Conflicting Strain Patterns in the Salt of Gulf Coast Salt Domes and Their Genetic Implications

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ABSTRACT

Anomalies are present in the structure of the salt exposed in Gulf Coast salt mines. Drag and shear structures suggest horizontal movements during folding that contrast sharply with the known vertical movement. Attenuation of vertically-plunging folds and tubes, and model experiments confirm vertical motion.

Explanations involving flexure, shear, and plastic flow supply partial answers. Preliminary mapping of the pattern of drag folds in complexly folded stocks confirm multiple stages and methods of movement, and yield promise for future differentiation of the fold structures impressed during horizontal migration in the mother bed from those impressed during much later flowage over long distances and at elevated temperature.

SALT STRUCTURES

Introduction.

The purpose of this article is to call attention to several minor structural features in salt that are ordinarily interpreted as having formed as a result of a certain kinematic response, but as observed in the salt of Gulf Coast salt domes this response appears anomalous. The structural features are those known in salt parlance as shear folds, refolded folds, shear zones, and drag folds. In general, the best explanation is flowage response to severe deformation, probably at elevated temperature; but alternate kinematic origins are also considered, as well as changes in response with time.

None of the material in this article is new, but I hope to give it a slightly different interpretation. My ideas are based on observations in the southernmost salt domes of the United States Gulf Coast and may apply only to that area.

By way of review, the mechanism of salt intrusion is vertical movement resulting from the difference in specific gravity between sediments and salt (Atwater, and Forman, 1959, and Trusheim, 1960). The salt is deformed into a series of vertically plunging folds (Escher and Kuenen, 1929 and Ramberg, oral communication, this symposium), and geologic maps of the mine workings give cross sections of these fold structures (Balk, 1949). The layers of salt, originally totaling about 5000 feet thick, were probably originally interbedded with other sediments as are the salt beds of the Salina Group of the north central United States (Rickard, oral communication, this symposium), and the Paradox Formation of the Colorado Plateau (Raup, Hite, and Groves: oral communication, this symposium). Thus the original salt sequence would have been much thicker, about 10,000 feet, but probably still within the same order of magnitude as the Paradox Formation (Hite, 1968, p. 325-326). The salt was tectonically purified during diapirism (Kupfer, 1968, p. 79-84).

During geosynclinal downwarping of the Gulf Coast basin, the early Mesozoic salt sequence was depressed by a gradually accumulating sedimentary load until diapirism occurred. With continued sedimentation and geosynclinal sinking, the diapirism went through the pillow structure of stage A (Fig. 1) and the salt massif of stage C. By stage E, maturity, the vertically-sided salt stock had pierced upward—possibly to the surface in some cases. During this process the top of the basement had been

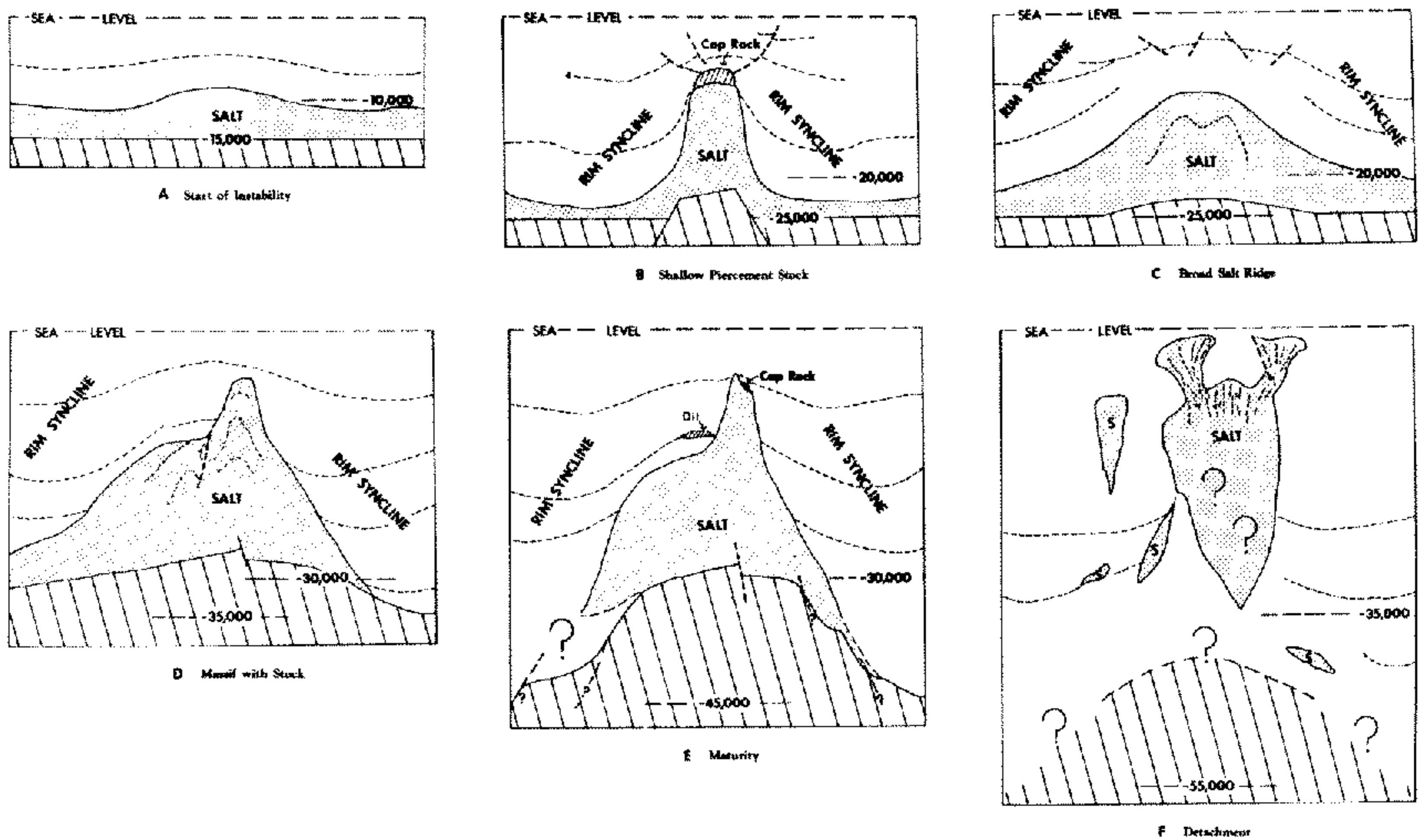


Figure 1. Domal Growth with Basement Participation (From Kupfer, in press). A. Incipient mobility at shallow depth. B. Shallow basement and thin overburden give rise to typical dome (Stock) of the northern interior, deformation by flexure(?). (?) and shear. C. In more rapidly subsiding coastal Louisiana areas salt moves into broad domes or ridges called massifs and stabilizes. D. With continued geosynclinal sinking and increased temperature, stock-like diapirism occurs by plastic flow, giving rise to complex flowage structures like those observed in the salt mines of the Five Islands. E. Geosynclinal sinking continues, but salt at depth transmits heat to the whole salt mass, diapirism keeps the salt mass high (downbuilding). F. Theoretical final stage that may not occur in the Gulf Coast.

depressed to about 50,000 feet below sea level. This model (Fig. 1) appears to be in agreement with subsurface; and incorporates most of the ideas of Atwater and Forman (1959) for the Gulf Coast, and Trusheim (1960) for North Germany.

May I particularly call attention to the fact that according to this model the salt flows horizontally along the original sedimentary beds, upward into the massifs (with sides that slope outward at approximately 45°); and at a later stage, into the vertically-sided salt columns called "stocks." We only have good structural control, by direct observation, on the salt in the stocks; here the folds are observed to plunge at 80 to 90° (Kupfer, 1963, Table 2). During this diapirism the coastal salt moves a minimum of 7 miles and possibly as much as 15 or 20 miles from its original point of deposition.

Isopachous studies from oil well data prove that the salt does not move continuously, but in a series of pulses (Atwater and Foreman, 1959; Trusheim, 1960). It is this intermittent movement over great distances that causes the extreme complexity of structure in Gulf Coast salt (Kupfer, in press). Each time the salt moves, it inevitably moves in a somewhat different pattern, thus modifying or destroying any previous structure. This explains why the interior domes of the Gulf Coast, in which the salt has moved relatively short distances—3 or 4 miles, are much simpler in structure than those of the coastal area to the south in which the salt has moved 7 to 15 miles (Atwater, 1968, p. 39).

Shear folds (Salt seismograms).

The terminology "shear fold" used by Balk (1949, p. 1805-06) has caused confusion—as much from the choice of name as from anything else. Contrast Figure 2B, Balk's drawing of a "shear fold" with Figure 2C, the classic interpretation of shear folding.

Figure 2 is taken from Balk and shows how the arch bend region of the "shear fold" is plicated into a series of tight crenulations. Other illustrations of this are given by Balk (1949, Figs. 5-10); Hoy, *et al.*, (1962, Figs. 9-10); and Muehlberger (1959, Plates IIC, III). Isoclinal folds of this type are commonly observed in flowage situations and have been described, for example, for the Malaspina Glacier (Sharp, 1958, p. 636 and Plates 1-3).

The unfortunate choice of the word "shear" may be responsible, at least in part, for the generally accepted assumption that salt deforms by shear folding, and with motion parallel to the axial plane. This leads to our first conflict. In shear folding the motion is not only parallel to the axial plane, but it is also parallel to the lines shown in Figure 2C. This direction is perpendicular to the b-axis of folding and a horizontal direction in the salt mines. Yet it is a well documented fact that the movement in a salt stock is parallel to the b-axis—the vertical direction.

Schwerdtner (1966, p. 71) revived Hartwig's 1923 term "salt seismograms" for these so-called "shear" structures, that term being more descriptive and less genetic. The term salt seismogram has the disadvantage, however, that it suggests a relationship with earthquake activity (as in Balk, 1949, p. 1806). Possibly a better term can be coined, but whatever term is used I agree with Schwerdtner that the term "shear fold" with its genetic implications, should be avoided.[1]

In the terminology of slip folds (cf. Whitten, 1966, p. 133-134) the main movement in salt stocks is vertical and parallel to the *b* (or Beta) fabric axis, which is thus the a-kinematic axis. This suggests that the motion reflected by the salt seismograms is a minor, sidewise, nonaffine shifting perpendicular to the a-kinematic axis that occurs during the main upward movement (Fig. 3).

Seismograms occur only at the crests of folds, and from this it may be assumed that only here do the planes of slip cross the bedding. Likewise, as this minor sidewise shifting is not recorded on the limbs, there the slippage must be parallel to bedding. The result is the inference that in salt movement is predominantly parallel to bedding and not to the axial planes of the folding—a point that will be considered again later.

Refolded folds (Ptymagitic folds).

Another misleading term, "refolded fold," was introduced in my paper on the Weeks salt mine (1962, p. 1461; see also Kupfer, 1968, p. 84). The complex structures of the type shown in Figure 4 were called "refolded" because isoclinal folds appear to have been refolded into a larger arcuate structure. In describing refolded folds of the third and even fourth order (1962, p. 1961, esp. Fig. 4), I was impressed by the fact that whenever one saw two black beds parallel to each other, they were commonly the result of isoclinal folding (as at point labeled "Same Bed?" in Fig. 5B). The implication of refolding as visualized in the 1962 paper

1. During the oral presentation the term ptygmatic fold was suggested, but this term is now preferred for the more general usage suggested later.

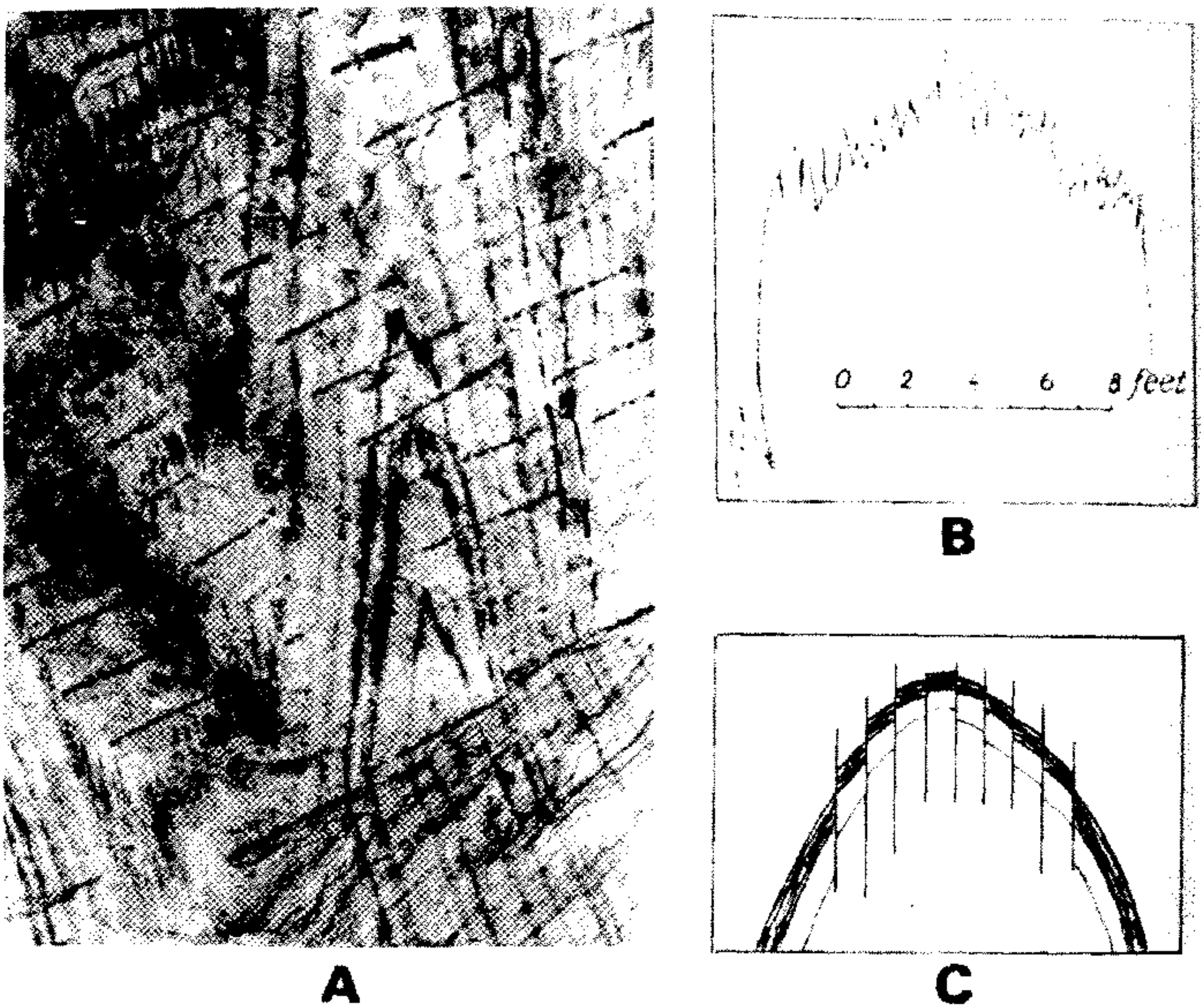


Figure 2. Isoclinal plication of bedding at crest of folds, termed "shear folds" by Balk, but better called "salt seismograms." A. Salt seismogram from the Grand Saline mine (Balk, 1949, Fig. 9). B. Sketch of the plications, also from Balk (Fig. 8). C. Classic displacement of bedding on a shear fold.

(see especially Fig. 4 of that paper) was the same as if a sheet of paper is folded in half, then folded in half again by a parallel fold, and then again, etc. This geometric pattern does occur, but again the mechanism implied by the terminology is wrong.

In the Belle Isle salt mine a complex fold of a quite different type is present (Fig. 5). With photograph in hand, I examined this structure under good lighting conditions and made a sketch (B), a diagrammatic interpretation of the structure. Notice that a single, one-inch-thick, black bed of anhydritic salt outlines the whole complex structure. It emerges from the wall behind the viewer and passes through the 35 numbered arch bends and then passes into the wall ahead. In addition the closures A to D are probably formed by the same bed, but this cannot be proved.

The structures in the three darkest areas (A, B, 31-35) are salt seismograms that repeat the bed from 6 to 15 times by isoclinal folding. Thus a single bed has been repeated, as a minimum, 35 times and possibly twice that number. It is also interesting to note that in the 35 numbered repetitions, starting from 1, the bed moves always to the

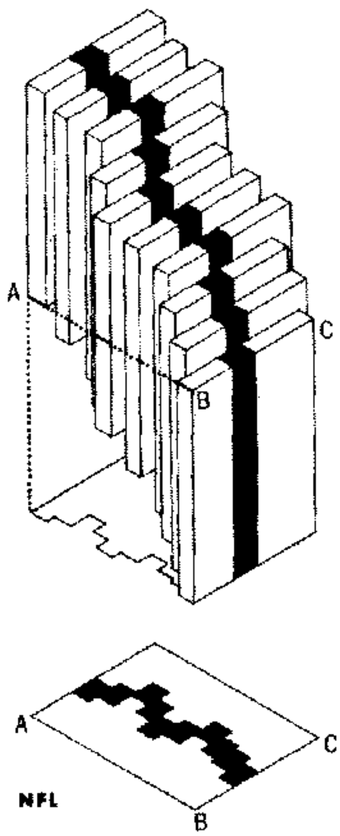


Figure 3. Diagrammatic representation of origin of salt seismograms by erratic cross-slip during vertical motion. The section ABC represents the view in the ceiling (floor) of the mine. In the model the number of slip planes is greatly reduced and each block is very thick, thus producing the "step" effect that is not observable in nature.

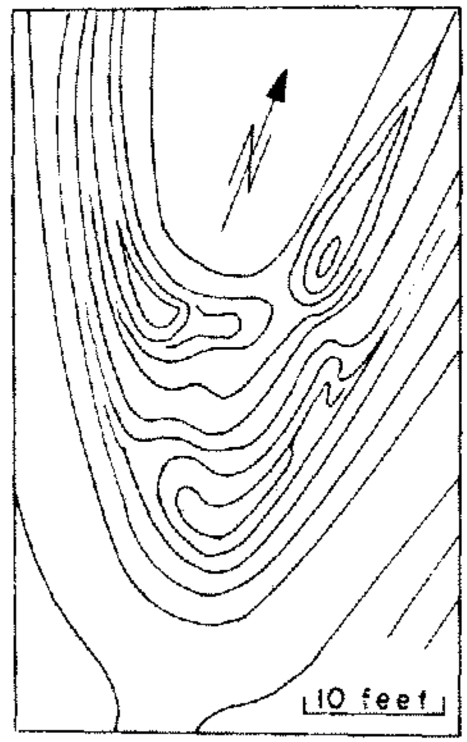


Figure 4. Isoclinal folds in the Weeks mine that appear to be refolded. (Kupfer, 1962, Fig. 5).

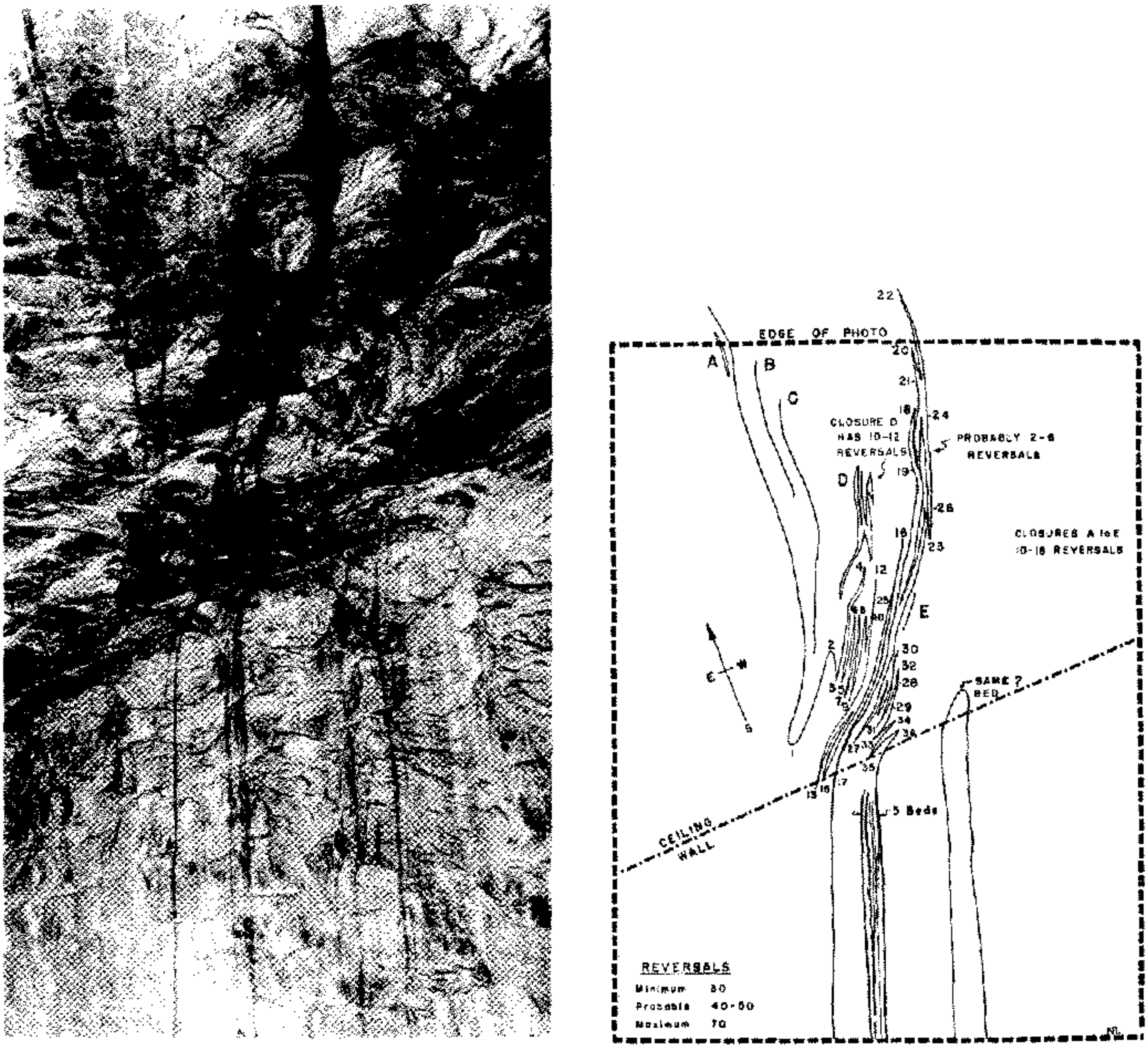
right except at beds 23, 31 and 32. This is an accordian-type of folding and not the pattern described above for refolding of folded folds. The term *ptygmatic* fold is very descriptive for Figure 5 and the kinematic mechanism is flowage—very fluid solid-state glacial type flowage. It is not axial-plane shear.

To summarize the first two points: Although there may be some shear folding involved in salt deformation at shallow depths, most of the folding in the southern domes along the Gulf Coast is of the flowage type. To me this is a strong confirmation of the suggestion by Heroy (1963) and Gussow (1965) that heat is very important in this fluid-type diapirism. The salt is so hot during its rise that it acts essentially like a liquid and flows. Secondly, this flow will be at different rates for each bed, as viscosity will change with composition and thickness. This means the primary differential movements will be parallel to the bedding rather than parallel to the axial plane.

Fabric analysis.

Now let us apply this to Figure 6, showing several typical fabric diagrams for salt in which the poles to the cubic cleavage are plotted in the lower hemisphere. For the simple case (A), this produces three orthogonally positioned, spot concentrations for one preferred orientation. In interpreting these diagrams the assumption is made that the glide planes are parallel to the axial planes of the folds, and from this, interpretation is made (as in Fig. 7A) as to whether gliding is parallel to the cubic cleavage (001 plane) or to the dodecahedral surfaces (110 plane). The latter is predicted by atomic bonding theory (Schwerdtner, 1967, p. 357).

But as has been indicated above, flowage (gliding?) is probably parallel to bedding rather than to axial planes in the case of many folds. Figure 7B illustrates how this can lead to a misinterpretation. Assume gliding is parallel to the bedding on the



A.

B.

Figure 5. Ptygmatic flowage structure at Belle Isle salt mine. A. Photograph looking up at ceiling in area where one thin dark layer of salt has been crenulated into between 30 to 70 folds. (Photograph by permission of Jesse T. Grice, Morgan City, La., and Cargill, Inc.). B. Diagrammatic interpretation of the photograph. Three areas: D, 3-12, and 18-26 are so tightly folded that the limbs blend and the amount of folding is indeterminate; the interpretation is the minimum amount of folding possible based on visible reversals at the edges.

limb of the fold and is on the dodecahedron as predicted by theory (Case L, Fig. 7B). If one assumes shear folding or slip movement parallel to the axial plane, this will be misinterpreted as gliding parallel to the cubic direction. It is not my intention here to arbitrate the cubic vs. dodecahedral controversy but merely to call attention to the fact that the interpretation of flowage parallel to bedding as shear folding can lead to misinterpretations.

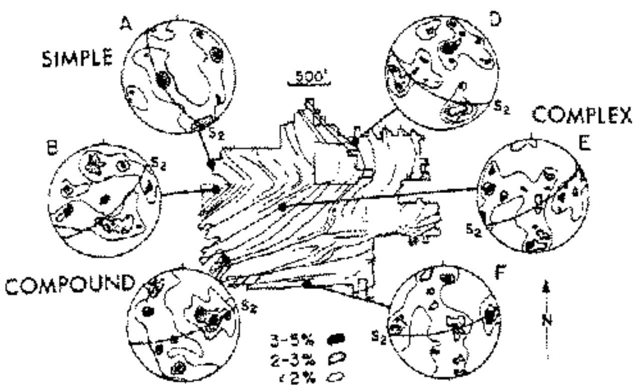


Figure 6. Typical salt fabric diagrams from Grand Saline salt dome. A (and F?) show typical three-fold concentration of poles to the basal (001) cleavage of halite as plotted in the lower hemisphere. B and C show a compound or dual orientation with 6 centers (3 for each orientation). D and E show more complicated patterns. (After Clabaugh, 1962).

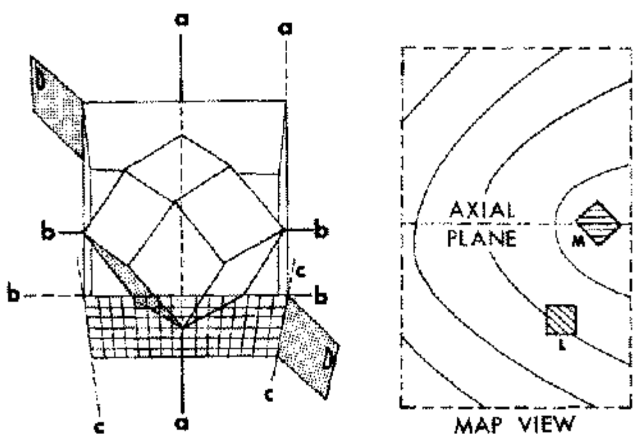


Figure 7. Cubic versus dodecahedral glide surfaces. A. If gliding is parallel to a cubic face (shown cross-hatched; this is also the 001 cleavage direction) then poles to two of the three sets of cubic cleavage for any one orientation (both b and c) will lie in the gliding direction. If gliding is parallel to the dodecahedral face (shaded) this is at a diagonal to the cleavage and only poles to one cleavage direction (c) will lie in the plane of gliding. B. If gliding is dodecahedral and parallel to the limbs of the fold (Square L), the cubic cleavage will be subparallel to the axial plane. If gliding is then interpreted as parallel to the axial plane, it will appear to be parallel to the cubic face. True axial plane gliding on the dodecahedron would appear as at M.

Shear zones (Transposition structures).

Next I would like to describe zones of intense differential movement between two unit masses, for which I believe the terminology "shear zone" is appropriate (Kupfer, 1968, p. 88-89). In these shear zones the differential movement of the opposite walls is so great that all previous flowage structure is stretched out, producing a pseudo-simplicity of structure (cf. southern edge of Fig. 6). The result is the deceivingly simple homocline first described at the edge of salt stocks by Balk (1949, p. 1816), but interpreted by him as primary. The true nature of the structure in these zones is revealed by the extreme lenticularity and discontinuousness of the sheared out layers. Thus the layering in such a shear zone is not true bedding but a transposition structure.

Two types of shear zones can be recognized. One at the edge of the salt stock, as just described, separates the main salt of the stock from the adjacent bedrock; the other is within the salt itself. In the former the simplicity is due to the differential movement between the sediments outside the stock as they move downward and the salt which remains stationary or moves upward. A corresponding transposition structure occurs in the sediments; this is the shale sheath or gouge zone that surrounds the salt. Unfortunately a shale sheath and overpressured shales have similar physical characteristics and are difficult to differentiate; a problem beyond the scope of this paper.

The same shear conditions will prevail in the center of the stock between two spines of movement (Fig. 8). If, as is currently agreed by some workers, the salt in a stock does not move up as a single mass but in separate units or spines, each moving at a different rate and at different times, shear zones should appear between these spines of movement. The importance of seeking out and recognizing these shear zones need hardly be emphasized. However, this is difficult because of the subjective nature of the decisions involved, and it may prove worthwhile to show this subjectivity on maps.

What is emphasized here is that simplicity of structure can have two interpretations. If truly simple and primary, and for example the single large fold at Winnfield (Hoy, Foose, and O'Neill, 1962, Fig. 5), the implication is simple deformation, short distance of movement, and possibly even a single period of movement. If the simplicity is a pseudo-simplicity and a transportation structure as in shear zones within the Weeks and Belle Isle mines (personal observation) and the Avery Mines (Waldon and Jacoby, 1963, p. 367 and Fig. 1), something very akin to faulting is implied and the opposite conclusions are warranted. Movement

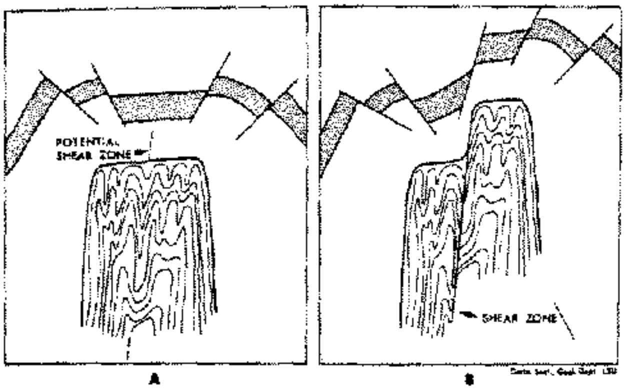


Figure 8. Shear zone within a salt stock caused by differential movement between adjacent masses (spines) of salt. (Kupfer, 1968, Fig. 8).

is complex, long continued, and/or over great distances.

Drag folds.

The final conflict to be discussed is "drag folding." Figure 9 shows typical drag folds between two blocks slipping horizontally past each other as shown by the small black arrows. The sense of motion is clockwise and the b-axes of the folds are

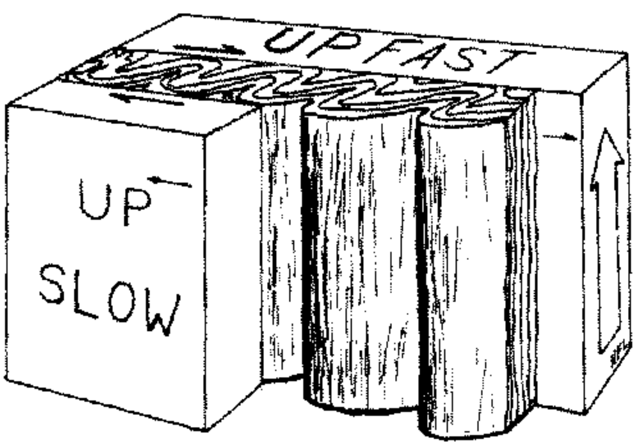


Figure 9. Drag folds in salt. Right-lateral (horizontal) shear indicated by the small black arrows would cause the clockwise "Z-drags;" but the primary motion both actual and differential, is vertical as shown by the large white arrow.

vertical, as observed in the salt mines. If the blocks were to shear past each other in the opposite horizontal direction the folding would be reversed (s-shaped), giving a counterclockwise sense of direction. Clockwise and counterclockwise drag folds can be recognized in the salt mines, but they present a conflict because the true direction of salt motion is vertical as indicated by the large white arrow, not horizontal. Presumably the differential motions are also vertical, as between faster and slower moving beds, and thus unlikely to cause the observed drags.

In the typical drag fold pattern observed in Gulf Coast salt domes (Fig. 10), the drag folds are

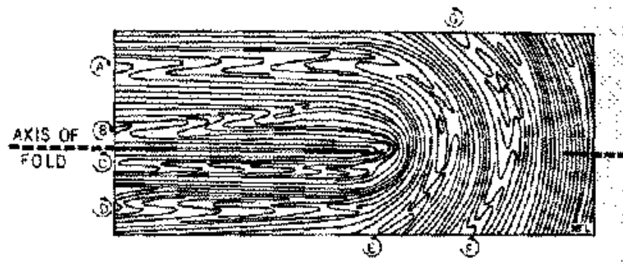


Figure 10. Clockwise Z-drags (A, B) and counterclockwise S-drags (C,D,E,F) typically occur on opposite limbs of folds as in classical theory. Locally, as G, the distribution is wrong.

paired, clockwise on one side of the axial plane and counterclockwise on the other (as predicted by classical flexure-folding theory). The photographs by Muehlberger (1959, Plates V, VI) and the second and third order folds of Evans and Linn (oral communication, this symposium) are also very fine examples of paired drag structures.

Note however, the situation from F to G (Figure 10), which is relatively common. Here despite the crossing of the axial plane, the sense of drag remains unchanged. Again a conflict with kinematic theory.

ORIGIN OF DRAG STRUCTURES

Drag structures thus present two conflicts. They suggest differential horizontal movement in situations where the movement is known to be vertical, and in places they do not pair-up correctly. The several origins for drag folds that will be considered are superposed slip folding, early flexure folding, a non-tectonic late depositional origin, and diverging and converging lines of flow. All of these explain some of the observed effects, but no one of them explains them all. Possibly, however, early formed "drag folds" may eventually be able to be separated from those imposed later during "flowage."

One possible origin of drag folds is two stages of vertical slip movement superposed on each other. Each slip occurred on a different set of slip planes. O'Driscoll (1962, p. 156-159) showed how this could produce sigmoidal folds similar to drag folds. In considering this mechanism for the development of drag folds in Gulf Coast salt domes (Fig. 11), it is assumed that in the massif stage (Fig. 1D) the folds in the salt plunge at a moderate angle, about 45°. In Figure 11B one of these early folds is deformed by slip folding along a new axis, B. This would correspond to a second period of salt movement. Maximum vertical motion is upward in the center of the cross structure and dies out to each side. This produces a sigmoidal fold in the area of intersection. Figure C shows the structure of Figure B as it would probably appear in the ceiling of a Gulf Coast salt mine--a minor change in the style of the fold, but no real change in the kinematics involved.

Figure D is an actual fold in the Weeks Mine taken from Kupfer (1962, Fig. 1, area F3) and inverted. This is the structure most similar to Figure C that could be located, and in looking for other folds of this type one is impressed by the marked difference between the model and the folds of the Weeks dome. In all of the folds illustrated by O'Driscoll (1962, Figs. 6, 7) two directions of movement are plainly visible even though one may dominate the other. At Weeks (Fig. 14) only one direction is present in any one area, but orientation changes from place to place. Figure 12 compares these two interpretations of Figure 11D. Bending (12B) appears to be the better explanation.

Also, there is some question whether two superimposed vertical shears, alone, can account for the drag folds, which are more tightly appressed than the sigmoidal bends. Thus the superposed slip mechanism proposed by O'Driscoll may explain some of the sigmoidal bends found within the salt, but it is certainly not a general explanation of drag folding.

Another explanation is possible. Figure 13 shows how Escher and Kuenan (1929) interpret folds to form as the salt migrates towards the center of a domal rise. These folds form as a result of the every-constricting circumference of the salt as it moves towards the center of diaprism. In the illustration the fold does not form until the bend upward occurs, but, in fact, the folds might also form during the horizontal migration. In either case the folding would take place at a relatively

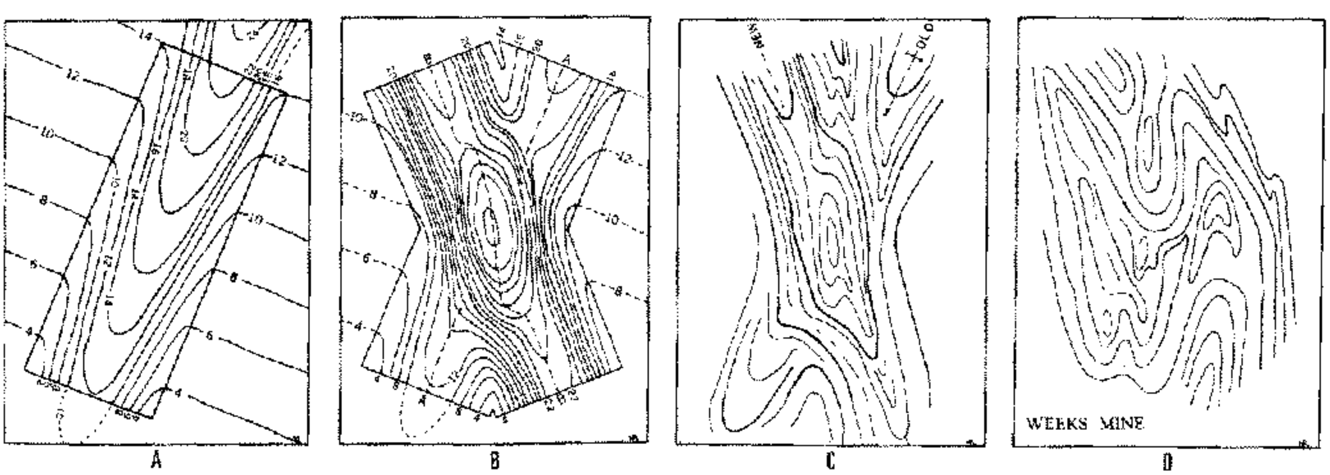


Figure 11. Superposed slip folding as a cause of pseudo-drag. A. A moderately SSW plunging anticline of the massif stage is shown by structure contours. B. The fold is reactivated by vertical slip centered along the new axis B-B; the result is a sigmoidal fold similar to drag. C. Fold B is redrawn in the style of the structures seen in salt mines. D. An actual fold observed in the Weeks Mine, with the unexposed areas drawn to conform with the style of C.

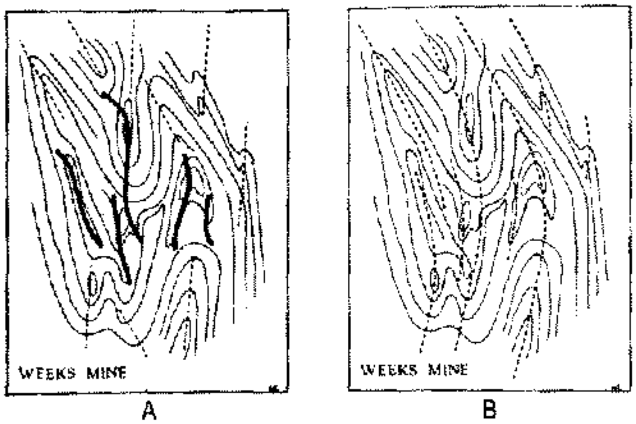


Figure 12. Figure 11D can be interpreted as slip cross-folding (A) or as a bend in the fold trend (B). The latter seems to fit the rest of the map.

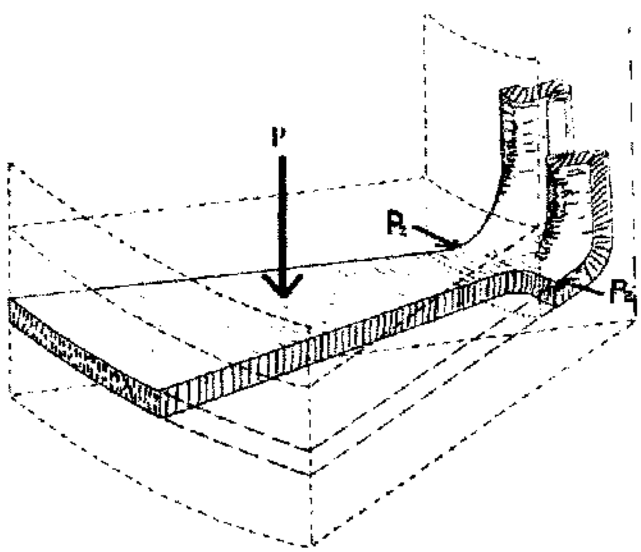


Figure 13. During horizontal movement of salt toward a center of diapirism, the salt layer is compressed laterally (arrows P_2), causing folds (After Escher and Kuenen, 1929, Fig. 2).

shallow depth (as in stages A, B, or C of Fig. 1). The pressures and temperatures would be such that the salt might well fold competently by flexure folding, and this would cause typical drag structures with horizontal axis.

Figure 14 is a portion of the geologic map of the Weeks mine (Kupfer, 1962, Fig. 1) with the drag structures emphasized. Note that in the central area the majority of the drag structures are

Figure 14. Drag folds in one small portion of the Weeks Mine. The clockwise z-drags are shown diagrammatically emphasized by heavy black lines and the counterclockwise s-drags by heavy dots. (Base map from Kupfer, 1962, Fig. 1).

clockwise, and on the side they are counterclockwise, though less dominantly so. Possibly this can be interpreted to mean that most of the area of this diagram was part of a single primary fold formed early in the diapiric process. The central area represents one limb imprinted with mostly clockwise drags; the few counterclockwise drags are on second-order folds. The side area with predominantly counterclockwise drag structures is the adjacent limb. If this is true, we have a mechanism by which we can differentiate early formed folds with their associated drag folds from later and younger flowage folds. An attempt to field check structures illustrated in Figure 14 was unsuccessful because the structures are now obscured by soot.

Still another approach to "drag folds" must be considered. In the paper by Evans and Linn oral communication, this symposium), folds of this type are found in relatively horizontal and undeformed beds. Likewise Anderson and Kirkland (1966, p. 251, 252) have described drag-like folds in the horizontally bedded evaporite beds of the Castile Formation of Texas. Interestingly, the Texas folds are confined to the crests of the regional warps, suggesting a connection with the salt seismograms. More work is warranted.

It is not clear if these early-formed folds represent the first phases of tectonism, or some late phase of depositional compaction or similar basinal process. In any case, these "drag folds" are also early, but unfortunately they may not be symmetrical about a high or fold (Kirkland, 1967, personal communication). In this case they may be difficult to tell from later formed drag folds which might also be random. The folds described by Evans and Linn, however, are remarkably symmetrical as drag folds should be.

The final method of producing drag folds is that described by Carey (1962, p. 128, Fig. 31) in which he proposes that the folds formed by flow lines (vertical in salt domes) diverging and stretching the beds and then converging again. When they converge, the beds do not rethicken but rather wrinkle. Small wrinkles should look like the "drag folds" in salt. I believe the Carey "paraboliodal" or better "slip-folding" undoubtedly accounts for many of the structures observed in Gulf Coast salt domes and goes a long way toward explaining many of the complexities observed (such as closures, Kupfer, 1962, p. 1461-1466). But it is difficult to imagine this effect, alone, producing the remarkable symmetry of the drag folds shown in Figure 10. Clearly, also, it cannot apply to the structures mentioned in the preceeding paragraph.

In fact, in the general sequence of diapiric events, the type of slip-folds described by Carey will be very late and very irregular (Carey also notes the process is transitional to flowage). Thus the "drag folds" that form by this method will be random in distribution and difficult to separate from those that formed by the method proposed for formation in the Castile Formation.

In summary, more study is needed of the "drag folds" that form by all four of the proposed methods, and then hopefully they can be distinguished by their physical characteristics.

CONCLUSIONS

The so-called "shear folds" are wrongly oriented and also kinematically wrong for "slip" parallel to axial planes; they should be interpreted as flowage folds. The true shear zones are transposition structures that can conceal complex earlier structures. Finally, some "drag folds" should be interpreted as early-formed structures, and as such may give us a means of differentiating the early stages of folding from the later stages.

Let us now apply these concepts to the Gulf Coast geosyncline. During the early phases of sedimentation salt diapirism was possibly by flexure-slip folding and/or shear folding. The domes of northern Louisiana may have experienced only these mechanisms. But as deposition continued, the southern salt was depressed to considerably greater depths and subjected to increased heat. Deep wells in coastal Louisiana confirm modest to high temperatures even for the sediments as shallow as 20,000 feet. Salt is very temperature sensitive and becomes rheologically "fluid" at even the modest temperatures. Thus the "high rise" domes of southern Louisiana that may be 8 to 10 miles above the basement, have been "fluidly" injected through great distances. The resulting complexities impressed on the earlier-formed, more simple structures will be of the complex flowage type. This flowage probably also occurred in pulses, each pulse in a different orientation. The result is the highly complex structures observed in the salt mines of the Five Island trend.

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