Boundary Shear Zones in Salt Stocks

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ABSTRACT

The gross features of salt diapirism in the Gulf Coast and the spine concept of diapirism are reviewed. Spines range in size (measured by number per dome) from two to a dozen or more per dome and the shear zones between these spines of movement range from wide to narrow. The shift-slip that has occurred across the zone is from a few feet to several miles. Shear zones can be external to the salt stock and composed of both shale sheath and salt sheath. When these external zones, with their contained foreign sediments, are caught up into the interior of the salt stock they form boundary shear zones between two spines of salt. Other internal shear zones occur in the salt stock, but they are more difficult to recognize. Boundary shear zones are from 10 to 1000 feet (3 to 300 m) wide, extend thousands of feet through the dome, are composed of 5–50% sediment, have physical properties distinct from those of salt, consist of material that is generally not salable, and may make for hazardous mining conditions. By proper exploration the economic liability of these zones can be reduced, and they can be used for engineering purposes such as ventilation and flood barriers. Boundary shear zones are described at Avery, Belle Isle, Jefferson and Weeks salt mines.

INTRODUCTION

In recent years it has become well recognized that some Gulf Coast salt stocks consist of several separate spines of salt that have moved independently. The fact that these spines, in some cases, are bounded by shear zones of significant width and markedly different physical and chemical properties has not been as well publicized. These shear zones are transitional in nature between faults and zones of flowage, and are one member of the group of shear zones associated with Gulf Coast salt domes. For convenience, three zones are recognized and termed external, boundary, and internal, and described separately. They are, however, transitional to each other.

Acknowledgments

The management and staff at all of the Five Islands mines have been most cooperative toward my endeavors to study and map the salt stocks. Without their help this report would not have been possible. In particular I would like to thank Mr. L. J. Broussard of Morton Salt Company and his staff at Weeks Island mine for their early interest in my work and their continuing help and assistance. Mr. Nicholas Nicola of Cargill, Inc. and his staff at the Belle Isle mine have allowed me to map freely in that mine and have kept me informed of developments. Most recently, Gayle Petrick, Dick Sieferman and the personnel at the Diamond Crystal Salt Co. at Jefferson Island have aided me in mapping both the surface and underground at the Jefferson Island mine.

Salt diapirism

A very brief review of Gulf Coast salt tectonics is given for those unfamiliar with the details. A more comprehensive review is given elsewhere in this volume (Kupfer, 1974). The Louann salt was deposited horizontally about 150 million years ago (Kirkland and Gerhard, 1971) and since that time this horizon has been buried to a depth of 2 to 12 miles (3–20 km) with shallower depths to the north (Fig. 1). In the north, the salt moved upward shorter distances and occurs in simple stocks like those at Grand Saline, Texas and Winnfield, Louisiana. The internal structure of the salt in these two domes is reasonably simple (Balk, 1949, and Hoy et al., 1962). To the south, where the original horizon is now very much deeper, the story of salt movement is more complex. It is now commonly assumed that the salt first moved into broad arches (Quarles, 1953; Bornhauser, 1958), mounds (Johnson and

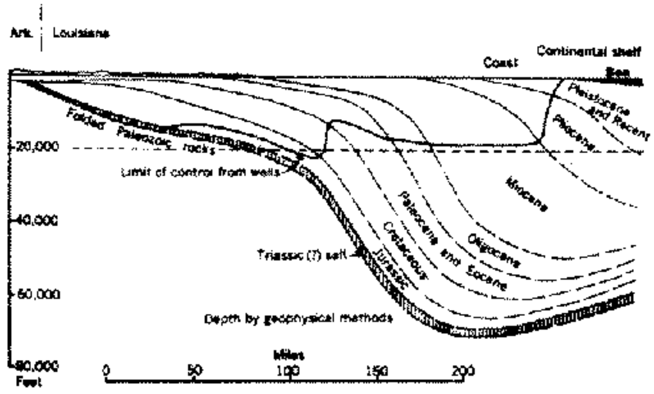

Figure 1. Diagrammatic cross-section of Louisiana showing how the original horizon at which the salt was deposited (vertical cross-hatch) has been depressed to greater and greater depths southward. (From Kay and Colbert, 1965, Figure 18-8 as modified from G.C. Hardin, 1962.)

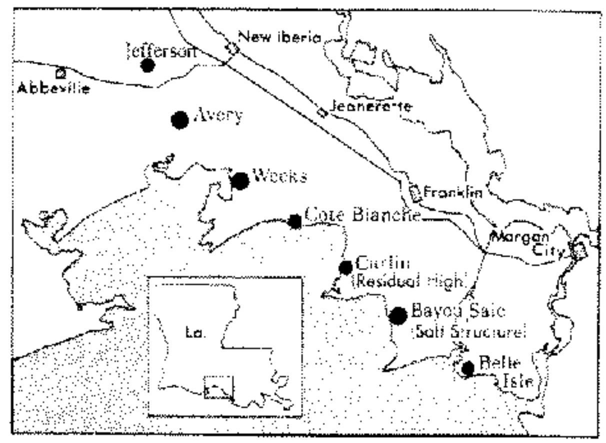

Figure 3. The Five-Island diapir trend showing the five salt domes with surface expression, the Bayou Sale structure (which may be a deep-seated salt dome or massif), and the Bayou Carlin structure (a residual high from an older salt-ridge stage).

Bredeson, 1971) or massifs (Atwater and Forman, 1959). These structures are 5 to 15 miles (8–25 km) across at the upper levels and expand rapidly downward as the sides dip outward at angles of 45 degrees. These broad structures are now deeply buried and generally beyond the reach of the oil drill, but they were probably much shallower when they formed (Fig. 2). After these salt arches were buried in still more sediment, starting about 25 million years ago, they moved up into smaller stocks, such as those we see today in the Five Island trend (Fig. 3). They did not, however, move all at one time, but rather in pulses. These salt stocks are 1 to 3 miles (1.5–5 km) in diameter, have nearly vertical walls, and are encased in a shale sheath.

Spines

The concept that the salt stock consists of several parts or "spines" that have moved independently of each other is now commonly accepted. In the late 1940's, Balk (1949) mapped the internal structure of the Grand Saline salt dome and was impressed by the lack of faulting in the Grand Saline salt stock and the great abundance of faults in the overlying sediments. To explain this he suggested that the roof of a salt dome was probably "a multitude of irregular salients, recesses, and sags" adjusting to the fractured sediments over it, and "Each irregularity of the roof is likely to give rise to fields of greater or lesser shearing stresses, and thus should generate velocity differences between individual groups of salt layers." Thus he recognized that salt domes might not move as a single mass, but as a series of unit cylinders moving at different speeds. Muehlberger (1960, p. 32) expands this idea: "Although Balk could not prove his statement, the mapping of the new workings demonstrates the accuracy of his predictions. The sharp changes in direction of the fold axes suggest fracturing of the roof rocks . . . The salt moved up along these fractures, . . ."

In this concept, emphasis might be placed on the words a "multitude of irregular salients," implying that each stock consisted of a great number of spines, and consequently that each spine had relatively small dimensions compared to the stock itself. This is the concept, for example, used by Howard (1971) in his computer simulation models, although in the later stages of his studies he modified his parameters so that the number of individual spines was considerably reduced.

At about this time Kupfer (1963) suggested at the First Symposium on Salt that the sandy zone at Avery Island was the boundary zone between two salt spines which he called "large unit cylinders" (he noted the possible occurrence of "small" units also). The extreme of the large unit was shown in the diagram of his later paper (1968), where the stock consisted of only two spines. It seems probable that spines of all sizes occur (as implied in the 1971 Howard studies) and that the larger spines move through

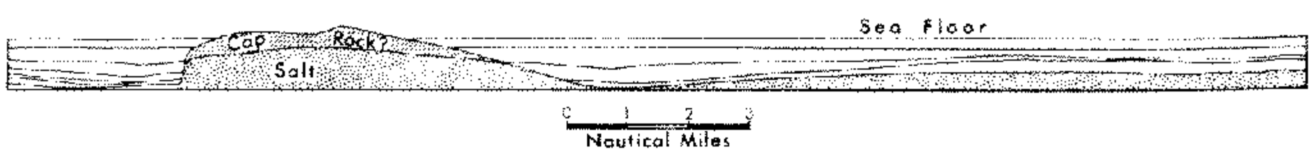

Figure 2. The "typical Sigsbee Knoll and dome" of Ballard and Feden (1970, Fig. 2) drawn to true scale to show that the structures are broad massifs or pillows and not vertical-walled diapirs. This probably represents an early stage of diapirism.

greater vertical distances and more independently. The small spines may, in many cases, be just zones of differential rate of advance; the salt moving essentially as a unit. The analogy here might be to a crowd of people moving out of a football stadium, with one plume moving more rapidly for a short distance, and then another plume moving ahead as an opening develops, but the crowd as a whole moving rather uniformly.

In summary, spines of movement occur in every size from large to small, but the shear zones between separate spines become more discrete and more important as the spines and the displacements become larger.

Large spines

The most compelling evidence for large spines comes from the petroleum industry and its work with the distribution and thickness of the sediments around the salt stocks and the faults that cut these sediments. The *salt dome* is the whole mass that has been deformed and domed upward, including the sediments and the salt, whereas the *salt stock* is only the salt. In studying the whole dome, it has been observed that changes take place in the surrounding sediments that are deposited at the same time as the salt is intruded (Currie, 1956, Fallow, 1973), the most notable of which is the bow-tie effect (Fig. 4, lower). A down-faulted block (graben) develops directly over the rising salt mass and receives more sediment (the knot of the bow tie) at the same time that the rest of the dome is rising upward and receiving less sediment across the top. But out beyond the area of domal growth the basin is sinking and so sediment is deposited to a greater thickness (the wings of the bow tie). When this bow-tie effect is observed tilted and displaced to one side of a salt mass, as at Lake Washington (Fig. 4, upper) two stages of

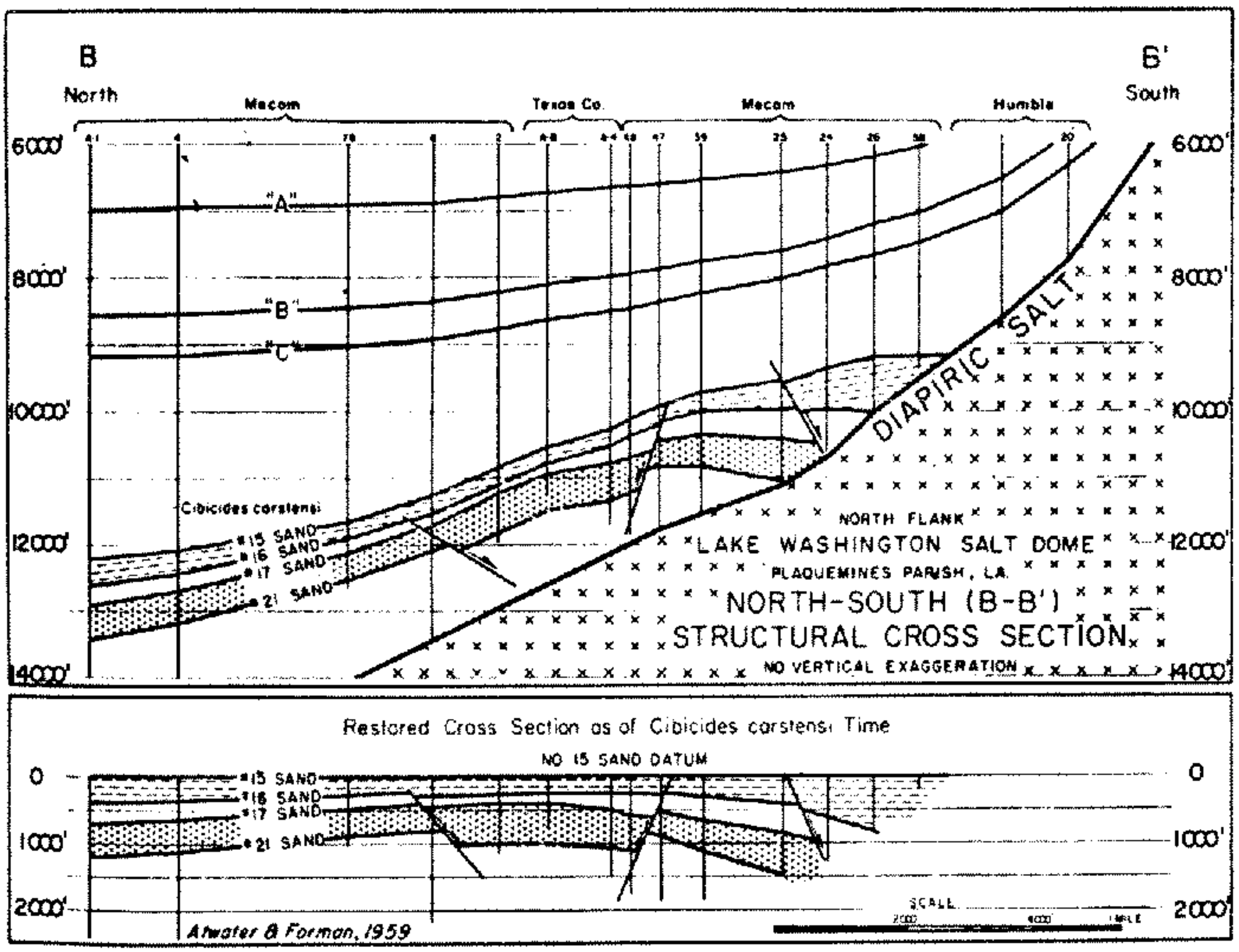

Figure 4. The upper part is a cross-section showing the Lake Washington Dome as it is today with the "bow-tie" structure tilted to the north and by-passed by the salt massif which pierced through adjacent sediments to the south. The lower section shows the bow-tie structure in its normal, formative position over a deeper stock-like salt diapir. (From Atwater and Forman, 1959.)

movement are clearly indicated. The salt moved up in the area under the bow tie, and then at a later time it bypassed the salt under the bow tie and moved up into an adjacent area as a separate spine of movement.

Studies of the changes in thickness of sediments from place to place (isopachous studies) and of the time of movement on "growth faults" give detailed knowledge of the times and places of salt movement (Atwater and Forman, 1959; Trusheim, 1960) and from these studies examples of spines of movement of the "large" type have been established, and many others suggested.

Small spines

Evidence for movement of spines of the smaller type comes mainly from the mapping of the internal structures of the salt. Cross faults that completely disrupt salt layers have not been commonly reported, but this may be from lack of proper observations. In the only room at the Weeks mine that was kept very clean and brightly lit (Fig. 5), faults were observed. It is then highly probable that faults would be seen elsewhere if other rooms could be observed in similar detail. In any case, zones of shearing are commonplace (Kupfer, 1968), and these zones mark boundaries between units of salt that are moving differentially. Balk (1953, p. 2465) recognized that there is every gradation between zones of attenuation and zones of slip (Fig. 6), and thus between masses of salt that are being stretched during movement and small spines of movement.

In summary, few if any shear zones have been mapped in the past; but in part this is because they have not been actively sought; in part it is because lighting conditions prevent their recognition; but primarily it is because the very shearing action obliterates the evidence of their existence.

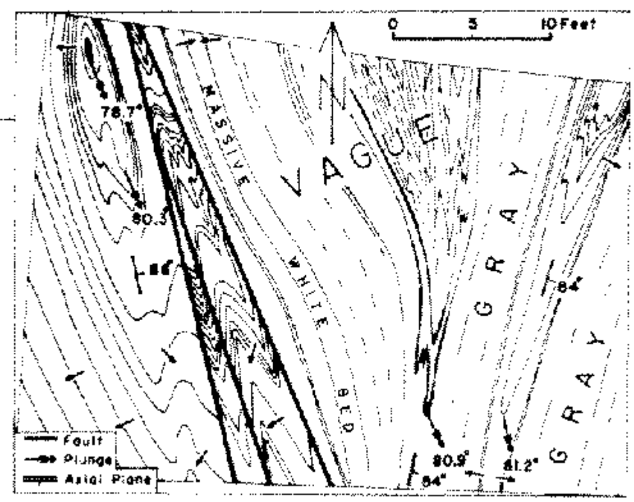

Figure 5. Faulting as observed in the low-ceiling brightly-lighted storage room of the Weeks Island mine. It is assumed that structures like this could be observed in any of the coastal salt stocks if conditions for observation were right. Arrows show direction of younger strata, i.e., they point out of the anticlines and into synclines. (Reprinted, with corrections, from Kupfer, 1963)

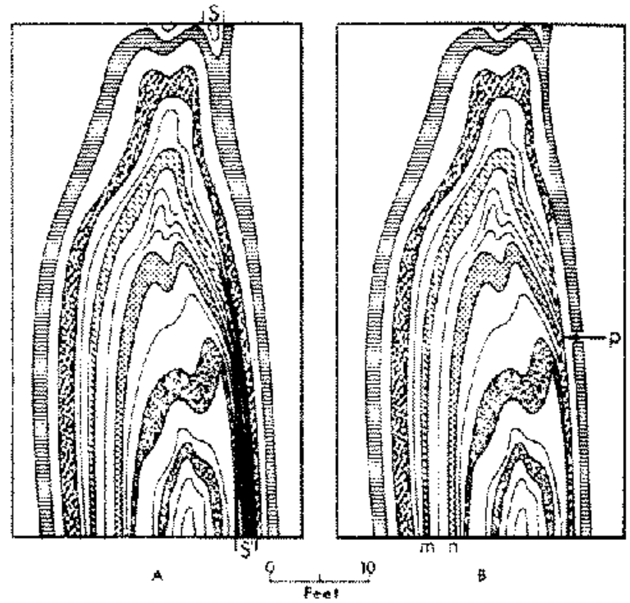

Figure 6. *A.* Beds on left limb of fold are 6 feet thick and are attenuated to 2 feet on the left limb (Kupfer, 1962, Fig. 6). S-S' marks a potential shear zone. *B.* After removal of zone S-S', the beds would look like this, but this shear zone would never be recognized under normal conditions as the beds would blend together. Beds *m* and *n*, for example, might be mapped as the same bed (isoclinally folded) with a fold axis at "p." Thus attenuation and shear are gradational, and most shear zones are undetected in normal mapping.

SHEAR ZONES

The main topic of this paper is not the spines of movement, but the shear zones which separate the spines. Just as there are many transitional types of spines from large to small, there are also transition types of shear zones. For purposes of exposition, consider three members: external, boundary, and internal. The external shear zones separate the salt from the surrounding sediments, and the internal separate salt spines from each other. The boundary shear zones are a special class in which external sediments are incorporated into the internal shear zone.

External shear zones

Since diapirism is, by definition, the cold intrusion of one mass of material into another, the boundary between the two masses is either a shear zone or a fault. For the average salt stock this zone consists of two parts, the shale sheath and the salt sheath. The shale sheath has long been recognized (Hanna, 1953; Johnson and Bredeson, 1971) as a clay-like gouge of surrounding sediments that has been sheared out against the salt. Adjacent to this zone, shale commonly is brecciated outward for thousands of feet

(Kerr and Kopp, 1958), contains abnormally pressured water, and grades into other abnormally pressured shales that are still in their normal stratigraphic position. The two shales can be separated by the breccia-like character of the inner one, and both can be differentiated from gouge-like shale sheath (Kerr and Kopp, 1958, Fig. 1).

Balk (1953, p. 2470) clearly recognized a sheared-out zone of salt at the edge of the salt stock in which the layering had been sheared into a parallelism with the outer boundary. This zone can be recognized by its pseudo-simplicity (folds are sheared into parallelism), and by the fact that the dark and white layers in the salt are thinner and discontinuous. In extreme cases the layers become almost lenticular. The width of this combined zone of shale sheath and salt sheath has never been accurately measured, but in the Weeks mine I found the shearing to extend at least 500 feet (150 m) into the salt stock. Thus a reasonable guess would be that the external shear zone can be between 300 and 1000 feet wide (100–300 m) and probably averages about 500 feet (150 m).

Boundary shear zones

If a spine of salt diapirically pierces sediments and is surrounded by a shale sheath (Fig. 7A) and then another spine of salt moves up and along side of it, it is reasonable to assume that some of the shale sheath will be caught between the two salt masses. When this occurs, the shale marks the boundary between the two spines of salt movement. But just as the shale sheath can be caught up between the salt, so can any other rock type that happens to be adjacent to the salt. Thus any material can be found in the salt; all the commonplace sediments: shale, sandstone, and limestone, are found in Gulf Coast salt domes.

The above process is reasonable, but it implies that it is easier for the salt to push aside adjacent sediments than the salt itself (Fig. 7A). Under normal conditions this will be true, because the top of the salt column is hot and semi-fluid and pierces into soft and uncompacted sediments. Once it has stabilized, the salt cools and becomes very competent and difficult to remobilize (Gussow, 1966, 1970). Instability will then be transferred to some point much deeper in the salt column where the salt is still hot, and less dense than the surrounding sediments which are compacted and of increased strength. At such a point (indicated by the arrow in Fig. 7A), it may be much easier for the salt below to push up the overlying hot and mobile salt than the surrounding dense, hard, and compacted sediments. The result will be as shown in Figure 7B: the boundary shear zone and surrounding salt will be carried up in a new spine of movement. In this case, the foreign sediment of the boundary shear zone will be in the middle of the salt spine and subject to the same forces, and distorted in the same manner, as the salt. In later movements it will flow into the same type of vertical folds as are

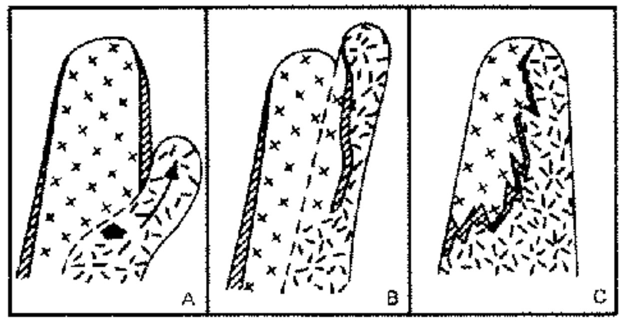

Figure 7. *A.* New spine of salt being activated by heat and buoyancy will exert pressure on the soft and mobile salt at point of arrow. *B.* This is the more probable type of movement that will take place under the conditions at "A," resulting in a boundary shear zone. Dashed line is also a shear zone (internal type). *C.* Shale sheath of "B" has been folded by a second remobilization (flowage) resulting in a folded boundary shear zone (as at Weeks Island).

typical of Gulf Coast diapirism (Fig. 7C). Thus one should expect to find that in some places the sediments of the boundary shear zone are themselves contorted. This has been observed at Weeks Island (to be described later).

Internal shear zones

In Figure 7C, the boundary between the two spines is between salt and salt, with no intervening sediments; this is an internal shear zone. As this is between two "large" spines, the displacement could also be very large. Thus this shear zone would be transitional, in every sense, to the salt sheaths of the external shear zones, and like the boundary shear zones in everything except the content of foreign material.

Internal shear zones also occur between "small" spines, with much less differential movement across the zone. In general, these would be thinner, and every transition exists from small scale shears to attenuation and to faulting (Figs. 5 and 6). As already noted, most internal shear zones are not recognized during mapping.

Characteristics

The boundary shear zones that have been observed contain foreign sediments (by definition), which may occur as a fine powder, or in sizable fragments up to a foot (30 cm) or more in diameter; both are scattered through the salt matrix. Shale or limy shale is most common, but sandstone and limestone are also present. The larger fragments are generally rounded, as if rolled around during movement, but all shapes and sizes are observed. The percentage of foreign material may locally approach 100, but over the whole shear zone it is commonly very minor.

The foreign material part of the shear zones ranges from widths of a few inches (decimeters) to greater than 35 feet (10 m) and zones may be repeated by either shearing or folding so that impure rock is found over zones up to several hundred feet wide (100–200 m). Too few have been observed to make any firm generalizations.

Most of the observed zones have been continuous over the range of exploration, but one at Belle Isle (Fig. 8) was observed to fork into two parts and thin out to almost nothing. In theory all could do this laterally, and should do it vertically. Probably most zones also extend out to the edge of the salt stock and become part of the external

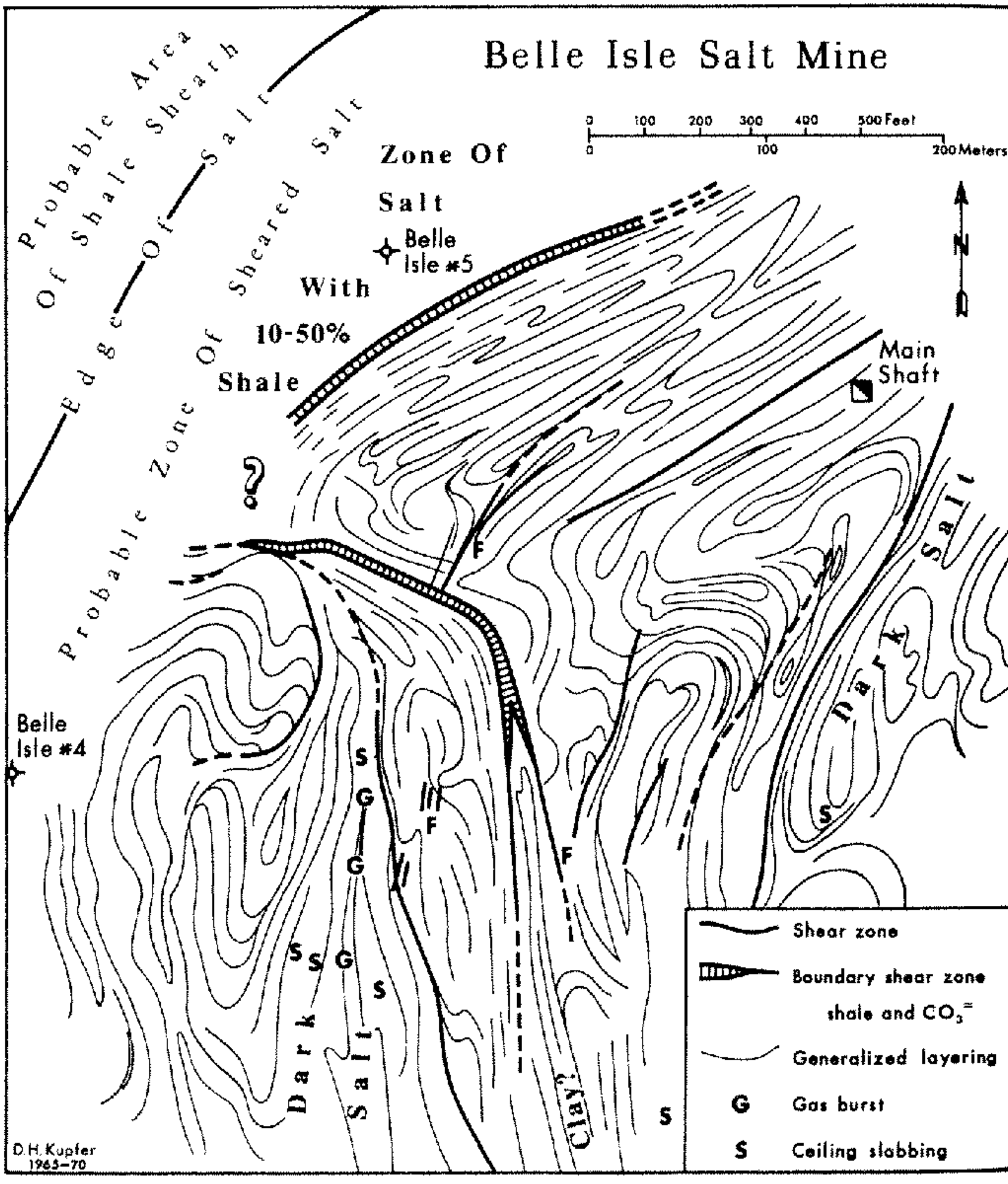

Figure 8. Shear zones at Belle Isle salt mine, Louisiana.

shear zone, but for safety reasons none has been followed that far. The zones can be simple and straight (Avery, Belle Isle), semi-complex (Jefferson Island), or highly contorted and infolded (Weeks).

Importance

Recognition and understanding of the significance of the boundary shear zones is of considerable importance to the scientist, as it aids him in understanding the times, conditions, and methods of salt stock movement (halokinesis). Older spines of movement can be differentiated from those of younger age and, with the aid of the evidence from the external sediments, the geologic history of the dome can be understood. This, in turn, allows prediction of physical and chemical factors of economic importance.

Of interest here, however, are the much more obvious and immediate effects that these boundary shear zones have on the mining of the salt. These zones separate two individual spines of salt, which may or may not have had different histories; may or may not be different in physical and chemical properties. The law of probabilities suggests that differences will occur, and in passing from one spine to another, the mine operator may discover significant changes in the grade of the salt and its potential uses. Massive white salt with few impurities may give way to darker salt, banded salt, gray salt, or even brown salt; and vice versa. The physical properties of the salt, such as grain size, hardness, friability, or ease of extraction may also change from one spine to the other. Thus the operator, upon coming to a boundary shear zone, may wish to do exploration before proceeding, especially if a significant investment is involved. Each spine is a separate physical entity, and may be like or dissimilar to its neighbor in any of the common variables associated with Gulf Coast salt. It is quite possible that salt in two adjacent spines might be more dissimilar than salt in two adjacent mines.

An even more important factor in the economics of mining is the nature of the boundary shear zone itself. First, by definition and origin, it will be less pure than the adjacent salt, and very probably will be waste. Once mined, it must either be sold at a reduced price or disposed of as backfill or waste. Second, experience has also shown that this salt has very different mechanical (strength) properties, most of which are disadvantageous to mining and mine safety. Wall and ceiling stability are impaired and the possibility of ceiling slabbing is greatly increased.

Certain other problems have appeared that may be associated with these boundary shear zones, but our experience with them is too limited to make any positive correlations at this time. For example, large pockets or porous networks of brine are associated with some of these zones. Associations of other foreign contaminants such as petroleum accumulations and high pressured gases may also be related to these zones, although the occurrences of such seepages and explosions show no clearcut pattern at the moment. These materials can, however, migrate rather freely and may have moved considerable distances along lesser shear zones. Thus the other internal shear zones, although less easily recognized and possibly of lesser magnitude, may also be important. All of this, however, is largely speculation at this time, but is in agreement with the mine descriptions in the final section of the report.

Suggestions

Because of the probable importance of boundary shear zones (and possibly of the other shear zones) to mining, it is advisable to make some attempt to locate these zones as soon as possible. Once located, their probable extent and importance should be determined. For the boundary shear zones the diamond drill is presently the most useful tool (Walden and Jacoby, 1963), but radar (see articles by Unterberger and Cook, this symposium) may have a much greater future potential. As will be noted in the following descriptions, knowledge of the geology of both the internal structure of the salt and the external structure of the dome can also be very helpful. Internal shears can only be recognized by detailed mapping of the layering by a geologist trained to know what to look for.

Once the zone has been recognized and something of its nature determined, several steps can be taken. First, since the salt is waste salt and has some potential danger, the workings penetrating it should do so at right angles (shortest distance through it) and with workings as small (low and narrow) as possible, consistent with good mining practice. This produces less waste and greater safety. Second, extra precautions can be taken in this zone against such problems as brine cavities, gas explosions, and ceiling slabbing.

Because the boundary shear zone is present and cannot be avoided, this disadvantageous feature should be turned into as much of an asset as possible. Because mining entries through this zone can and should be kept to a minimum, it can be used as a barrier wall separating the mine into discrete units for purposes of ventilation, unitized mining, and similar activities. The barrier could be made even more impermeable with automatic safety doors, concrete seals, and similar devices, and could be used to save part of the mine if another part should become flooded, gased, or otherwise disrupted.

EXAMPLES FROM THE FIVE ISLANDS
(Figure 3)

Avery Island

It was at Avery Island that foreign sediments were first recognized in a Gulf Coast salt mine (Heald, 1924). It was here also that sediments were first recognized as a possible boundary between salt spines (Kupfer, 1963). The first horizontal diamond drill probing in a Gulf Coast dome was done here (Walden and Jacoby, 1963). The boundary shear zone has been exposed for a distance of 3500 feet (1 km) and has been penetrated at two points, first by drilling and later by workings. (Note: the scale on the Walden-Jacoby Plate I, p. 368, appears to be in error.) Where penetrated, the zone is about 6 to 10 feet (3 m) thick and consists of 5 to 10 stringers of sand ¼–½ inch (5–15 mm) thick and locally up to 3 inches (80 mm) thick. The sand is reddish (probably the ubiquitous iron staining present in all mine waters) and consists of rounded to sub-rounded quartz grains. Similar sandstone zones are present over a much wider zone, so that the whole boundary shear zone is over 50 feet (15 m) thick. This zone, which now serves as a ventilation barrier between the old and the new workings, contained considerable water (brine?) in local pockets. In one area the amount of drainage was so large that a section of the workings had to be dammed off for a period of time until the flow ceased. The fact that the flow in all of these areas eventually does cease strongly suggests that the brine-filled network of interconnecting passageways does not connect to the outside of the salt stock, and thus to fresh water which would dissolve large openings and flood the mine.

Belle Isle

At the Belle Isle salt mine (Fig. 8) operated by Cargill, Incorporated, I have had an opportunity to map the boundary shear zone and several lesser shear zones. The boundary shear zone appears to start at the edge of the salt stock as an external shear zone and penetrate into the salt mass and disappear near the center of the salt stock (mining has not yet progressed far enough to confirm this). The Belle Isle #5 drill hole (Fig. 8) penetrated the "salt sheath" zone and contained 35–45 percent shale from 400 to 800 feet (100–250 m) below the surface and from 950 to 1200 feet (300–365 m). At 1200 feet (365 m), the level of the present workings, samples ran 50 percent shale. In contrast, drill hole #4, equally near the edge of the dome, was in nearly pure salt.

In the mine the shale zone has not been penetrated where it parallels the salt stock boundary (on the northwest), but it is 8 to 20 feet (2–6 m) thick where it turns into the mine proper and continues as such for over 600 feet (200 m) before forking and thinning out.

The zone appears, on first observation, to be similar to any of the other zones of dark salt which are commonplace in all the Gulf Coast mines. But on inspection, fragments of black, hard, limy clay are observed. Most appear as rounded pebbles or cobbles surrounded by a dark salt matrix (Fig. 9). A much more detailed description of this zone with up to 95% clay, siltstone, and sandstone is given in Paine et al. (1965) along with a good photograph of the zone.

The boundary shear zone at Belle Isle is notable because the sediment has been dated (Paine, et al., 1965) as

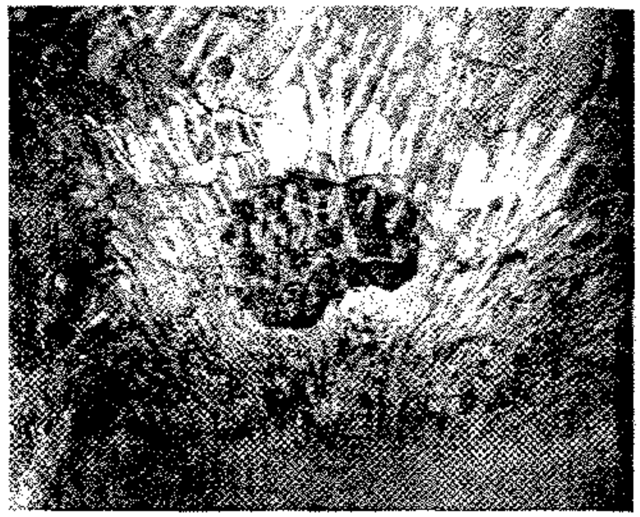

Figure 9. (Photo) Large inclusion of clay in ceiling of Belle Isle salt mine; probably about 2 feet in diameter. Photo by J.T. Grice, Morgan City, La.

Miocene and thus only 20 million years old as compared to the salt which is 150 million years old. This clearly established the foreign nature of the sediments and shows that their inclusion is related to diapirism. The salt in this area is now about 40,000 to 50,000 feet (12–15 km) above the horizon in which it was deposited (Fig. 1), but the equivalent Miocene rocks on the side of the dome are now at 22,000 feet (7 km). Thus the salt had a relative displacement of about 4 miles (7 km) before the Miocene sediments were incorporated into the salt and about 4 miles (7 km) afterward.

As shown on Figure 8, several lesser shear zones radiate out from the boundary shear zone. Some of these zones were recognized by the presence of large, vertical, flat surfaces covered with striations of movement (slickensides). In others, minor cleavages or shears were observed at a small angle to the layering, and displacement was evident, but the amount of separation was not determined. Other shear zones were inferred by the rapid attenuation of strata and the sudden disappearance of a particular type of lithology. The abrupt terminations of bedding shown are somewhat interpretive and could be shown equally well as just attenuations (Fig. 6).

It is worthy of note that most of the areas of significant ceiling slabbing occur near the boundary shear zone. The several "blowouts" (areas of overbreakage during blasting) are also near this zone and in very black salt with abundant foreign material and a strong odor of methane gas.

Cote Blanche

I have not mapped the Cote Blanche mine and have not visited all parts of it. In those areas that I have seen, no evidence of a boundary shear zone was noted. A very thin

(5–20 cm) zone of reddish salt in discontinuous stringers can be observed in one part of the mine and is reported to occur in several other areas along a more or less straight line. This layer is reported to be about 16 percent potash (equivalent to about 35% KCl) by U.S. Geological Survey chemist Lloyd S. Woodruff (personal communication from D. H. Eargle, USGS, June 1972), and so it is less likely that this is a boundary shear zone, yet potash was recognized by Balk (1953, p. 2462–4) at Jefferson Island in what is now known to be a boundary shear zone.

Jefferson Island

Jefferson Island was first recognized as having a possible spine by Balk (1953, p. 2470–71), but he discarded the idea in favor of a leaching hypothesis. The basis for this suggested spine is the fact that one part of the salt stock (spine 2, Fig. 10) is now 800 feet (250 m) higher than the adjacent more flat-topped part of the main salt mass (spine 1). The flat-topped part is overlain by cap rock (mined for sulfur in 1933–36) and a subsidence lake. The attitude of the sediments over the spine appears to have been controlled by the intrusion of the main salt mass and then modified later by the intrusion of the spine (Kupfer and graduate student M. Raymond, personal observations, 1971).

A boundary shear zone separates the salt of the two spines and probably grades upward into an external shale-sheath shear zone around the younger and higher spine (Fig. 10). Shale was first encountered during the mining at the 1000-level, where it was left as the limit of mining along a zone 1800 feet (550 m) long. Balk (1953, p. 2462–4) gives a detailed description of the sediments, particularly the red sands. It is present vertically below along the edge of the workings on the 1300-foot level. Its boundary-shear-zone character was unrecognized, and an attempt was made to penetrate it to gain access to the main

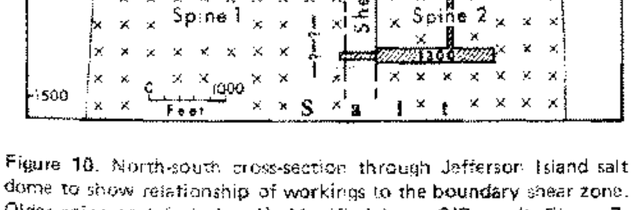

Figure 10. North-south cross-section through Jefferson Island salt dome to show relationship of workings to the boundary shear zone. Older spine to left (spine 1). Modified from O'Donnell, Figure 7, 1935.

mass of salt. At this point it is very much thicker than the normal boundary shear zone, and probably has been refolded, sheared, and otherwise repeated. Along this north-south line the foreign material has been found by mining and drilling over a length of in excess of 1000 feet (300 m). With the background of the present paper available, it is now easy to see that this is a boundary shear zone, and its true character recognized. It is worthy of note, however, Balk (1953) concluded after a study of the data available at that time, that the area of spine was not a "spine."

Except for the complication of extreme thickness noted above, the shear zone is very similar to that of the Belle Isle mine. Rounded pods of fine-grained sediment up to one foot (30 cm) in diameter have been noted at various points along the zone, but much of the impure material is fine-grained and generally disseminated through the salt. Locally the dark sediment-rich salt is in layers 2–3 feet (1 m) wide, and these layers can be followed for over 300 feet (100 m) before they disappear in the walls of the workings. Thus the character of the zone appears to be that of several layers of shale-sheath folded together and penetrated by salt; it is not a simple boundary shear zone.

In drilling to determine the overall shape and character of the shear zone, a brine pocket of nearly pure $CaCl_2$ brine was intersected and a great quantity of brine flowed out into the workings at high pressures. This flow continued at a rate of many gallons per hour (several liters per minute) for several days. Also in this zone a slab of salt about 70 feet (20 m) in diameter and up to 6 feet (2 m) thick fell from the ceiling; it killed three men and destroyed equipment.

Weeks Island

At Weeks Island the external shear zone present along the south and west side of the workings was mapped by Kupfer (1962, Fig. 1). In the southwest corner of this map the pseudo-simple parallel-layered and sheared-out zone is exposed over a width of 300 feet (100 m) in the workings and the salt sheath is probably twice that thickness as the southeast edge of the salt stock is about 300 feet (100 m) distant.

As mining progressed eastward and northward, toward the center of the zone, darker salt was encountered and ceiling slabbing was associated with this salt. The darker salt has persisted and, about 1000 feet (300 m) farther along, a boundary shear zone has been encountered. This zone has not been penetrated, but the edges are highly sheared and folded. Most of the clay-like material is very fine-grained and intimately associated with the salt. One clay layer less than 1-foot thick was checked for fossils, but none were found (R. Rosen, Texaco, New Orleans, 1973, personal communication).

This zone extends from the south edge of the salt stock to essentially the geographic center of the salt mass, and has been exposed for a distance of over 1500 feet (500 m).

The sediments in the zone are highly contorted and the very impure layers are highly sheared and discontinuous, suggesting a boudinage-like disruption of the more competent sediments by the mobile salt. The present interpretation is that this was an external shear zone that had been incorporated into the salt and moved relatively upward a long distance as indicated in Figure 7C. It has been involved in the later movements of the salt, and the foreign material has thus been strongly infolded and sheared into the salt.

CONCLUSIONS

The most important consideration of this report to the mine superintendent is that he should be aware that in each salt dome in the coastal area of the Gulf Coast one to several boundary shear zones are to be expected. At present, it is difficult to predict just what they will be like, but in general they will consist of one or more 2- to 6-foot (0.5–2 m) thick layers of interbedded sediment and salt in a zone from 10 to 1000 feet (3–300 m) wide. Boundary shear zones are mappable, and their trends are considerably more predictable than the trends of ordinary banding. They can be detected by horizontal exploratory holes and may be able to be detected by radar.

Recognition of these zones in active mines is very important as the zones commonly are composed of low-grade, non-marketable salt with different strength characteristics. Locally this zone may contain large brine cavities. Probably the most important economic factor is that the zones bound spines of salt that are very different in grade, hardness, banding, and other physical properties. Early detection of these zones is not difficult; detection will aid in proper penetration, considerable saving in mining costs, and increased safety.

In addition, lesser shear zones are also present in the mines. As these have been relatively undetected up to the present time, little is known of them, but petroleum leaks, gas pockets, and other mine problems may be associated with them. These probably can be detected by very careful mapping and photography of the layers by an experienced geologist who is specifically looking for them.

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