Structure of Salt in Gulf Coast Domes

by
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ABSTRACT

Of the six Gulf Coast salt domes with subsurface salt mines, five have been geologically mapped. Coarse-grained, colorless, nearly pure halite layers and darker halite layers with 1-10% anhydrite occur in folds with vertical axial planes and axes -- thus ceilings give transverse, and walls longitudinal sections. Balk observed that tight sinusoidal, chevron, or isoclinal folds predominate and most crystals are elongate vertically, suggesting vertical plastic flowage of originally bedded salt as found in the experiments of Escher and Kuenen. Loop-shaped closures in the ceilings are cross-sections of elongate tubes formed from vertical isoclinal folds with limbs squeezed in and sheared together.

Shear folds, faults, sedimentary inclusions, and pockets of oil, brine, and/or gas occur locally, but not in every mine. Present mine openings, all shallower than 1000 feet, exfoliate, spall, and walls flow inward -- but with decreased intensity with time. Continued mapping of minor folds, drag folds, graded bedding, and detailed stratigraphy promises not only theoretical, but practical results, such as location of mining hazards (water flow, blowouts), improved grade, and reduced breakage costs.

SALT MINES

Introduction

Salt domes occur in the Gulf Coast region of the United States in many sizes, shapes, depths, and areas (Murray, this volume). The structures associated with the salt domes have been used as commercial sources of gas, oil, sulfur, gypsum, anhydrite, and limestone. Large internal openings have been created in some domes by solution and used for the storage of petroleum, chemicals, and other products. The salt mass itself, called a stock, yields remarkably pure commercial salt (halite, rock salt or NaCl) either by solution mining, by underground mining, or (in the older days) indirectly by evaporation of associated surface waters.

Underground salt mining operations in the Gulf Coast occur only in Texas and Louisiana (Figure 1), but Mississippi will soon be added. There are six operating mines, but four others are in various stages of development. Table 1 gives the current status of the geological investigations in these mines and the sources of information on the six mines for which maps have been made. At the time of this symposium the only published maps were of Grand Saline and Jefferson Island domes, but by the time this is published the maps of Weeks and Winnfield domes will probably also be available.

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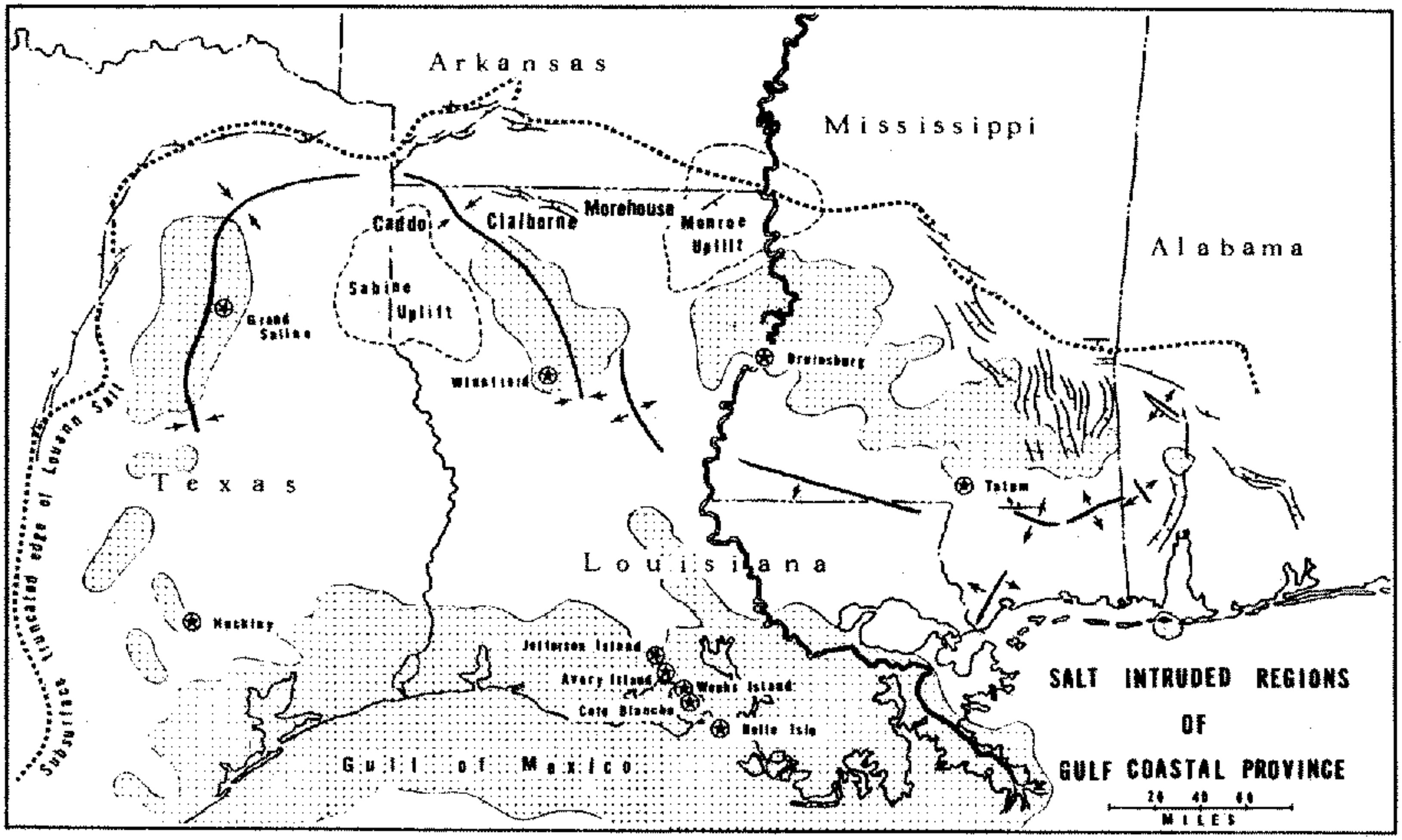

Figure 1. Index map showing areas of intrusive salt (stippled) and location of underground salt mines (star) of the Gulf Coast region of the United States. Map courtesy of Louisiana Geological Survey (Jux, 1961).

Table 1

STATUS OF GEOLOGIC MAPPING IN SUBSURFACE SALT MINES OF THE GULF COAST OF THE UNITED STATES

NAME AND DESCRIPTION	MAPPED BY	COMMENTS
Grand Saline Dome Kleer Mine Morton Salt Co. Van Zandt Co., Tex.	Robert Balk AAPG, 1949	Classic paper Remapped by Muehlberger, Tex. Bur. Ec. Geol., 1959 Int. Geol. Cong., 1960
Jefferson Island Dome Jefferson Mine Diamond Salt Co. Iberia Parish, La.	Robert Balk AAPG, 1953 (Asstd. by G.T. Duvall)	Similar to Grand Saline Needs mapping in newer workings
Winnfield Dome Carey Mine Carey Salt Co. Winn Parish, La.	Hoy, Foose, and O'Neill AAPG, 1962	Stanford Research Inst.
Weeks Island Dome Weeks Mine Morton Salt Co. Iberia Parish, La.	Donald Kupfer AAPG, 1962	Lower level mapped, upper level to be mapped
Avery Island Dome Avery Mine International Salt Co. Iberia Parish, La.	McMullen and Doxey (Unpublished)	Mapped summer 1961
Hockley Dome Hockley Mine United Salt Co. Harris Co., Tex.	Muehlberger and students (1961) (Unpublished)	Reconnaissance map, structure is very simple (personnal communication, 1962)
Cote Blanche Dome Carey-Monsanto St. Mary Parish, La.	Unmapped	Shaft sinking now in progress
Belle Isle Dome Cargillie Corp. St. Mary Parish, La.	Unmapped	Shaft sinking now in progress
Tatum Dome Lamar County, Miss.	?	Atomic Energy Commission
Bruinsburg International Salt Co. Claiborne Co., Miss.	Unmapped	Exploration drilling under lease and option

Mapping problems

Most of the information that goes on the geologic maps must be gleaned from the ceilings of the mines (Balk, 1947). The walls give supplementary data only. The workings range from 10 to 130 feet high, but most are between 60 and 100 feet high, so that ceilings, in general, are difficult to see. In some places the ceilings may be flooded with several thousand candlepower of light and be dazzling white, but in most places they are poorly lighted and moderately dusty, and some are very high and dismally dark. Thus in a single mine mapped by a single geologist, great variations exist in accuracy of work and resulting interpretations. I have had the experience of mapping rooms with a battery of flashlights and seeing nothing, only to come back later when the ceilings were well lighted and find them to be a maze of "structure." Likewise, when examining, at some later date, maps which were made under optimum lighting and visibility conditions, it is difficult to convince myself that the squiggles on the paper are not opium dreams. It seems impossible that I could have extracted such complicated structures from the ceilings which now appear blank and featureless under present conditions. Muehlberger (personal communication, 1962) says that the Hockley mine appears to be very simple, but that this may be a function of the extreme dust cover.

Mine openings[2]

The salt mines of the Gulf Coast are all room-and-pillar mines, but each has a distinct and unmistakable character. In Winnfield mine the giant rooms are worked from the base upward; at Weeks mine from the top downward. Jefferson mine has an upper level and a lower level, and then the two are joined by blasting out the floor of the upper level, leaving towering vaults of emptiness. The Avery mine has both large and small rooms, great irregularity in plan, and ceilings of several heights.

Production methods show equally great variability. Drilling, blasting, loading, and haulage techniques are a heterogeneous collection of the new and the old that have developed in each mine as a result of its own distinctive history. The results are a great diversity in mine openings, exposures, accessibility, and mapability.

Location within the stock

Salt stocks in the Gulf Coast are of several types (Murray, this symposium) but most of the early known ones are reasonably cylindrical masses of salt standing vertically. The stocks mined for salt are all of this type, and either reach the surface or very close to it. Each mine is located at the base of a shaft that penetrates through overlying alluvial and sedimentary materials and/or cap rock, and then for several hundred feet into the salt (Figure 2). The salt is very plastic and highly impervious, so that the mines are dry and the overlying layers of salt form a very effective seal against ground water. To preserve this seal, mining operations are always kept well inside the salt stock and a few hundred feet of unmined, undrilled, and completely untouched salt is left on all sides. The importance of this seal is best illustrated at Weeks Island, where Vermillion Bay laps on one edge of the dome and the workings are 700-800 feet below sea level. Water coming in through the slightest opening would quickly dissolve open a major conduit, tapping the Gulf of Mexico and, if reserves were necessary, the Atlantic Ocean. The disadvantage of all of this to the geologist is that he never sees the edges or tops of the salt stock or even any near approach to it.

Each mine, besides being 500-1000 feet down and several hundred feet in from the side, is commonly off center; generally to the southwest (cf. Figure by Walden and Jacoby, this symposium). Thus each gives a picture of only a small portion of the total stock; in horizontal cross-section never more than 15 per cent of the total. Vertically the exposures are distinctly insignificant, as the presumed base of the salt stocks are at least 20,000 feet and possibly as much as 60,000 feet down.

STRUCTURE OF THE SALT

Properties of salt

The *composition* of Gulf Coast salt is remarkably pure sodium chloride (halite) with traces of calcium sulfate (anhydrite) and very little else. Despite considerable variation from mine to mine and from place to place within the mines, all of the mines maintain a grade of better than 97% NaCl, and with just a little care in choosing the proper faces to mine, grade can be maintained above 99% NaCl at most of the mines.

[2]See also the paper by N. Nicola, this symposium page 390.

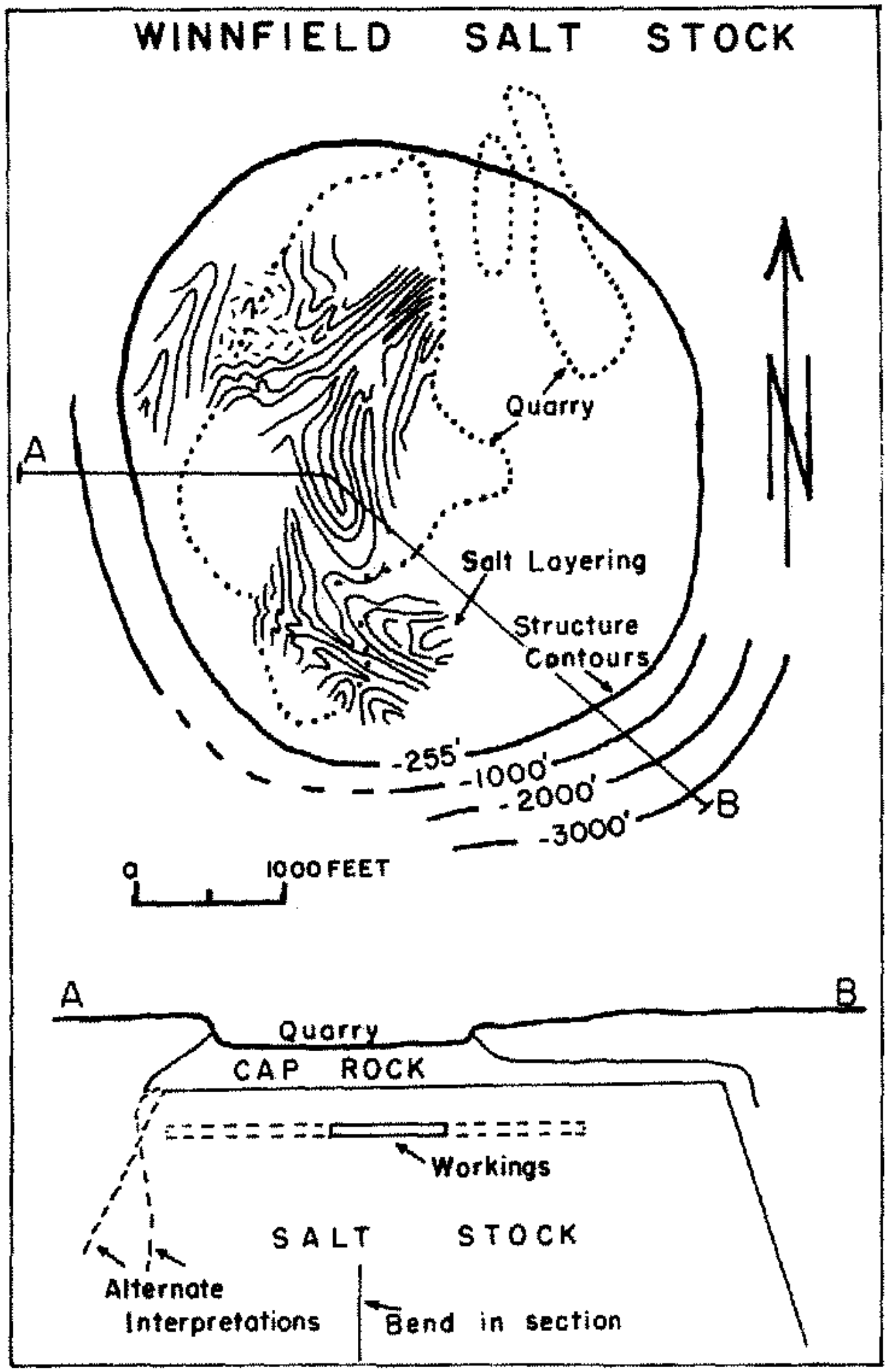

Figure 2. Plan and section of Winnfield Salt Stock showing structure contours on the top of the salt (adapted from Belchic, 1960).

Layering as exposed in the Carey Salt Mine is taken from Hoy, Foose, and O'Neill, 1962. The underground workings in this stock are better centered and cover a larger per cent of the cross-sectional area of the stock than in any other Gulf Coast mine. Since presentation of this paper, a more accurate map and section are available in Figures 2 and 3 of Hoy, Foose, and O'Neill (1962).

The anhydrite content of the salt domes has commonly been quoted at 5-10% (cf. Taylor, 1938, p. 37), but for the operating mines this seems high. High individual samples are sometimes quoted, like the "slab anhydrite" samples at Winnfield that run 80% anhydrite (Belchic, 1960, p. 29), but these are rare and probably are inclusions. Selected samples of dark layers in the salt running 5-30% anhydrite, are quoted (Taylor, 1938, Table II), but, except possibly at Winnfield, these also are exceptions. Many dark layers run only 2-5% anhydrite and dark layers form only 5% to 30% of the typical salt. There is a need for accurate figures, but a "guesstimate" would be that the average anhydrite content is well under 3%.

Taylor (1938, p. 47) says that 99% of the insoluble impurities in salt are anhydrite and that the other 1%, more or less in order of abundance, includes dolomite, calcite, pyrite, quartz, iron minerals, celestite, sulfur, and traces of other minerals. Dissolved impurities include less than 1% of ions like carbonate, sulfate, calcium, magnesium, and sometimes potassium. Bloomberg and Ladenburg (1959) reported Al, Fe, Mn, K, Si, and Sr in concentrations of about 100 parts per million from what is probably the Avery mine.

Layering (Figure 2) in the salt is its most distinctive physical feature in all of the mines. Most layers average 1-10 inches thick and consist of interbedded light and dark bands in shades of white, light gray, light tan, dark gray, and locally even black. Thinner layers are common, and some massive beds of white or dark salt are several feet thick. The darker layers are generally richer in anhydrite, but much, possibly most, of the darkness is due to internal reflection in colorless crystals; some is due to impurities. The layers are assumed to represent original bedding and, to the author's knowledge, this primary sedimentary origin has never been questioned. It fits all of the available evidence — stratigraphic, lithologic, paleontologic, chemical and tectonic. The layers have been folded, stretched, recrystallized, and deformed, but still preserve their sedimentary character. Except for attitude, the layers in salt of the Gulf Coast look similar to those in horizontally bedded salt deposits of other areas.

Another often-quoted statement (cf. Taylor, 1938, p. 20, 22, 29, etc.; Belchic, 1960, p. 37) is that these darker layers represent "year rings," the result of seasonal variations in temperature and evaporation rates. There is no proof or disproof of this.

Grain size is coarse, distinctly crystalline, with prominent cubic cleavage everywhere apparent. Most crystals range between 1/4-1/2 inch in diameter and are equant. The vertial elongation described later is only evident on close inspection. Fine- to very fine-grained salt is rare. Pods of extremely coarse-grained salt occur in all of the mines; and crystals, or more correctly, cleavage fragments 1 or 2 inches across can easily be procured if you go to the right places. According to Balk (1953, p. 2468) poikiloblasts (irregular areas of uniform orientation) of halite can reach 16 inches in size. In several of the mines the coarsest crystals look like coarse secondary recrystallizations, and the miners comment on their association with water seepages and with oil inclusions, but nowhere do they display vein-like walls or cross-cutting relations to the layering.

Because grain size is an important economic property of the salt, determining its classification and sales price, more study of this property needs to be made. Preliminary studies suggest that areal correlation is possible, but the controlling factor is not yet recognized. Also, grain size in the wall is only part of the story; natural cohesion, mining methods, and handling, help determine the grain size of the product that leaves the mine.

Folds

The layers in the salt all stand essentially vertical and are isoclinally folded around vertical axes. This means that the ceilings (and floors) of the salt working show transverse cross-sections of the folds and display all the twists, turns, and pattern complications of the fold (Figure 3). The vertical walls, like longitudinal sections, show little else than a series of parallel, vertical bands. If the walls are perpendicular to the strike of the layers, the bands are generally distinct, parallel, and vertical; if at an acute angle to the strike, the bands are abnormally wide, vague, and sometimes very sinuous (Figure 3A).

The *geologic map* of the layering (Balk, 1949, 1953; Hoy, et al., 1962; Kupfer, 1962) shows the pattern observed in the ceilings as if viewed from above. The same structure is

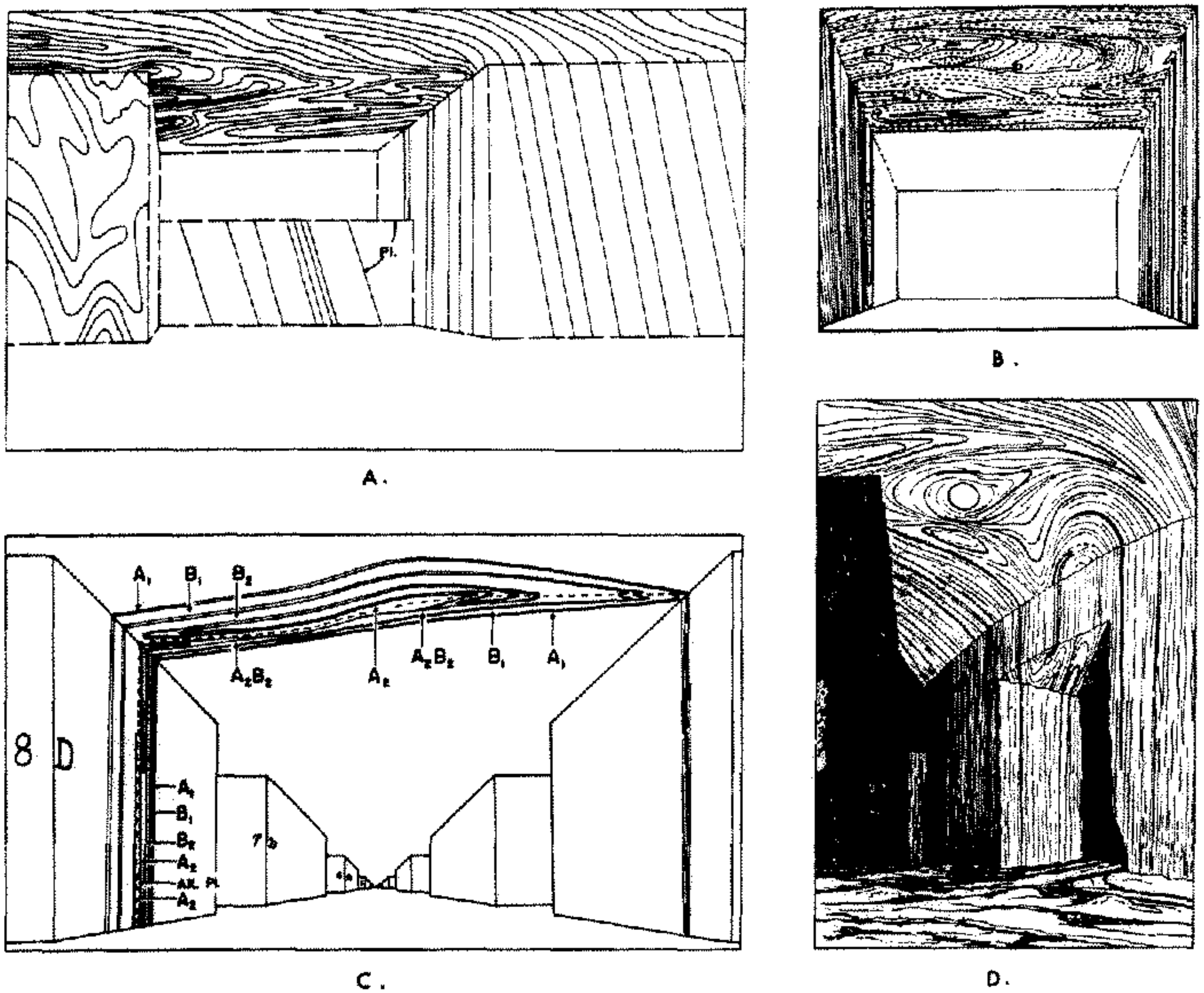

Figure 3. Block diagrams showing salt layering in walls and ceiling of Weeks and Jefferson mines.

A. Moderately complex fold pattern in ceiling of Weeks Mine (Room E 1-2). The approximate plunge of the folding is indicated by "Pl."; the true plunge, 81°, is unusually flat for this mine. Wierd apparent dips on left wall are caused by vertical section essentially parallel to axial plane of minor fold; apparent dip pseudo-structures of this type are not uncommon in the walls in certain parts of the mine. Near ceiling is 50 feet high and far one is 25 feet high (Kupfer, 1962).

B. Isoclinal folds that have been folded around new axial planes and into more open structures. Continued vertical movement has stretched the limbs together to form closed structures ("closures"). Weeks Mine, Room I 7-8; ceiling is 25 feet high.

C. Multiple folded fold in Room D 7-8 of Weeks Mine. First isoclinal folding placed beds A_1 and B_1 on one limb and A_2 and B_2 on the other. A second folding on the indicated axial plane caused the present repetition of beds and continued vertical uplift removed some beds by thinning and attenuation. The ceiling is 50 feet high, but distortion has been introduced in the drawing in order to show all the beds. Total width of zone involved is about 15 feet. Note room and pillar method of mining with corridors 50 to 60 feet wide and pillars 100 feet on a side. (Kupfer, 1962.)

D. Sketch by Balk, 1953, of "closures" in isoclinal folds of the Jefferson Mine, Room F 5. Ceiling is 100 feet high. Note the vertical axes of the folds.

theoretically exposed in the floor, but due to debris accumulations on the floor and the markings left by the undercutting machine, they cannot be seen there. In one special room in the Weeks mine, the tool room (Figure 4), banding could be observed in the floor as well as the ceiling. Every minor wiggle and crenulation in the ceiling was present 13 feet vertically below in the floor in the same orientation. The actual position had been shifted about 4-8 inches due to plunge.

Axial planes of the folds are essentially vertical. As the folds are isoclinal, the axial planes are parallel to the limbs of the folds and therefore with most of the observed layering. Thus, with only minor modifications, the map of the layering can be transformed into a map showing the traces of the axial planes (Figure 5; also Muehlberger, 1960, Figure 2). Axial planes are broadly curving in some areas and tightly folded in others. Kupfer (1962, p. 1460-61 and Figures 3-6) has described isoclinally folded axial planes in the Weeks mine as commonplace. (See Figures 3B, 3C, and 4 of the present paper.) Balk (1949, p. 1803-4) observed that the axial planes become less folded and the layers straight and parallel near the edges of the salt stock, and the layering (and axial planes) conform closely in attitude to the external margin of the salt stock. This parallelism seems to hold true at Grand Saline, Jefferson, Avery, and Weeks. Hoy, Foose, and O'Neill (1962, p. 1454) have applied this technique to interpret an overhang at Winnfield (Figure 2). Thus, although the outer margin of the stocks cannot be observed directly, their shape and attitude can

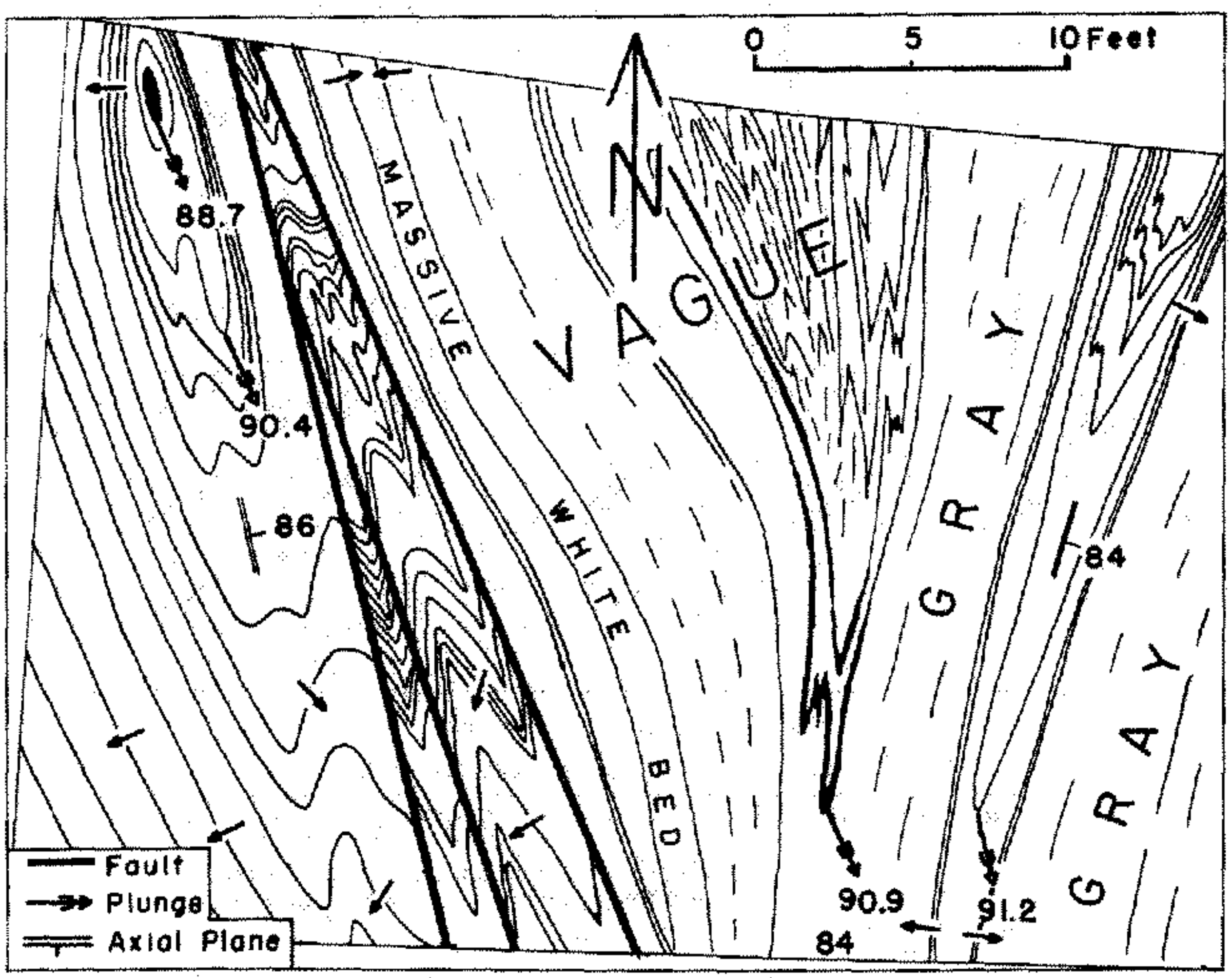

Figure 4. Detailed map of layering in 13 foot high ceiling of tool room (Room G.7-8), Weeks Mine. Arrows indicate direction of probable younger beds as suggested by "graded bedding." Identically shaped structures are locally visible in floor and give accurate plunge of folds. Closure in northwest corner of room has identical dimensions in floor (i.e., it is tubular). In area marked "vague," layering is difficult to see, but the rendition is as accurate as possible (not diagrammatic).

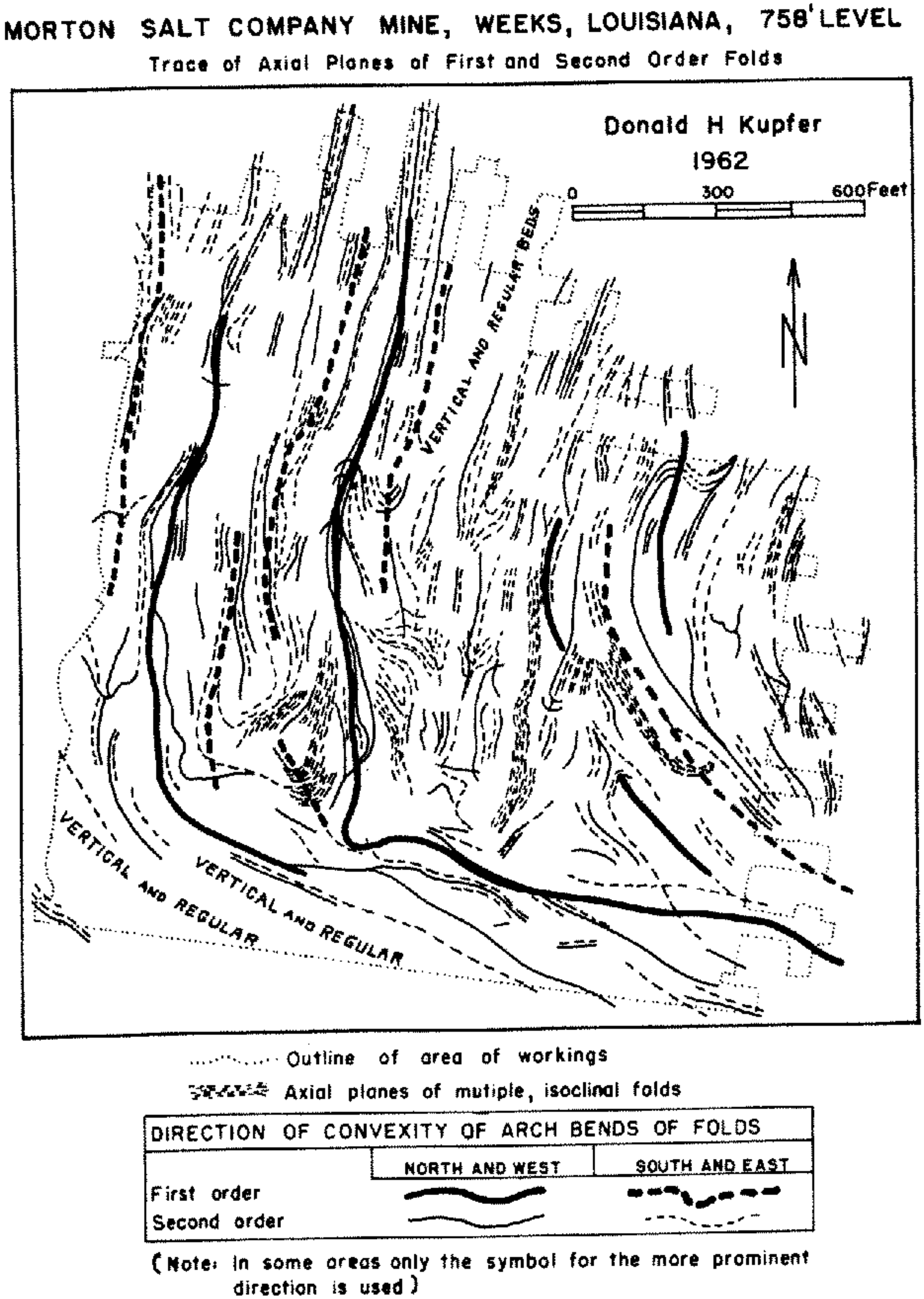

Figure 5. Trace of axial planes of first and second order folds, Morton Salt Company Mine, Weeks, Louisiana, 758' level.

be inferred from the mapping. It may be that locally this involves a bit of circular reasoning, but at the moment it seems like a reasonable assumption.

Axes of folds are also nearly vertical. The majority of the observations show an axial plunge of 80°-90°, and a little less at Grand Saline and Winnfield domes. This consistent verticallity of the axes is probably one of the major clues to the origin of the domes. Many more readings are needed, but measurable axes are difficult to locate in the mines. As a substitute, reasonably accurate attitudes can be calculated by finding the line of intersection of two limbs of the fold.

The *attitude* of all structural elements in the salt is steep. Most significant is the 80°-90° plunge of the axes just described. Layers also dip very steeply. Table 2 lists ranges and averages (estimated, not calculated) of the data on available maps. Strike and dip of axial planes are less frequently noted than strike and dip of layering, but in most cases the two can be considered as similar. The attitude of axial planes should show less variation and fewer extreme values than layering, because in a general way the attitude of an axial plane is the average value for the two limbs. The mean standard deviation for averages is always less than for original data.

Table 2

TYPICAL ATTITUDES OF FEATURES IN THE SALT AT FIVE MINES

SALT DOME	DIP OF LAYERING	PLUNGE OF LINEATIONS	PLUNGE OF FOLDS
Grand Saline	51°-90°, Avg=80°	53°-90°, Avg=75°	78°-80° (two)
Jefferson	75°-90°, Avg=90°	70°-90°, Avg=88°	
Avery	66°-87°, Avg=77°		
Weeks	78°-90°, Avg=86°	(Ax. pl. of folds dip 80°-90°, Avg=85°)	79°-90°, Avg=83°
Winnfield	50°-90°, Avg=75°	55°-87°, Avg=75°	

Closed structures, called "closures," appear on the geological maps as small areas completely bounded by a single band or by a group of concentric bands. They occur in a variety of shapes (Figure 6) and sizes. The commonest shapes are elliptical, but many are distinctly elongate and more like the cross-section of a banana. They range in size from so small as to be barely discernible, to one hundred or more feet in the long dimension. Many are 5-50 feet in maximum dimension. Balk recognized closed structures at Grand Saline dome, Texas, (1949, p. 1804-5) and described them as elongate pipe-like bodies with subvertical axes drawn out by the flowage of the salt until they were hundreds or even thousands of feet long. Kupfer (1962, p. 1465) was impressed by the point or "tail" present on most of them (Figure 6D) and emphasized the effects of lateral squeezing on the limbs of vertical isoclinal folds. In other words the limbs of isoclinal folds are squeezed together until some beds are eliminated (Figure 6C). This origin fits very well for the closed structures observed at Weeks. At Grand Saline dome a different origin seems likely. Muehlberger (1959, p. 10 and 1960, p. 31) describes the closures as the highest part of anticlines or the trough of synclines. By this he means that the folds started out as domes (doubly-plunging anticlines) or basins (doubly-plunging synclines) that became very greatly elongated vertically by flowage. The closure he pictures (Figure 6A, present paper) strongly substantiates his view, as the drag folding is that of a doubly-plunging fold, not a fold of the origin described by Kupfer. On the other hand, his statement seems to imply that he thinks the true crest or trough of these folds is nearby. If true, this would require flat dips, or at least considerably flatter dips than any observed in any of the mines to date (Table 2). Closed structures seem to be cross-sections of essentially vertical tubes, not open cones. Crests of any original domes have been long since removed by erosion, and troughs of basins probably lie

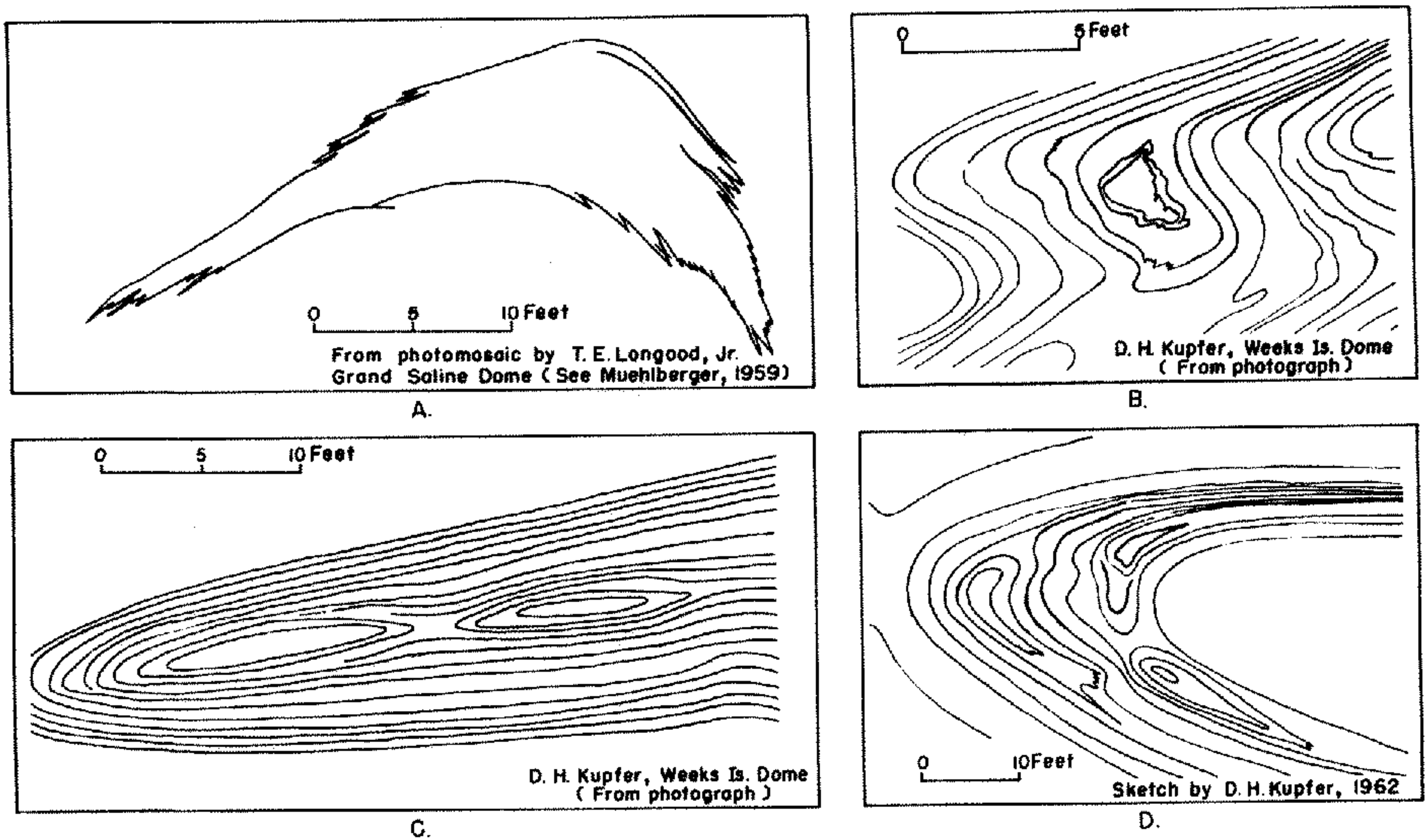

Figure 6. Comparison of closed structures or "closures" of various types. Note the shear folds in the upper left diagram and their "drag fold" character, characteristic of the Grand Saline Mine. This indicates a domal or basin type of structure in the initial stages of movement. The other three diagrams are from the Weeks dome and appear to represent the results of refolded folds and attenuation.

thousands of feet lower (and probably quite unrecognizable). In the "tool room" at the Weeks mine (Figure 4), an elliptical closure 8 × 18 inches in horizontal cross section showed no change in size or shape between the ceiling and the floor, 13 feet apart. It plunges 88.7° S. 21 E.

Faults

In his pioneer study of Grand Saline, Balk (1949) failed to find any evidence of faulting, and you can almost read his disappointment between the lines. However, since that time considerable evidence of faulting has been found, but none of it very startling.

The fractures radiating out from blast holes very commonly show striations, due to the differential movement of the salt during blasting, so artificial faults can be formed. Fault-like structures are common (cf. Kupfer, 1962, Figure 1, north wall of room B-5). Balk found minor evidence of faulting at Jefferson (1953, p. 2471). McMullen and Doxey (1961) found a bedding plane fault with horizontal striations traceable for about 150 feet. A trio of minor faults are shown in the "tool room" at Weeks (Figure 4). All of these are essentially bedding-slip faults.

Escher and Kuenen (1929) made a series of experiments that duplicated salt structures rather well (see below). In experiments involving homogeneous materials (differentially colored for identification) fold structures did not develop, but in layers of differing physical properties they did. They concluded that some slipping of one bed past another was essential to the formation of the typical folds found in salt stocks. Whether one wishes to call this deformation flexure folding, flow folding, or actual faulting is a matter of definition. In the case of the isoclinal folds squeezed on the flanks to produce a closed structure (Figure 6), the beds are disrupted and this might be called "faulting" by many, possibly most definitions. The displacements shown in Figure 4 are clearly faults.

In a salt stock every transition can be found from folding to faulting, but the faults are all of the bedding-slip type. Displacements, so far, have been indeterminate. Stratigraphic separation appears to be negligible on most, although slip might be quite large.

Large, distinctive, and sharply transverse faults appear to be absent in most salt stocks. Probably salt, under most conditions, is too plastic to fault in this manner. Movements close to the surface might cause cross-cutting faults, but this zone is not open to observation at present. Gypsum at the surface does fault.

Other structures

Elongation of crystals of halite and anhydrite were studied by Balk (1949, p. 1806-11; 1953, p. 2465-68). The overall shape of halite crystals is slightly elongate in the vertical dimension, parallel to fold axes. The ratio of the vertical to the horizontal axis is commonly about 1.5, but ratios of up to 6.0 are shown. The less abundant anhydrite crystals are needle-like in shape and show a very strong preferred vertical orientation. Studies of internal crystal orientation by Clabaugh (1962) also show that a distinct vertical orientation is present and that gliding has probably taken place on the cube and dodecahedral faces. (See also Schwerdtner, this symposium.)

Shear structures, probably the result of shear folding (Billings, 1954, p. 91-92), are abundant at Grand Saline dome (Balk, 1949, p. 1805-6; see also photographs in Muehlberger, 1959), and at Winnfield (Hoy, et al., 1962, Figure 9), but are not common features at the other mapped mines. At Weeks, for example, they occur only at the arch bends of a few of the folds.

Drag folds (Billings, 1954, p. 78-83) or folds that look very similar to drag folds have been recognized in the isoclinally folded beds at Weeks mine (Kupfer, 1962, p. 1461). They are pairs of folds, a syncline and an anticline, that occur close together in an otherwise uniform set of homoclinal layers (note limbs of Figure 6A). In one part of the mine all of the drag folds may be right-handed or clockwise (as viewed from above), and in an adjacent part they may be all left-handed or counterclockwise. This suggests that the axial plane of a larger fold is present between the two areas. In other areas the two types occur close together and intermixed, suggesting several smaller folds rather than one large one -- these latter areas are much more difficult to interpret unless visibility is at an optimum. Drag folds cannot be used to tell synclines from anticlines (Billings, 1954, p. 82) because the axes of the folds are vertical.

"Graded beds" as interpreted in the salt layers, are distinctive dark beds that have one sharp contact and one gradational contact. The sharp contact is assumed to be the lower contact and to represent a sudden precipitation of anhydrite that occurs when the anhydrite content of the mother liquor builds up to a saturated or even supersaturated value. The gradational contact is the upper contact and reflects the gradual diminution of anhydrite precipitation with time. These "graded beds" may allow the differentiation of anticlines (older beds to the center) from synclines (younger beds to the center), even though the axes are vertical. "Graded beds" are most easily recognized in very thick and dark beds that are uncommon in most of the mines. Grading can also be found in many of the more typical layers, but a brief examination of the horizontally bedded salt deposits of the Morton Salt Company's mine near Cleveland, Ohio, showed some "graded beds" that appeared inverted. A careful investigation of other horizontally bedded salt deposits will have to be made before the reliability of "graded beds" of this type is established. I understand that it has been used with success in Germany.

Negative features

Balk (1949, p. 1811) listed a group of "negative features" whose absence in the Grand Saline dome he felt was significant in the genesis of the salt stock. As these have been quoted at various times (cf. Muehlberger, 1960, p. 32) some discussion of them seems worthwhile. The negative feature is given in italics and my comments which follow refer to information from all the mines, not just Grand Saline.

1. Not a single fracture is exposed in the mine. Natural fractures are understood, as blasting causes numerous fractures to open up. Also, exfoliation fractures develop as the rooms remain open, and corners become quite rounded with time. Manfred Burchard (1961) made a study of the artificially developed fractures and proved that although their orientation was due primarily to the direction of mining (Figure 7), bedding exercised a strong secondary control. Because blasting fractures and exfoliation fractures are so numerous, natural fractures are hard to recognize. The presence of faults and of areas of dripping suggests, however, that fractures probably do occur in several of the mines.

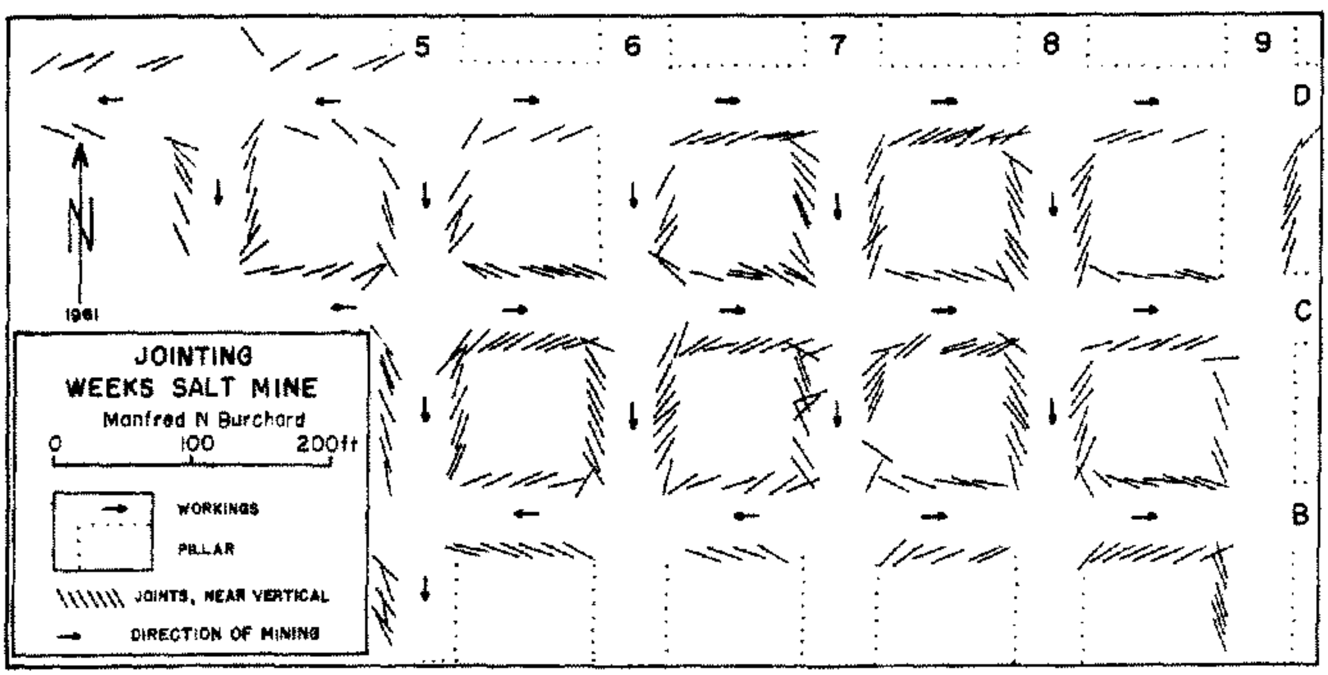

Figure 7. Pattern of blast and exfoliation joints in a portion of the Weeks Mine as mapped by Manfred N. Burchard (1961). The direction of mining is the primary control of strike direction, but Burchard's report proves that the direction of layering exerted a secondary control.

2. Nowhere is salt displaced by a fault. See section on faulting.

3. Salt layers are nowhere crossed by others and there are no unconformable contacts between layers. The first part of this feature is generally interpreted to mean that the layers were originally sedimentary beds, which is still considered correct. "Figure eights" occur, however, and could be misinterpreted as crossings (Figure 6C). Unconformities, if present, would be difficult to recognize and prove. Unconformity-like areas have been recognized in all of the mines, but generally are interpreted as the results of tectonic thinning or as faulting.

4. No brine or gas is encountered, except as microscopic interpositions in halite crystals. This may still hold for Grand Saline and the lower workings at Weeks, but brine and oily seeps have been found in the other mines. Gas at Winnfield is common and has caused "blow outs," at least one of which was quite damaging (Belchic, 1960, p. 38-39). These blow outs are reported to be near the lateral edges of the dome.

5. No inclusions of foreign rock have been found in this (Grand Saline) mine. This may be true at Grand Saline, but inclusions of sandstone, clay, and/or anhydrite can be found locally at the other mines. The largest reported so far is a sandstone layer about one foot thick at Avery Island mine that measures 80 or more feet in vertical dimension and strikes east-west for 75 feet (Rogers, 1918, p. 470). The clastic inclusions are highly altered and impregnated by salt.

6. Although no systematic search has been made for minerals other than halite and anhydrite, it is believed that additional minerals, such as dolomite or sulfides, are very rare. See section on composition of the salt.

Muehlberger (1959, p. 10 and 1960, p. 32) has added a seventh negative feature:

7. Porosity and permeability are effectively nil. The engineering studies of Reynolds and Gloyna (1960) have effectively proved this for most salt, but care should be exercised where this factor is economically or radioactively important. The seeps reported at several mines suggest local exceptions, probably due to faulting and/or jointing. Also, the anhydrite bands at the Winnfield dome are reported to be porous and permeable (Belchic, 1960, p. 38-39).

Thus these negative features, although possibly true locally, should not be given significance when considering the origin of all the salt stocks.

MAPPING TECHNIQUES

Previous mapping of the internal structure of Gulf Coast salt has consisted primarily of determining attitude, position, and patterns of the layering in the ceilings of six mines (Table 1) and the representation of this data on plan-view maps. This work has also included the determination of the attitude of the axial planes and axes of the folds, and some attempt has also been made to locate the position of the mine workings with respect to the overall shape and position of the salt stock (Figure 2).

The second type of investigation has been fabric studies of crystal orientation, including both external shapes and internal structure. A very close parallelism has been found between crystal orientation and fold axes, both being essentially vertical.

Studies related to the general salt stock problem include pollen studies (Jux, 1961), isotope studies (Feely and Kulp, 1957), cap rock origin (McLeod, 1960), salt origin (Andrews, 1960), and gypsum intrusions (Wall, Murray and Diaz, 1961; see also Figure 9 of that paper).

Current investigations include a continuation of the above studies and experimentation with new methods. Many people are currently working on salt structure and the other properties of salt in salt domes. The investigations that the author happens to know about are first, the several projects by personnel connected with the salt companies; these are geological, chemical, exploratory, and mechanical (engineering). Second, investigations by university staffs, of which those at Louisiana State University and the University of Texas are currently well-known. These include geologic mapping, structural, fabric, crystallographic, pollen, radiation, and various engineering studies. Finally, investigations are being carried out in behalf of the Atomic Energy Commission; many of these latter are classified, and data about projects, methods, and results are difficult to obtain.

The following published papers give some hint of the direction and variety of present endeavors. In this symposium are the papers by Walden and Jacoby on exploration drilling, and Scharon on electric resistivity studies. Clabaugh (1962) of the University of Texas is studying crystallographic orientation and fabric. Jux (1961), while at Louisiana State University, discovered spores and pollen in the salt stocks of five of the geologically mapped domes and tentatively placed the age of the salt as late Triassic to early Jurassic. The engineering studies of Reynolds and Gloyna (1960) show rock salt to be effectively impermeable and to have some tendency to flow into artificial openings for a short period of time after opening. About 95% of the total deformation occurs within five years.

All of the above papers are concerned with those salt domes that have openings which man can enter. No attempt has been made to cover brining and storage operations (Part III of this symposium), and the extensive data accumulated through boreholes and geophysical operations of the petroleum industry.

As for my own investigations, I have been asked to give this talk at a time when I have just completed preliminary geologic studies of the type described above under "Previous Mapping." Structural features like drag folds and graded bedding have been little more than recognized; their usefulness is yet to be proved. I am now starting research on several new techniques, some of which are mentioned in the next section. My search of the literature is also quite incomplete, even for just the Gulf Coast.

The future will bring many new techniques and revisions of the old ones. Among the types of investigations that should be done are stratigraphic, structural, chemical, and position studies. The technique of plotting of macrofabrics on a stereographic or equal area net can now be done on computers (Robinson, Robinson, and Garland, 1962). Sufficient data is now available to justify this approach. This, combined with drag fold studies and careful inspection of axial plane patterns, should help to identify the structural units involved in individual masses of salt moving independently, as described later, and probably in other ways.

Another approach possible at Weeks Island, Jefferson Island, and possibly to some extent at Grand Saline, is to map the third dimension. Mapping on levels above or below levels already mapped with help to determine how much vertical continuity is present.

The one direction of study that seems to have the most to offer, however, is the stratigraphic or formational approach to mapping. At Weeks it has been possible to differentiate the salt into different "formations," and work is now in progress to map these "formations." Units are differentiated according to color, thickness, and proportion of the various layers involved.

Chemical studies have been made on a general basis, but the overall grade of the active mines is not published information, even though it is probably well known. Detailed information is needed on the chemical changes in individual units. McMullen and Doxey (1961) have investigated the chemical changes, inch by inch, in dark and light layers, and more of this type of work is needed. What are the areal variations within an individual salt stock? and between different stocks?

Position studies, the effect of horizontal position and of depth, are essentially untouched. Structural simplicity and parallelism at the edges of the salt stock has been suggested, but needs confirmation. Does depth effect grade, creep, jointing, shear folds, drag folds, faulting, and/or inclusions? The new mines opening up will be deeper and may give some information, but other aids, particularly those of the petroleum geologist, will have to be used (cf. Scharon, this symposium).

How does the type of salt dome effect structure? For example, do the deep salt "ridges" like those under domes of south Louisiana and Tehuantepec, Mexico (Murray, this symposium) have the same vertical fold axes and vertical crystal elongation, or are the layers flatter and more like typical anticlines? This can be checked easily by examination of oil well cores. Oil companies have made extensive geophysical studies of the size and shape of Gulf Coast salt masses, but little attempt has been made to correlate these data with the internal studies. Much petroleum investigation is keyed to deeper studies, but the gravity, magnetic, and seismic studies can be made on shallower salt features. Ground water studies, too, can yield much useful information.

GENESIS

Origin of the salt stocks

The current ideas about the origin of Gulf Coast salt domes are summarized by G.E. Murray in the companion paper to this one (this symposium). The salient points germane to the present problem can be summarized as follows. In Triassic-Jurassic times salt formed in a large basin, several small ones, or in contemporaneous grabens. The salt was buried under later sediments and depressed by geosynclinal sinking. With increasing depth the consolidating sediments increased in density as the salt remained almost unchanged, with the result that the sediments became heavier than the plastic and mobile salt. At some point in depth, for each local area, the inequilibrium became so great that the internal strength of the sediments was exceeded and the salt began to rise and accumulate in ridges or highs and then to push through the downsinking sediments. Whether the salt movement with respect to some more stable datum such as sea level was up, down, or oscillated irregularly, is not vital to the present problem. What is important is that the salt moved horizontally within its beds and radially inward toward a center, and then upward with respect to the surrounding sediments. The center may have been circular or elliptical, resulting in a rising cylindrical salt stock; or it may have been more linear and a salt ridge or anticline formed. If the latter is the case, more cylindrical stocks must have formed later.

As the downsinking sediments carried the base of the salt to greater depths, erosion and/or solution removed large amounts of the salt from the top of the column so that other salt continued to rise through the column to replace it. The importance of this fact is that the salt now at the top of the column was not there originally. The structures related to the crest of the "dome" have been removed. Even though the present salt mines are essentially at the top of the salt stocks, the structures exposed within them were formed at considerable depth and were modified as the salt rose and the surrounding sediments sank.

Escher-Kuenen experiments

The relationship between the rising salt stock just described and the isoclinally folded salt layers described earlier is clearly demonstrated by experiments performed about twenty years before Balk's classic studies at Grand Saline dome. Escher and Kuenen (1929) made "cakes" of paraffin and clay and deformed them in a piston that compressed the cakes everywhere except at the center. The center was allowed to rise in a cylinder. The artificial "salt stocks" that resulted (Figure 8) had deformed beds with vertical fold axes very similar to those in the natural salt stocks, except that they were far less contorted. Figure 9, a pie-shaped wedge from the deformed cake, illustrates how the vertically direct pressure P_1 forced the "salt" radially inward. The decreasing circumference inward caused a compressive stress P_2 that folded the beds around a vertical axis as they changed direction of motion from inward to upward. Three significant points to note here are; first, the synclines are bent inward and the anticlines outward. Second, in these experiments the external (younger) beds are less deformed than the beds of intermediate position, a relationship already described for the mapped domes. Third, the folding of the central (oldest) beds may be the simplest (Figure 8, C-D) or the most complex (A-B). The simple "core" structure at the center may be the explanation of the giant closed structure near the center of the Winnfield dome (Figure 2).

Unit cylinders of movement

Balk (1949, p. 1815) 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 the "Each irregularity of the roof is likely to give rise to fields of greater or lesser shearing stresses, and thus should generate velocity

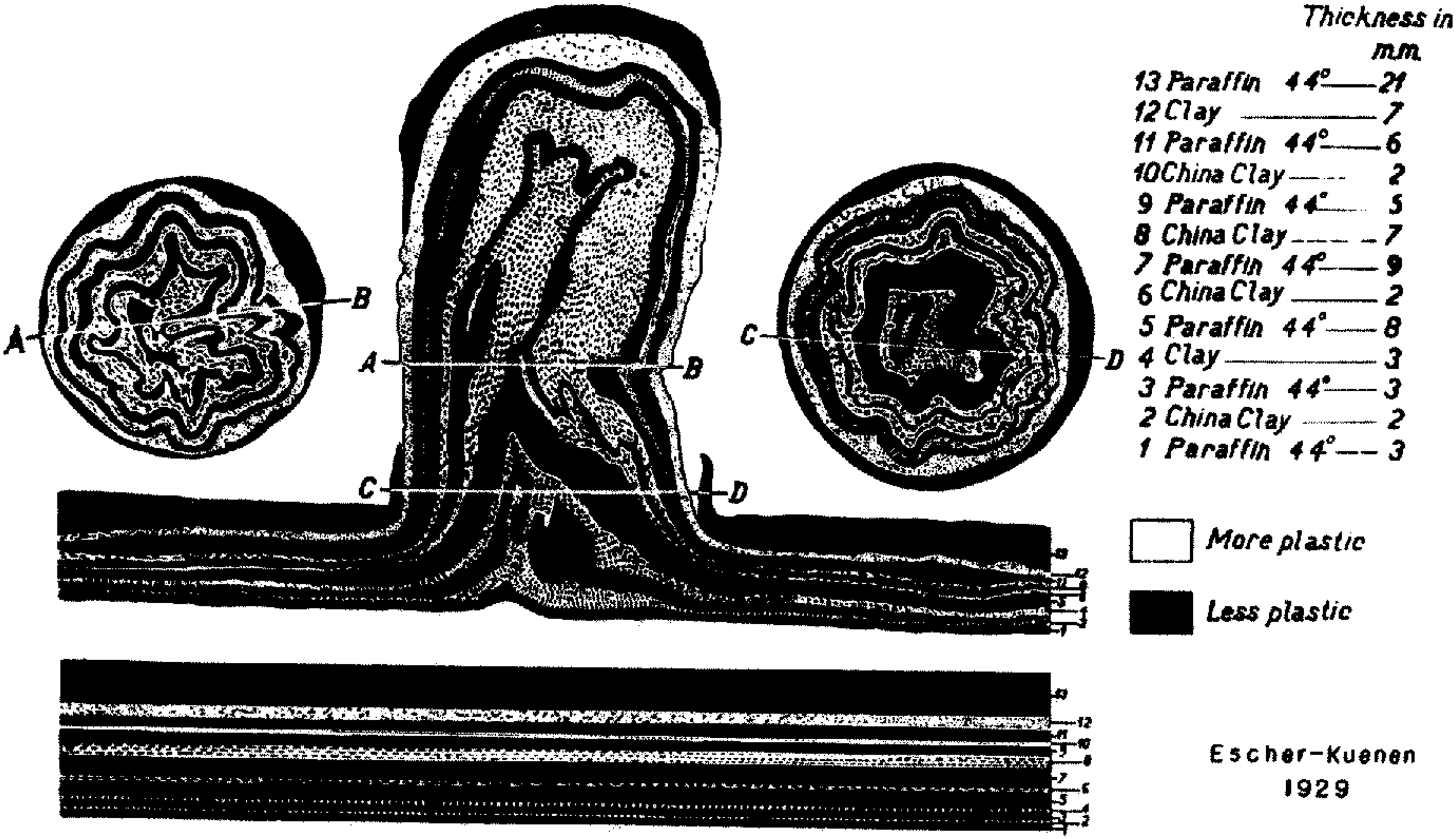

Figure 8. One of the numerous laboratory experiments by Escher and Kuenen (Figure 8, 1929) that duplicates the salt dome structures. Note that the central structure can be simple at one elevation and complex at another. Maximum deformation does not occur at the center or periphery of the stock but in the intermediate areas.

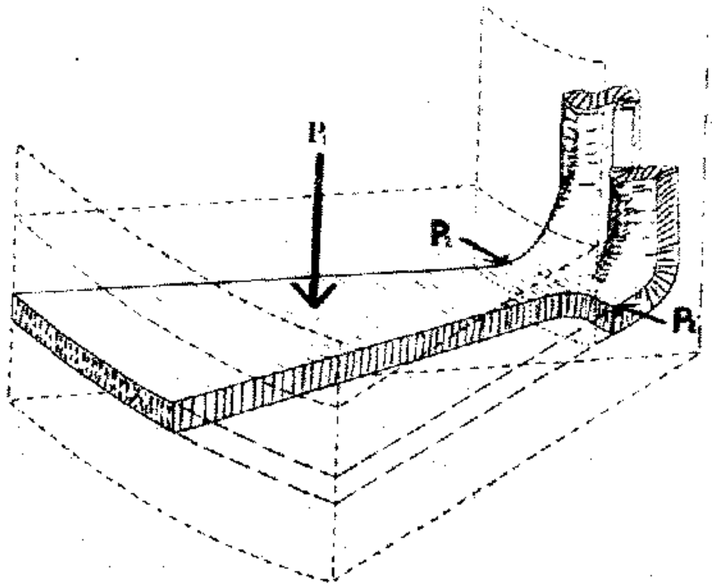

Figure 9. Diagram by Escher and Kuenen (Figure 2, 1929) to indicate how a vertically directed pressure (gravity) causes a horizontally directed compression as beds flow centripetally with ever decreasing circumferences. As the layers bend and flow upward, vertical isoclinal folds result.

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, ..." As the salt moved into these fractures as "spines," the northeastern part of the mine moved up farther than the southwestern (old) part.

It seems that it might be very reasonable to interpret the area of mining at Avery Island as a single spine of movement. The mine has zones of weeping, inclusions, and oil stains not only on the southeastern side, -- presumably near the southern edge of the stock; but also on the northern and northwestern side, beyond which lies the presumed center of the dome. (See figure by Walden and Jacoby, this symposium.) This northern boundary is relatively straight (McMullen and Doxey, 1961) and has been interpreted as a fault (Walden and Jacoby, this symposium). An alternate interpretation to faulting might be that this is the zone of major movement separating the salt spine of the mine area from the rest of the stock. The inclusions and impurities dragged into this area make it a zone of unusual physical properties (more joints, seeps, etc.). The distinction between this and the "fault" of Walden and Jacoby is more a matter of difference in terminology than difference in interpretation.

Large unit cylinders of movement or "spines" cannot be considered as proved, however, even though movements in salt spines were suggested even before Balk's mapping (Balk, 1953, p. 2470) and have been since that time (Atwater and Forman, 1959, 2605-6). At one of the best of these, Jefferson Island, Balk states: "....several authors have suggested ... that the spine has advanced somewhat more than the rest of the dome. As Plate 1 (Balk's map) shows, the continuous, uninterrupted system of strike lines does not support this view." Later (p. 2471) Balk suggests that the "spine" is due to differential leaching of the salt and not differential movement.[3]

[3]The reader of Muehlberger's description (1960, p. 32) might incorrectly conclude that Balk favored the unit cylinder or "spine" hypothesis for Jefferson Dome.

Small unit cylinders of minor differential movement are another possibility. Balk (1953, p. 2469-70) in discussing areas of massive salt described them as "a slender spindle, anywhere from a few to several hundred feet across, with a vertical axis probably thousands of feet long," and inclosing "twisted, short lenses of darker, layered salt." The author is not sure whether Balk considered these as separate cylinders of movement, or rather just cylinders like those related to closed structures that move along with the adjacent salt.

Thus the major problem of salt movement is still largely unsolved. Did a single salt stock move essentially as a unit mass despite much internal differential movement, or did it move in units? If as units, how big? How far apart in time? And how far did one unit move ahead or behind another?

ECONOMIC GEOLOGY

The economic advantages of the several surveys of the internal structure of salt have yet to be shown by practical application, but the preliminary work is now done and this step should come shortly. These studies can be used for prediction, engineering, and utilization.

Prediction of the edge of a dome has already been suggested as tenable, and even its attitude may be determined. Prediction of where to find better grade salt is possible and, with stratigraphic studies, can be greatly improved. Prediction of other factors, such as when and where to expect water problems, are much more difficult with the present meager knowledge, but may not be too far away.

Mining engineering studies can be made within the present framework of knowledge. Determination of physical properties of salt is well underway. Soon it should be possible to predict how large an opening can safely be left open at each depth, how much exfoliation can be expected, what types of joints will occur in each area, and how much expansion room will be required in doors, beams, and other constructions to keep them from being crushed by inward flowing salt. Mine foremen are aware that differences exist in the ease of breaking the salt in different areas and in different directions. These differences are predictable. They also affect the size and degree to which crystals break up, and therefore their grade and price. Internal structure studies can reduce breakage costs and/or increase the grade of the salt produced.

Utilization of the existing mine openings for scientific and storage purposes has already started. Many of the studies currently being made are related to potential uses of salt mines as bomb shelters, fallout shelters, anti-radiation storage facilities, atomic waste disposal, and sites for atomic explosions. They are also being considered for routine storage of grains, machine tools, perishables, and other items. Salt mines are ideal for certain types of scientific experiments that require constant temperature, constant humidity, low radiation, low seismic background, or other special properties.

As knowledge of the internal structure of salt stocks increase, so will the industrial uses of this knowledge. Industrial uses will, in turn, generate more complete and comprehensive investigations. These studies will give practical facts about the physical properties of salt, its behavior, distribution, and structure, and will aid in the more theoretical problems of how salt got where it is, when, and why.

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N. Nicola, Dome mining: floor vs. roof extraction
L. Scharon, Electrical resistivity surveys in salt mines
W. Schwerdtner, Petrofabric analyses of some anhydrite rocks
Wm. Walden, and C.H. Jacoby, Exploration by horizontal drilling at Avery Island, La.