Coast Geosyncline, a prism of sediments ranging in thickness from 35,000 feet (10 km) on the north to about 60,000 feet (18 km) on the south (Hardin, 1962). Hardin also notes the presence of numerous depocenters. The present Gulf of Mexico is 10,000 feet (3 km) deep. Assuming this approximates the depth of the proto-gulf, then the wedge of sediments has sunk, presumably isostatically and with a phase change at the Moho (Kennedy, 1959), through 15 to 50 thousand feet (8–15 km). Hardin (1962, p. 11) gives 35,000 feet or 10 km. But throughout this time of clastic deposition and subsidence there was (Fig. 3C) a continental mass of relatively low relief immediately to the north, and so these Tertiary sediments must have come from mountainous areas well to the west and north (Rockies), although some contribution may have come from the east (Appalachians). By contrast, in Mexico where the Laramide Mountains were adjacent to the Gulf (Durham and Murray, 1967), much less clastic debris has accumulated. In both examples, either the deep marine Gulf of Mexico basin must have been there the whole time, or it must have been forming as the deposition proceeded. In the latter case it could have subsided, basified, or expanded or some combination of these.

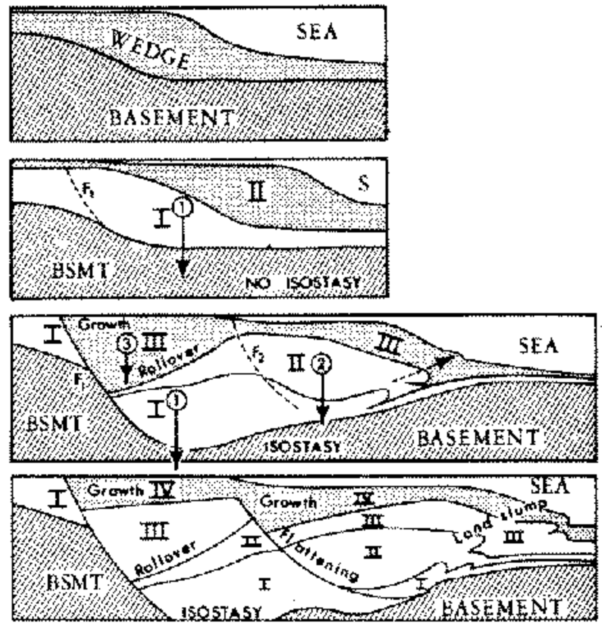

Figure 7. Stereotyped and diagrammatic sections to show the effects of sedimentation and loading on the Gulf Coast geosyncline. Sediment wedges I and II are shown to accumulate as if without isostatic adjustment. Wedges III and IV are affected and show both growth and rollover. The downward directed arrows show diagrammatically the center of gravity for isostatic adjustment. The general overall slumping of the total sediment pile into the void of the Gulf of Mexico is also illustrated, with the formation of hummocky landslide-like topography at the base of the continental slope F_1 and F_2 are faults.

Structure

In addition to the above-described wedges of sediments, and probably as a result of them, roll-over and growth faults are the dominant structural features of the Gulf Coast. Although many faults show both roll-over and growth, each should be considered separately.

Growth faulting is a term introduced by Ocamb (1961) to describe the well-established contemporaneous thickening of sediments in the down-thrown block of normal faults actively "growing" as deposition proceeds (F_1 and F_2, Fig. 7). The age of the thickened sediments clearly indicates the time of active faulting, and thus the age of domal growth if the faults are caused by diapirism (Hughes, 1968). The most recent review is that by Bishop (1973).

As wedges of sediment are introduced into the basin, various parts of the basin subside differentially to accommodate the increased load (Fig. 6C and 7). The adjustment faults that result grow during the process of sedimentation. The northernmost growth fault is the "hinge" fault; it faithfully records the inner boundary of the sinking prism. (Only the hinge faults are shown in Figure 7.)

Rollover is a term introduced into the literature by Durham and Peoples (1956) to describe the structural feature by which the sediments in the hanging-wall block of a normal fault in an active depositional basin reverse their dip and "roll over" into the fault plane (Fig. 6D). The term was, however, in common usage in the Gulf Coast at the time and the phenomenon had been recognized previously under terms like reverse drag and dip reversal. Summary papers describing the phenomenon include those by Quarles (1953), Russell (1955, p. 122–4), and a comprehensive review by Hamblin (1965). Two very important features of rollover (Fig. 6D) are the flattening of the dip of the fault with depth and the tendency of the overall horizon to remain at the same elevation or same slope gulfward, despite the faulting. The latter is presumed to be proof that the fault becomes a bedding-plane fault with depth. More recently the pervasiveness of the phenomenon has been emphasized in the Lafayette and New Orleans Geological Societies paper (1968). Most of the recent authors recognize the strong influence of contemporaneous basin subsidence and of the general gulfward sliding of the whole geosynclinal prism as shown in the lower two diagrams of Figure 7.

The commonly suggested idea for the origin of rollover faults is that the vast mass of geosynclinal sediments, saturated with water near the surface, and riding on undercompacted and overpressured shales at depth (Fig. 6C), is unstable with respect to the 10,000 feet (3 km) deep Gulf basin to the south. This unstable mass tends to move downward and outward (Fig. 7) into the basin like a gigantic landslump. The roll-over faults mark the inner limits of this movement. The rollover has two general causes, one local and one regional. The local rollover is caused as the sediments of the hanging wall of the "normal" fault subside downward and into the fault plane to fill the potential tensional gap left by normal-type faulting as the sediments pull away and slide gulfward. The regional effect is the tilting and rotation of the whole hanging-wall block, as is typical of landslide-landslump movements, causing a complete reversal of dip from slightly gulfward to slightly cratonward. (In all illustrations used in this paper and in most papers, the vertical scale is exaggerated ten to a hundred times and the apparent steep dips are generally a matter of less than two degrees and commonly only a few tens of feet per mile.)

For those who accepted this philosophy that the geosynclinal wedge of sediments is slumping seaward and into the gulf (Figs. 6C, 6D and 7), the discovery that the foot of the continental slope was a landslide-like hummocky topography (Gealy, 1955; Uchupi, 1968), was a very strong indication that this hypothesis was correct. That this topography conceals many salt diapirs (Lehner, 1969) does not detract from this conclusion, but is a further indication of load mechanics on salt (Wilhelm and Ewing, 1972, esp. Fig. 23).

Subsidence

All of the above is strongly in accord with the hypothesis of subsidence under load, as originally proposed by James Hall in 1857 (Hall, 1882). The proposed sequence of events is illustrated by a series of cross-sections (Fig. 7) showing a continuous sequence of events as a series of discrete events. The sections are thus highly diagrammatic and show only the gross details, and, as noted above, the vertical scale is greatly exaggerated.

The depth of the proto-gulf marine basin receiving the sediments is unknown. The present floor is at 12,000 feet (3.6 km) and is now underlain by about 16,000 feet (5 km) of sediments (Wilhelm and Ewing, 1972, p. 580). It must have subsided under the load of these sediments and so its original depth would have been only about 5000 feet (1.5 km) deeper than the present floor of the Gulf of Mexico. If there was a phase change at the Moho, it would have been even less. Thus the original proto-gulf must have been about 14,000 feet (4 km) deep.

Each wedge of sediment filled the edge of the basin (Fig. 7A and 7B), compacted, and made room for more sediment. But as the weight of these sediments depressed the original crust to a considerably greater depth (Fig. 7C), room was made for a still greater quantity of sediment and more isostatic adjustment. These effects, combined with that of basinward slumping of the sedimentary pile, would account for all of the major features: growth, hinge-faults, rollover, and gulfward migrating centers of deposition.

Assuming that the increased weight on the earth's crust triggered a phase change in the Moho (Kennedy, 1959), this sequence would allow for three types of subsidence to be operative. Compaction effects occurred first and were localized, and probably accounted for the local depocenters. Isostatic adjustments were more widespread and linear and contributed (along with original topography) to the east-west, elongate wedges of sediment. The phase change at the Moho caused a more regional and delayed subsidence, which may have been responsible for the long-term and rhythmical transgressions and regressions, and certainly was responsible for the overall continued regional subsidence. Phase change would also account for the anomalous rise of the Moho discontinuity under this area (Ewing et al., 1955; Dorman, et al., 1972).

SALT TECTONICS

Initiation

Most of the spectacular diapiric movements of salt everywhere in the world are now considered to be due to density and strength differences between salt and the surrounding sediments, rather than orogenic contraction (the older view). Even the classical "tectonic" salt anticlines of the various parts of the world are now recognized to be dominated by early halokinetic movements that determined the location of the anticlines, and conditioned the later orogenic movements. Examples of this newer viewpoint are given by Trusheim (1960) for north Germany and Elston and Landes (1960) for the anticlines of the Paradox Basin in the western U.S.A.

Immediately after precipitation and burial salt is denser than the surrounding unconsolidated sediments. With greater depth of burial, the compacting sediments become denser and the salt, which is relatively uncompactable, does not. Eventually the salt is less dense than the sediments and it rises, piercing through the overlying sediments (diapirism). The depths at which these density changes occur are far from well-established, but equal density occurs no shallower than 3000 feet (1000 m). Temperature, not pressure, is probably the dominating factor in determining the actual start of mobilization (Heroy, 1968 and Gussow, 1966 and 1970). Because movement is not only dependent on density difference and temperature, but on other factors such as lithology, thickness and slope (Trusheim, 1960), the depth at which movement starts is highly variable. This helps to account for the fact that the top of salt domes in the Gulf Coast occur at a great variety of elevations (Murray, 1961, Fig. 5.103; Hawkins and Jirik, 1966; and Paulson, 1968). Some domes are very deep and apparently not moving, and movements on others are known to occur at very shallow depths.

Shallow salt movement

Movement of salt soon after burial and at very shallow depths presents a special problem. For well-established domes, shallow movement is easily explained because the salt stock extends down to great depths. Density difference at depth is the motivating force, and the salt at the top easily injects into overlying lighter sediments. In fact the mushrooming of the top of salt domes is commonly attributed to this and to later density adjustment.

But salt also moves soon after deposition, and long before the salt is buried deep enough to make the density differential significant. Some of those in the present Gulf are attributed to a steam-roller effect, with the motive power coming from the weight of the thick column of sediments pushing the salt out from underneath it (Antoine and Bryant, 1969, Fig. 2).

But the real problem arises from the growing body of evidence that suggests that the salt is actively moving soon after burial and while at very shallow depths. For example, the salt in the Mississippi salt basin may have moved in Norphlet time and did move in early Smackover time, when the overburden was possibly as little as 1000 feet (300 m) and certainly no more than 2000 feet (600 m) (Badon, 1973). Similar early movement is shown for the Paradox basin (Elston and Landis, 1960; Cater, 1972). (1) Some of these early movements may be due to downhill slumping of salt under gravity (Bornhauser, 1968) while it is still denser than the surrounding sediments. (2) As the evidence of movement comes mainly from thickening and thinning (growth) as seen on isopach maps, which may have several causes, some may be pseudo-movements. (3) Local dis-solution of the salt soon after burial triggers thickness differences in the overlying sediments as they are deposited. (4) Still others may be shale diapirism, not salt. (5) In other cases, super-pressures in the surrounding shales may be transmitted to the more mobile salt. (6) Early compaction of carbonates over salt make for a very shallow gravity differential.

The evidence of early halokinesis is important and growing, and generally unexplained by density differences. Its importance cannot be underestimated, as these early movements determine the pattern of later deformations.

Basin-margin diapirism

Another important observation from a study of early halokinesis is that the slope of the depositional basin appears to be an important factor in triggering the salt movement (Trusheim, 1960, p. 1523; Paulson, 1968). Many diapirs appear to be localized along the margins of depositional basins (Halbouty, 1967, p. 52 and Fig. 5–5). This location at the basin margin (which is sloping) is certainly related to the influx of sediments at this point (hinge faulting) as previously described. The weight of the sediments causes this part of the original basin floor to be depressed isostatically, tilting the sediments along the edges into dips of one to three degrees. The layer of salt on the resulting slopes starts to move, either down or up depending on local density differences and other factors. The movement causes local thickening of the salt, which in turn determines the site of later diapirism (Kupfer, 1970, Fig. 9B). The salt in the adjacent areas is then also triggered into movement by the instabilities that result; the adjacent salt either moves into the area of active diapirism, or initiates diapirism in its own area. Thus all of the salt along a wide belt that has sufficient thickness and purity to become diapiric may be mobilized nearly simultaneously.

The next belt of salt that is sufficiently thick for potential diapirism has not yet been covered by a wedge of sediments. As sedimentation advances into this new area, the salt on the floor of the basin is either flat, or slopes upward to the gulf (Fig. 7). Thus as the load builds up and salt mobility is initiated, there will be a tendency for this new mass of salt to flow southward and upward, leaving a domeless area behind. This origin has been suggested for the domeless area of central Louisiana (Fig. 2). The problem here is how far can salt flow laterally under the advancing edge of a "steam-roller" of sediment before it will start upward into diapirs. I do not feel that the distance will be great, probably only a few miles, and thus not enough to account for a domeless area of very great width. More probably the central Louisiana domeless area (50–75 miles wide; 80–120 km) was originally an area in which thinner or less pure salt was originally deposited. As indicated earlier, it was probably a horst-like block and a topographic high during the period of sedimentation.

Time of diapirism

If the age of the Louann Salt is somewhat enigmatic, the time of its mobilization and diapirism is even more so. As has already been indicated, some movement occurred very early. Along the inner margin of salt deposition the salt began to move shortly after it was deposited (Halbouty, 1967, p. 52; Badon, 1973), forming pillows and salt anticlines. The main salt diapirism of the inner belt of Texas and Louisiana was large by the Cretaceous and Eocene, but by the Miocene the movements had nearly stopped. Those thickness changes observed in the Miocene sediments could as easily be due to differential compaction, dissolution of salt, or similar causes as to genuine salt diapirism.

In south Louisiana, however, the salt is clearly moving in the Miocene and strongly affecting all of the sediments being deposited at that time. How much earlier than that the salt movement began is speculative, as generally the drill has not penetrated deeply enough. But there is a growing body of information that suggests that prior to the Miocene the salt was already present in giant anticlines, massifs, or walls and had risen well above the level of surrounding sediments of comparable age. Thus the younger sub-circular-plan diapirs or "salt domes" needed only to pierce through the accumulating Miocene and Pliocene sediments, and did not need to pierce all of the older sediments. Whether the salt stocks in this area are still rising today is a mute question. I feel (Kupfer, 1970,

p. 48) that most of the stocks are stabilized, and this appears to be confirmed by the internal structures within the salt, geomorphology, and some elevation measurements. The opposing view is very well documented by Gera (1972). Still further south, on the continental shelf and slope, there is no doubt that the salt is currently very active (Lehner, 1969; Walker and Ensminger, 1970).

In summary, in the Louisiana Gulf Coast, salt movement began in the Jurassic, reached its peak in the interior in the late Cretaceous or early Tertiary and in the coastal belt in the Mio-Pliocene, and is just commencing active diapirism on the continental slope.

EXPANSION TECTONICS IN THE GULF OF MEXICO

Up to this point I have been attempting to summarize the generally accepted ideas about the location, distribution, age, and tectonics of Gulf Coast salt. These ideas range from the well-accepted to the speculative, and I have tried to indicate which are which. In the case of the speculative hypotheses, I have tried to give the current, commonplace ideas and be as factual as possible under the circumstances. In the following section I will show how I think these ideas and hypotheses can fit into the current ideas of an expanding Gulf of Mexico as a result of a rifting of North America away from the South American-African plate during the Triassic and Jurassic. The rifting apart of Africa from South America is a later event, occurring in the Cretaceous, as has been demonstrated by the age, correlation and composition of the salt deposits along the margins (see particularly Wardlaw, 1972 and this symposium).

Time

Despite the fact that Bird and Dewey (1970) have suggested that rifting began in the Devonian (Acadian orogeny), most of the evidence appears to suggest a Mesozoic date. For example, the shape of the Triassic grabens previously described (Fig. 2) and the age of the associated Triassic mafic intrusions, including basalt dikes and sills (May, 1971), support this date. It has also been suggested that as the floor of the Gulf has no magnetic anomaly patterns, it must have opened during the time of the magnetic quiet zone (148–160 m.y.). This is not necessarily true, because in areas of rapid sedimentation, such as the Gulf Coast, the sediments form a thermal blanket, allowing the cooling new-formed crust to pass through the currie-point slowly and under a variety of magnetic conditions, thus causing a confused magnetic pattern.

Thus the best evidence for the time of spreading comes from the sediments, as previously described. Continental splitting probably commenced in the late Triassic (Eagle Mills, Triassic dikes), but by the early Jurassic had progressed enough to allow the sea to enter from the west (Fig. 3A). There is a considerable body of evidence, however, that suggests that a proto-Gulf of Mexico was already present, but land-locked (Paine and Meyerhoff, 1967; Wilhelm and Ewing, 1972). This mediterranean (Fig. 8) had a simatic floor and was probably about 14,000 feet (4 km) deep. This proto-gulf was intersected by a long, narrow, gash-like trench similar to the present Gulf of California; closed on the northern or eastern end and opening across a shallow sill or trench to the Pacific Ocean on the west or southwest. By earliest Jurassic the sea had sabkha-like shorelines in a dry temperate to semi-arid environment. Evaporites began to form (carbonate, sulfate, halite) and halite deposition dominated in local deeper basins. As spreading continued, the deeper portions of the developing basin filled with sale brines as carbonate reefs kept entrances shoal and narrow. Fluctuating pycnoclines (Sloss, 1969) allowed simultaneous deposition of thick salt layers over wide areas, and this also allowed the concurrent deposition of the anhydrite with the salt instead of in separate basins (Kupfer, 1970, p. 56). Epeirogenic changes caused basin instability and, at times, the influx of large amounts of sediments (probably mostly fine-grained). As the basin enlarged during the late Jurassic and early Cretaceous and the adjacent highlands were eroded down (Fig. 3B), carbonate deposition dominated the northern and shallower part of the embryonic Gulf of Mexico. Salt continued to deposit in the deeper water, but as the opening to the ocean became larger and more open, carbonate deposition spread everywhere except a few isolated basins.

As a result of this sequence of events, the Louann sediment-evaporite series developed with thicknesses locally of up to 10,000 to 15,000 feet (3–5 km). Many local and isolated basins of anhydrite and related evaporite deposition of various sizes also developed, particularly on the margins and in the overlying sediment column. The main Louann sequence was, however, an interbedded sequence of sediments and salts en échelon upward and to the south. In the deeper parts of the migrating basin of salt deposition the total thickness of NaCl commonly was at least 5000 feet (1500 m). The salt basins were seldom restricted enough to allow evaporation to proceed to the stage of precipitation of the complex and highly-soluble K-Mg salts, and the only presently known occurrences are at Palangana, Cote Blanche, and Pine Prairie.

During Cretaceous time, the spreading rate surpassed the sedimentation rate and the open Gulf of Mexico formed. Salt deposition ceased and the once reasonably continuous salt deposits were permanently split apart and now lie scattered on the periphery of the present oceanic-type and generally "new" floor of the Gulf of Mexico. With the early Tertiary epeirogenic rejuvenation of the orogenically deformed Rocky Mountain System, vast floods of clastic sediments were deposited in the gulf area and caused diapirism to reach its most dynamic stage, first on the north, and then in steps southward. Diapirism also occurred in the various other isolated basins such as those of Mexico, Cuba, and Honduras.

Pattern

No general agreement has been reached on the geographic pattern of the Gulf-Caribbean area in pre-drift (early Triassic) times (Fig. 8). The classic Bullard (1965) fit is least appropriate in this area as it makes no allowances for Mexico and Central America. The Freeland and Dietz (1971) fit is considerably better, and probably gives the best basic outline. The movement and placement of the individual blocks within this outline has become a popular parlor-game of the jig-saw type, with highly plastic and deformable pieces. The extensive late Cenozoic volcanic cover conceals most of the critical evidence, and the continental or oceanic nature of many of the pieces is not even established. Basic field work on the metamorphic and igneous basement rocks is proceeding, and as the structural and petrographic trends are recognized (cf. Kesler et al, 1970; Kesler, 1973; Dengo, 1968, 1969), more restraints on interpretation are becoming evident.

Clearly a first step in working backward is to remove the very young and large strike-slip movements on faults like the Polochic and Motagua faults of Guatemala (Kupfer and Godoy, 1967), Mexico (Viniegra, 1971), and other strike-slip zones. For example, palinspastic removal of about 200 miles (300 km) on the Polochic-Cayman zone places the Honduran salt as part of the Chiapas basin salt (Pinet, 1972). Walper and Rowett (1972), by following a variation of this reversal of movement on strike-slip faults, ended up with the troublesome Mexican mainland on the northwest side of South America.

Events

The early Mesozoic distribution of the land masses must have been something approximating that shown in Figure 8, with an ocean somewhere to the west including island arcs and subduction zones. With the Triassic inception of the spreading, playa lakes formed in the grabens, but as marine waters entered, the main evaporite cycle commenced, probably in early Jurassic. In the first phases the topography would be similar to that of the southern Mojave Desert and Salton Sea, but a larger more mediterranean-like basin developed and the remainder of the period was probably similar to that of the Zechstein basin of the Permian. Probably the principal difference was that in the Zechstein basin each succeeding evaporite phase was essentially in the same area, but in the Gulf of Mexico the spreading sea-floor was opening up new basin areas to the south, and each succeeding phase was displaced somewhat to the south. The edges of the basin were shallow shelf-like shorelines and with local sabkhas on the coast. As the main deep sea basin progressed southward, the northern area continued as a broad shelf receiving mostly carbonate

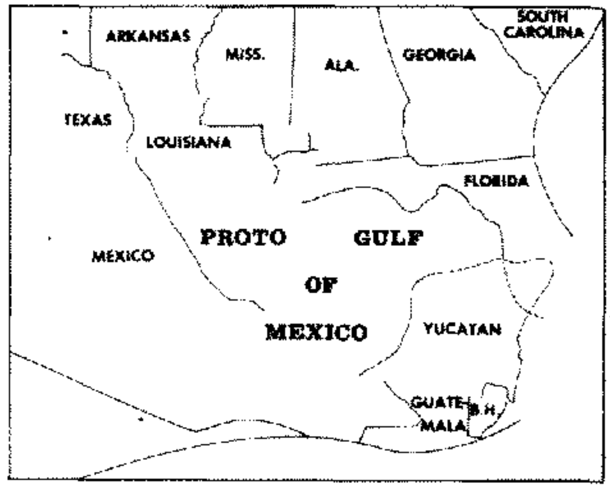

Figure 8. Approximate size and shape of original mediterranean-type pre-Triassic Gulf of Mexico. This assumes later sea-floor spreading during the Mesozoic.

deposition, but on the extreme north this interfingered with clastic sediments derived from the north. Local isolated basins of calcium sulfate and carbonate evporation also formed at this time.

By the end of the Jurassic, North America was topographically subdued, clastic sedimentation practically ceased, and new oceanic-type basement was exposed in the floor of the newly developed sea. Open oceanic circulation was established, evaporite sedimentation ceased, and carbonate deposition dominated on the broad continental shelves that surrounded the new sea. South America now began to drift away from Africa, and a new salt basin formed between these two continents.

In the Tertiary, the orogenically deformed backbone of western North America began to rise epeirogenically, reaching a maximum elevation in the Miocene and again in the Recent. The resultant flood of clastic debris brought to the Gulf Coast was deposited in a series of geosynclinal wedges of sediment that built out into the Gulf of Mexico. Each wedge depressed the basement isostatically and some triggered a phase change at the Moho discontinuity which allowed further subsidence. As a result the underlying Mesozoic sediments were tilted seaward (southward) causing upslope migration of the salt deposits.

In the *interior* salt belt this migration had commenced in the Mesozoic, and domal diapirism was probably most active then and in the early Tertiary. By the Miocene, diapirism had essentially ceased, and the domal areas acted as residual posiments affecting sedimentation, but not actively rising.

In the *coastal* belt the early sedimentation caused the salt to move into ridges and rolls. In local areas, probably those of thicker original salt, the salt moved up into giant massifs, the tops of which were 10–20 kilometers (5–10 miles) across. The timing of these earlier events is unknown, but by middle to late Miocene, as deposition continued and the basement was pushed down to depths of 15 kilometers (10 miles), smaller diapirs of rejuvenated salt started to move upward as the surrounding sediments moved downward. These movements continued actively into the Pliocene and then waned.

The third or *offshore* belt of salt domes is only little known, but probably is at the toe of a giant landslump. As the sediments inland are pushing downward and outward to fill the void of the Gulf of Mexico (Fig. 7), the salt in this area is acting primarily like the shales of Figure 6C. But in this case the movement is strongly modified by the diapiric tendency of salt to rise isostatically. In a sense, the salt is being steamrollered out from under the Miocene-Recent wedge of geosynclinal sediments, and toothpaste-like is squeezing up through the newly deposited sediments of the shelf edge. This crude analogy is not intended to be taken too literally, and as geophysical and drilling data accumulate, it is expected that the observed structures and resulting mechanisms will have to be strongly modified. But one thing is clear, this is an active process, and one that deserves every bit of the scientific attention it is currently getting.

SUMMARY

The purpose of this paper is to summarize the Gulf Coast setting for salt diapirism. Several points have been emphasized. The Louann Salt is not a simple one-stage deposition but a complex depositional event of several cycles and covering a significant part of geological time. The salt basin was probably expanding and at the same time geosynclinally sinking. Continental materials were contributed from three directions and the only opening to the open sea was probably to the west or southwest. All of this is compatible with the doctrines of sea-floor spreading and plate tectonics, but not proof; several other hypotheses are equally viable.

Using the classifications of Tables I and II, the evaporites were deposited at sabkha-to-bay depths (0–100 feet, 0–30 m), but the halite itself in basins of shelf-like depths (100–300 feet, 30–100 m). The environment I prefer is #5, restricted marine; but the evidence for #7, epicontinental shelf, is also compelling. Thus, the Louann Salt is mainly **5d**.

The Gulf Coast geosynclinal-tectonic history consists of a series of linear wedges of sediment deposited parallel to the shoreline and isostatically subsiding; continued deposition is aided by phase changes at the Moho. Salt, deposited over most of the basin in the earliest stages, rises diapirically under the influence of sedimentation. Earliest and simplest diapirism occurred at the basin margins in the late Mesozoic; later and more complex diapirism is more central and Cenozoic in age. Quaternary salt movements may be influenced by the steam-roller effect of the sediment wedges pushing the salt out from under the sedimentary column and into the zone of active deposition. Diapirism itself is strongly influenced by depth of burial, temperature, position of the salt in the above sequence, basinal position, original thickness, and purity; in short, by the total geological history.

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