Problems Associated with Anomalous Zones in Louisiana Salt Stocks, USA

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ABSTRACT

Salt typical of the Gulf Coast is medium-grained, vertically-bedded, and occurs in spines surrounded by inclusion-bearing anomalous salt that generates pressure-pocket blowouts, slabbing, leaks and other mining problems. Inclusions of sediments, petroleum, brine, and various gases are of primary and secondary origin. The anomalous zones are characterized by extensive shearing and tectonic lensing of the sediments; by folded, black, impure salt beds that localize both exfoliation joints and ceiling slabbing, and by coarse-crystalline or poikiloblastic salt in moisture zones. Three types of brine leaks are: short-duration leaks that soon dry up, catastrophic leaks, and an intermediate type of long duration. They occur either with the sediment, or as much as 100 meters out from it. Gas, particularly in explosive pockets up to 100 meters in height, may extend 200 meters out; and these pressure pockets tend to align along a single, black-salt horizon. Prior to explosion the gas is in tiny intragranular bubbles in the salt and along intergranular fractures; release is caused by mining. Most mining problems are concentrated in edge-of-salt shear zones and boundary shear zones within the salt. Zone size and shape are controlled by depth and time of formation. If these zones cannot be avoided during mining, they should be penetrated by small openings, and only after exploratory drilling has determined the nature of the anomaly.

INTRODUCTION

This paper is based on the author's experiences during the past 15 years while studying the salt structures in the Five Island salt domes of the Louisiana Gulf Coast (Fig. 1). Although called "islands," these are just domed Pleistocene sediments that rise above the surrounding marsh. Salt mines are in operation in each of these domes. The only other salt mines in the Gulf Coast are the Winnfield mine of north Louisiana, which was closed in 1965 due to flooding, and two mines in eastern Texas (Grand Saline and Hockley).

During the past dozen or so years a number of engineering and mining problems have developed in the Louisiana mines that appear to be related. The problems are pressure pockets, leaks, ceiling slabbing, and the occurrence of inclusions of foreign material. Each problem will be described separately, along with its individual characteristics and typical occurrence; then interrelationships and origin will be considered.

Literature on the origin, occurrence, and mining of Gulf Coast salt is extensive and will not be reviewed here. Text citations, in general, will give only the most comprehensive or latest reference.

The best introduction to Gulf Coast geology is the book by Murray (1961). Gulf Coast salt domes are covered in

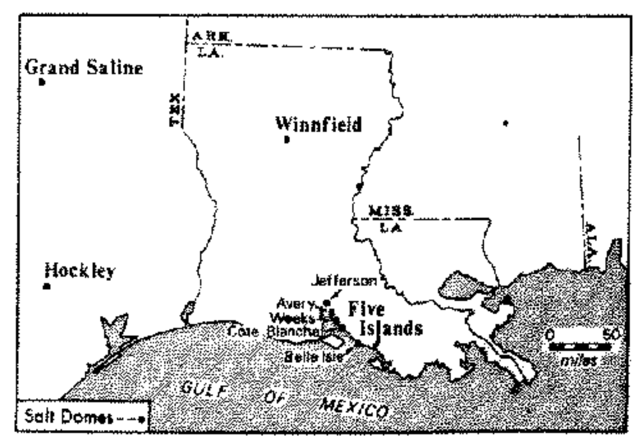

Figure 1. Index map of Gulf Coast salt mines, including the Winnfield mine, which is now flooded.

Chapter V, which quotes liberally from the literature and contains many tables and illustrations of individual domes. The book on salt domes by Halbouty (1967) is readable, comprehensive (for the Gulf Coast), and related to petroleum geology. For a bibliography of the Gulf Coast consult (Braunstein, 1970 and 1976). For a bibliography on diapirism, including salt, see Braunstein and O'Brien (1968).

Layering. The layering in Gulf Coast salt reflects primarily the original bedding formed at the time of deposition of the Louann Salt of Jurassic age. Unlike most other salt deposits, the salt in southern Louisiana is remarkably pure (98% NaCl) and devoid of any other salts except anhydrite. If large amounts of other sediments were originally interbedded with the salt, which now seems unlikely, they were left behind during the diapiric intrusion of the salt through 17 kilometers of overlying sediments. The zones described in this report are called anomalous because they deviate markedly from pure salt.

The individual layers in normal salt range from one centimeter to several meters in thickness and range from massive to well-bedded. The *massive* salt is generally just off-white to light gray in color, transparent, and even-grained (½–1 cm in diameter). If vague layering is present, it consists of white to milky salt alternating with zones that are more transparent and thus darker (due to internal reflection). The layers are commonly 10 to 50 centimeters thick. Every gradation exists from this massive salt to *well-bedded* salt with alternating layers of "black" and white salt that are generally thin. The dark beds are thinner (2–10 cm) than the more abundant opaque, white beds (5–20 cm).

Inclusions within the salt are very rare, but some of the darker layers contain flecks of anhydrite, shale, silica, or carbonate.

Spines. The concept that salt domes consist of several "spines" of salt that move upward independently and at different rates, is long-standing (Balk, 1953, p. 2470) and of considerable significance in explaining the zones of anomalous salt described in this report. Originally the spines were thought to be small and numerous. The horizontal cross-section of a single stock might consist of tens or even hundreds of spines. The work of Atwater and Forman (1959) emphasized larger spines that are few in number, possibly only two or three to a stock. This report will emphasize the larger spines (see also Kupfer, 1976), which is not to say that the smaller spines do not exist—they are common. The differential movement between smaller spines, however, is small and less important in controlling the overall structure of the salt mass.

As visualized for this report, salt stocks are thought to move upward in sausage-like protrusions of salt (Fig. 2) that are less than one kilometer in diameter. Each spine moves upward, through downbuilding geosynclinal sediments, and stabilizes as the top intrudes into less-dense, near-surface sediments. Differential stress at depth is still unrelieved and continues to exert an upward (buoyant) pressure on the total salt column. Because sediment deposition and downbuilding continue, the old salt spine is pushed down deeper and stress builds up again. It is now easier for a new spine to form at depth and move up along beside the old spine (Fig. 2) than it is to reactivate the old and now cold spine of salt. Probably undercompacted and geopressured sediments at depth strongly influence this motion, provide the locus of the new pathway, and possibly even some of the motive power. The new spine continues past the old spine, rising into the newly deposited sediments.

In the spine-building process the contact between salt and sediment is a shear zone (fault zone) that consists of both sheared salt and sheared sediment. As the new spine passes along side of the old spine, the shear zone is incorporated into the middle of the salt stock between the two spines ("boundary shear zone" of Kupfer, 1976). Much of this report will focus on these internal-type boundary shear zones that form the most common type of anomalous zone—herein referred to as CAZ or central anomalous zone. The edge shear zones are observed much less commonly, because any near approach to the edge of a salt stock is avoided during mining. Those penetrated will be referred to as EAZ or edge anomalous zone.

Anomalous zones. The easily observed and mappable anomalous features within a salt stock are the inclusions of solids, liquids, and gases. These may be primary, that is deposited along with the salt during Jurassic time, or they may be secondary and introduced during the movement of the salt. Both origins probably occurred. Most of the solid inclusions are probably secondary and were introduced along boundary shear zones. The origin of gases is complex and will be considered in detail later. Liquids, particularly

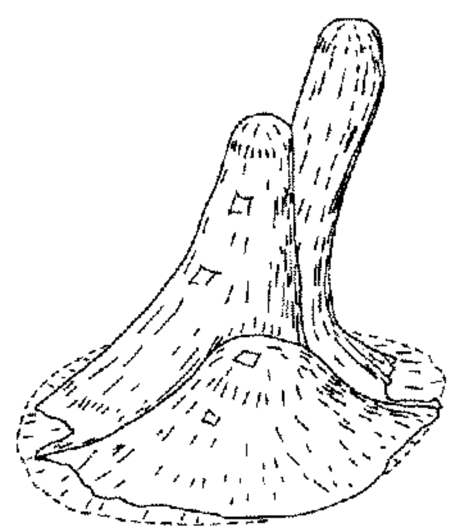

Figure 2. Three spines of salt that rose out of an older pillow of salt. The spine in the foreground is the oldest and still pillow-like. The background spine with the pronounced overhang is the youngest (highly diagrammatic).

petroleum, are probably secondary. Brines are both primary and secondary, and some may represent connections to outside water sources. If an outside water source is tapped during mining, the results are generally immediate and disasterous flooding due to the high solubility of salt even in rather saline water. All five Louisiana mines adjoin the Gulf of Mexico and operate at levels well below sea level (150–450 m below S.L.).

Some other features occur that are commonly associated with inclusions but are not always confined to their vicinity. These include pressure pockets or "blowouts," zones of giant salt crystals, poikilitic salt, jointed salt, and zones of abnormally black salt. Shearing is almost universal in the salt (Kupfer, 1976) and is characteristic of its movement (Muehlberger and Clabaugh, 1968), but wide zones of very disruptive shearing are less commonplace, and therefore are anomalous. One engineering problem that appears to intensify near anomalous zones is ceiling slabbing (the ceiling of a mine is also called the roof, as in "roof bolts," or the "back"—the latter term will not be used). Large slabs of salt, 10 to 150 centimeters thick, break away from horizontal exfoliation joints that form in the ceiling as the salt expands into the void created by mining.

Some features, such as poikiloblastic texture and shearing, may be found over large areas of highly irregular shape, and thus are not necessarily "anomalous"; under these circumstances the other types of anomalous features are less likely to be found.

The cause-and-effect relationship among these various abnormal features is difficult to assess. If any one type of anomaly is found in a particular part of a mine, several of the other types are likely to be found also, and all are generally aligned along a sinuous zone which is traceable for hundreds of meters. Many anomalous zones contain nearly all of these features, but each type of anomaly can also occur alone. Distribution of the features within the zone is discontinuous and in places appears to be almost random, but certain characteristics of distribution can be observed that apply to the majority of occurrences.

The geometry of the anomalous zone is also highly variable, changing somewhat with the type of anomaly; most are tabular and vertical. A typical anomalous zone may be from 3 to 100 meters wide and of very long horizontal extent, generally traceable completely across the mined area, and probably continuing across the complete salt stock. The vertical dimension is less well known, but is probably extensive.

INCLUSIONS

Inclusions described in this report are solids, liquids, and gases. The solids are clastic, non-salt materials that occur in significant amounts, such as sand, clay, and carbonate. Liquids can be of any type, but most are either brines or petroleum products. Gases detected during mining are either those confined under pressure (thus their escape is noted), or those with an odor. Their composition is poorly known, but includes hydrocarbons, hydrogen sulfide, and carbon dioxide. Inclusions can be of primary or secondary origin.

Origin. Primary inclusions are those in which the parent materials were incorporated into the salt at the time of evaporation and deposition of the salt. This would include the more conventional clastic materials deposited as interbeds in the salt sequence, as well as solid materials brought into the basin by dust and sand storms, flash floods, or turbidite flows. Primary brines of various compositions, and gases from organic decomposition could also be trapped in the highly impermeable salt. The size and shape of the cavities would be strongly changed by movement and recrystallization, generally reduced in size and elongated, but the materials would not escape unless within a few hundred meters of a salt border.

Secondary inclusions were introduced into the salt after it formed, probably during the movement process. Typical would be the sediments of the external shear zone plastered on the side of the salt stock and later incorporated into it when a new spine of salt is introduced along side. This would include not only clastic materials such as sand and shale, but organic matter and any liquids or gases that penetrated either the sediments or the salt (water, petroleum, natural gas). Spines of movement are not a necessary prerequisite; shallow salt is brittle and the sheath of salt around a shallow salt stock is known to be highly jointed, pockmarked by differential solution, and otherwise full of openings and pockets that can be filled with solids, liquids, or gases. Mining experience has shown that these foreign materials extend at least 100 meters into the salt from all sides. Similar materials included into the edge of the salt in the past would be caught up by later movements and infolded into the salt.

The origin of any inclusion can be primary or secondary, and it is very difficult to differentiate the two without expensive or time-consuming tests. Materials related to saline deposition, such as disseminated clay particles, anhydrite, calcium chloride brines, and carbon dioxide gas are assumed to be of primary origin if other evidence is lacking. Petroleum is assumed to be secondary because saline conditions are not favorable to oil generation and petroleum of coastal Louisiana is considered to be of middle Tertiary age. Firm evidence for the origin of the inclusions is lacking and exceptions to the above assumptions will be noted later. The only dated inclusion (Oligo-Miocene age) in any of the Five-Island domes is the sediment in the Belle Isle salt stock, and even this origin is the subject of debate (Wilson, 1977; Kupfer, 1977).

The salt of Gulf Coast salt domes is generally assumed to be the Jurassic Louann Salt, but this is far from confirmed (cf Wilson, 1977; Kupfer, 1977). The Louann Salt does not crop out at the surface and is only known from a few oil-well borings (Andrews, 1960), thus the character of the original bedding is poorly known. The salt may have contained significant amounts of sediment interbedded with it on the edges of the original salt basin, and possibly in the highest and lowest horizons of salt at the center of the basin, but if so, this has not generally been found. Even if originally present, this salt-clastic intermixture would not be likely to be found in the Five-Island salt diapirs because the impure salt would be far less mobile than pure salt. Thus, sediments are unlikely to have survived the 17-kilometer journey from the base of the Gulf Coast geosyncline, where the Louann horizon is today, to the present position of the salt near the surface.

Sediment. The principal solid material incorporated in salt, other than anhydrite, is sediment such as sand, clay, and carbonate. Most of the sediment occurs in irregular masses, and some as rounded balls. The balls are generally 1 to 3 centimeters in diameter, but they range from tiny globules to boulders. The irregular masses are somewhat pod-like and lenticular, with the larger pods being up to 30 centimeters thick and over 2 meters long. Sediment inclusions are generally aligned along bedding in the salt, but many variations exist, from those that appear to follow a single bed to completely brecciated and jumbled zones that locally cross-cut bedding. The salt associated with these sediment inclusions commonly also contains clay and sand disseminated through it.

The sediment zone is, in fact, predominantly salt. Clastic material is generally less than one percent of the total volume. Even a hand specimen selected for its high clastic content will be 10 to 60 percent salt.

On a larger scale, the sediment zones are lenticular and discontinuous in plan view; individual beds start and stop erratically. What happens in the vertical direction is less well known but probably similar. Sediment zones can be traced sinuously through the mine along a definite trend, generally from one border to the other. Minor zones of sediment may branch away from the main zone only to terminate within a few hundred meters. Most of the zones are probably boundary shear zones, but some may be primary. Sediment zones are from 10 to 400 meters thick, and most extend completely through the salt stock, separating it into spines. The wide sediment zones are highly sheared and also contain gas, petroleum, and brine. Thick layers of dark, impure, black salt are also common.

The salt in a sediment zone is non-commercial, and furthermore, mining within the zone can be dangerous. Thus, generally, mining stops at the edge of the sediment zone, but in a few places, the zones have been penetrated. The zones are easy to recognize, difficult to mine, and are associated with many mining problems. Sediment is, thus, the typical anomalous material.

Liquids. Two types of liquids occur in salt: brines and petroleum liquids. Small amounts of brine are ubiquitous in all the mines. Some "drips" appear to be condensations of moisture from the air. Tiny openings that drip brine for days or weeks after mining penetrates the area are common in certain mines and in some parts of all the mines. In general these openings dry up eventually, showing that they are not connected to fluid systems external to the salt. The interconnecting openings are very tiny and disseminated widely through the salt; they are not "cavities" in the normal sense of the word, as large natural openings are not found during mining. Porous salt (with tiny interconnected cavities) occurs in the brine areas. Brine drips are not yet adequately mapped, but they appear to follow bedding in a general way. Most brines are NaCl.

The origin of the brines is only just beginning to be investigated. Most brines are thought to be made from fresh water that found its way into the salt and then became saturated by dissolution. A few brines of composition other than saturated NaCl have been found and are assumed to be primary. For example, a heavy flow of calcium chloride ($CaCl_2$) brine at Jefferson Island mine lasted for a week. Brines at Cote Blanche Island mine that may be of primary origin contain calcium and magnesium and very little sodium. The origin of a brine could be checked by chemistry; primary brines might be of diverse composition particularly containing potash and magnesium, whereas secondary brines would be essentially pure NaCl with some $CaSO_4$.

Petroleum liquids are the commonest liquid inclusions other than brines. Oil occurs in colors from brown to blue to black, and in viscosities that range from that of about #1-distillate to light grease. Petroleum drips occur in many parts of the operating mines, but particularly near the anomalous zones of impure salt. Oil leaks appear to "dry up" with time, but unlike brine drips, this may take a few years rather than a few months; the difference is probably related to the greater viscosity. In theory it would be possible that one of these leaks taps an outside oil pool, but no evidence has yet been found that suggests this has happened.

Petroleum could be primary or secondary to the salt. Organic chemists can "type" the various organic compounds in petroleum oils and gases, and thus are able to tell if similar types are found in adjacent sediments. Thus the age and source of the petroleum products in salt could be determined.

Because liquids migrate short distances through salt after they have been incorporated into it, their presence gives advance warning of the approach to an anomalous zone. The presence of brine or petroleum seeping from the ceilings, floors, or mining face commonly precedes the penetration of a sediment zone by as much as 50 to 100 meters. Current practice at some mines is to stop advancing these faces, at least temporarily, and give them a chance to "leak" and possibly stabilize. If mining can be conveniently continued around these zones, they are left unmined permanently.

Gases. Both primary and secondary gases occur in salt and are of several types, but almost nothing is known about their occurrence, properties, or composition. If gas is observed, mine personnel make a routine check for methane using one of the standard simple detection devices. Commonly, trace amounts of methane are detected if the device is held close enough to the emitting face. Most gases are detected by their odor; hydrogen sulfide and certain organic compounds are common. Other gases are combustible. Carbon dioxide at Winnfield mine is described in the section on Pressure Pockets.

Most of the gas flow ceases within a few days or a month or so. Like the other impurities in salt, the gas pockets are more abundant near the boundary shear zones or other zones of impure salt.

Gases can, in theory, penetrate the highly impervious salt to an even greater extent than liquids, and thus should give indication of the approach to an anomalous zone at an even greater distance. But gases are also universally present, and thus interpretation of the meaning of the presence of a gas is subjective. In addition, most gases are colorless and odorless, and thus difficult to detect without special devices or techniques. A few, like hydrogen sulfide, can be detected by the human nose in trace amounts, and the smell of hydrogen sulfide (and similar gaseous odors) does commonly occur as mining approaches an anomalous zone. The odor of gas, like the presence of dripping liquids, can be used with judgment to indicate approach to a dangerous anomalous zone.

BRINE PROBLEMS

The hydrologic stability of salt mines is a critical problem because of the high solubility of salt in water. A tiny opening, even one of capillary size, can grow rapidly into a large open conduit if undersaturated brines are present. Any open connection to the external ground-water supply, no matter how tiny, will produce disastrous flooding of the mine. With this concept in mind, water drippings in Louisiana salt mines can be classified into three types. The first type, short-duration drips, are of limited volume, area, and duration. The second type, increasing-volume leaks, are leaks that grow rapidly in size and volume, and consequently in seriousness. The third type, which are less well understood, are the sporadic-continuing leaks of a character intermediate between the other two.

Short-duration drips. Short-duration drips occur in all five of the Louisiana salt mines, although in variable degrees. Typically, a "wet area" is limited to about 1000 square meters, but some are quite small and a few much larger. Soon after a working is opened up brine begins to drip from the ceiling, and for a few days to a month the volume may be quite significant. Shortly, however, the flow diminishes and stalactites form on the ceilings as evaporation exceeds the rate of flow. Generally, flow has completely ceased after six months.

Few analyses have been made of these brines, but most are composed largely of NaCl, as suggested by the stalactites. These, and the drip areas, are always stained rust-brown suggesting some iron content. The larger and more persistent drips are commonly within a hundred meters of an anomalous zone. In general, the salt in these drip areas is darker than average and more coarsely crystalline. Sand, clay, petroleum, and other impurities in the salt are not uncommon.

These short-duration leaks probably represent porous salt with bubbles of brine in the salt that are interconnected by capillary passageways and open fractures around the individual salt crystals. Some vertically-elongate, tubular openings may also have been generated during the upward flow of the salt. All the capillary openings and tubes were probably filled with brine and thus remained open despite movement of the salt and recrystallization. During the processes of mining the salt, exfoliation joints as described later, open and extend outward into the salt for 20 or more meters, thus connecting previously isolated brine passageways.

Some of the brine may be of primary origin, but most of it is probably water introduced into the salt during piercement and intrusion that has become saturated with NaCl. It is then sealed in by recrystallization and cannot escape. The fact that the brine takes days, weeks, or months to stop draining suggests that the capillaries are small, but rather extensive. The fact that most leaks eventually stop suggests that each set of passageways is isolated from other sets by the imperviousness of the salt.

Increasing-volume leaks. Some drips tap an external source of water and the leaks then grow in size very rapidly. They may start like short-duration drips, but if the passageways tap fresh, or moderately saline water, then the water dissolves the capillary openings into larger conduits and flow increases.

The Carey salt mine at Winnfield, in north Louisiana, had two of these leaks, both near the shaft, which probably acted as a passageway to near-surface ground-water. The first, in 1937, was in the shaft and was controlled by extensive grouting (Belchic, 1960, p. 35). The second leak, in 1965, flooded the mine and the mine was abandoned. The second leak was probably initiated by collapse of the caprock onto the salt (Elliott, 1970); openings under the caprock had been artifically enlarged by the activities of man (quarrying, pumping, storage reservoirs). The stresses created by the collapse of the caprock cracked the salt in the vicinity of the shaft, and in six hours a leak 60 meters from the shaft (in the mine level) quickly enlarged and flooded the mine (11:30 P.M. to 6:00 A.M., Nov. 17–18, 1965). It should be noted that a small seepage had developed in the same area (20 m from the shaft) a month earlier and was nearly under control at the time of the flooding (Personal communication, from C.M. Thorton, May, 1967).

Increasing-volume leaks flooded the Avery Island mine and the Belle Isle mine (both of the Five Island group), in the early days of mining when both mines were very shallow. In recent years, increasing-volume leaks have occurred at both Jefferson Island mine and Avery Island mine, but were controlled. At Belle Isle mine a new air shaft was drilled, and about a year later (possibly about the time the ground became completely "unthawed" after being artificially frozen) a shaft-leak developed. It increased in volume rapidly and swallowed up the shaft in a matter of minutes. Surprisingly, the sand above the salt flowed-in and plugged the hole; the mine only partially filled with water.

Sporadic-continuing leaks. The third type of leak has characteristics of the other two and has been found in two mines. Like the short-duration drips, they start very slowly at first, but gradually increase in volume until brine flow reaches up to several liters per minute. Then flow appears to stabilize at this rate and the increase is much less drastic, but continuing. At this stage the flow has always been stopped by grouting, so further development is speculative, but the area in which the leak occurs continues to be active. In a few months another leak develops and the sequence is repeated. These leaks have continued for several years, and thus must have access to external water sources. Yet the leaks do not increase rapidly in volume as would be expected if they were connected to fresh water.

The unusual nature of these sporadic-continuing leaks suggests that their origin is different from that of the other two types. It is suggested that shale (from the shale sheath surrounding the salt or in a boundary shear zone) is acting as a membrane. Fresh water from outside of the salt stock is transmitted slowly through the membrane and thence along a fracture zone and into the mine workings. The flow is not able to increase rapidly in volume because of the membrane separating the external water source from the mine proper. Once through the membrane, however, the fresh water (salt water does not pass through a membrane) can dissolve salt, open up existing passageways, and create new cavities—solution continues until the brine is saturated. The primary danger is that one of these cavities may get too large and collapse, flooding the mine. To date this has not occurred.

Recrystallization. Large crystals of recrystallized salt have long been recognized by salt miners as having a close association with salt brine, drips, and leaks. The horizontally bedded salt of the north-central United States, like domal salt, is uniformly medium grained (5–15 mm). Vertical veins that cross-cut the salt consist of coarse crystals of clear salt (30–200 mm diam) that have formed by solution and redeposition. Coarse-grained salt (20–100 mm) in Gulf Coast stocks is not generally in veins, but in irregular masses associated with brine inclusions. For example, at the Weeks Island mine the coarse-grained salt with associated minor drips, petroleum seeps, and even occasional gas pockets forms a wide zone about 50 meters out from the first occurrences of sediment, as mining approaches the central anomalous zone (CAZ).

Poikiloblastic salt is also a coarse-grained salt which breaks up into large single-crystal cleavage fragments (10–50 mm). The salt consists of randomly oriented grains of salt (about 10–20 mm) dispersed through a groundmass of more uniformly oriented salt. Thus, a hand specimen of the salt appears, at first glance, as relatively normal, but of a somewhat coarser grain size. When the salt is observed in place in the mine, however, large areas (up to several meters in diameter) appear to reflect as if from a single, spatter-marked cleavage face. The whole mass of salt has recrystallized in place since the salt stopped moving. Thus, it is a metamorphic texture (poikiloblastic). If the salt were to start moving again the poikiloblastic texture would be disrupted and the salt would revert to a normal medium-grained texture. This assumption appears to be confirmed by the preference of salt for medium grain size, no matter whether it is horizontally bedded and undeformed, or domal salt that has moved many kilometers. Coarse-grained salt and poikiloblastic salt are thus abnormal, and indicate stability since recrystallization.

Poikiloblastic salt is commonly associated with brine. Much of the salt just described at the Weeks Island mine (second paragraph above) is poikiloblastic as well as coarse-grained. Most poikiloblastic salt at the Avery and Belle Isle mines is associated with zones of abnormal brine content. The exception is the Cote Blanche mine, which is one of the drier of the salt mines, yet it contains more poikiloblastic salt than any of the other mines. The abundance of poikiloblastic salt at the Cote Blanche mine may indicate that the salt in this mine has some moisture content—but not enough to drip; or that the salt has been stabilized for a long time—long enough for significant recrystallization to have taken place. More must be known about poikiloblastic texture, however, before either or both of these conclusions can be justified. Poikiloblastic salt may have several origins.

SHEARING AND FRACTURES

Shearing. Shearing in salt is universal and has been described by many authors. All salt in Gulf Coast domes has flowed through thousands of meters by what is essentially a shearing motion (Muehlberger and Clabaugh, 1968). Movements can range from intragranular gliding, through granular rolling, to development of minor shear zones. Striated fault surfaces in salt are uncommon, but present.

Intense, pervasive shearing can be mapped over large areas of salt. In these areas the salt has a pseudo-simple structure of parallel beds of nearly constant strike. Examination of the bedding, however, shows it to be highly sheared and deformed. Layers are attenuated and even lenticular. It is difficult to follow a single bed for more than a few meters before it either thickens markedly or disappears completely. In the latter case it may reappear again at the same horizon in another few meters. Folds have been sheared out until they are unrecognizable. Some large areas of shearing of this type appear to be unrelated to other anomalous features, for example, one area of 75,000 m^2 in the east central part of the Belle Isle mine is sheared until bedding has almost disappeared: it appears almost structureless unless examined in detail. Its origin is not yet completely understood, and is beyond the purview of the present paper.

Similar shear zones occur at the outer boundaries of the EAZ and CAZ. Salt as much as 200 meters or more away from the outer edge of the salt stock is pervasively sheared, and thus commonly gives ample warning of the approach of mining to the edge. Thus the major characteristic of the EAZ, edge anomalous zone, is pervasive shearing (Balk, 1953, p. 2470). Similarly, the approach to the sediment part of the CAZ is also sheared as much as 30 to 150 meters away. The outer shear zone may exist even if the inner zone has been recrystallized and has lost its "sheared" character. At the Weeks mine, for example, the salt is highly sheared 30 to 100 meters away from the sediment-bearing salt, but the black salt associated with this sediment zone has apparently been recrystallized and refolded (see next section). This might appear as a fortuitous juxtaposition of two anomalies of different origin, but it is so persistent that this seems improbable. The sheared salt away from the sediment zone is best interpreted as the sheared salt of a former EAZ.

Black salt. In the introduction of this report, a common type of salt was described as "black." Well-bedded salt appears dark in the mine, but it is merely transparent; it contains several percent of anhydrite. Much less common are beds of black salt that are up to several meters thick and are black even when examined in the daylight. The composition of these beds has not been adequately checked; but, in addition to a high anhydrite content, many contain disseminated clastic material. Some, possibly most, of these black salt zones are primary; especially if they are of uniform thickness and persist over long distances. Others may represent secondary sediment-rich shear zones that have been remobilized and thus given a more uniform texture. These recrystallized beds can be recognized and distinguished by rapid changes in thickness and by a high degree of lenticularity.

The CAZ (central anomalous zone) at the Weeks Island mine has the best available example of a shear zone that has been remobilized. The sediment found in this zone is lenticular, sheared, and similar to most other sediment zones, but locally it contains thick beds of black salt that look well-bedded and are strongly folded. For example, in Room G-24 the black salt forms a triple-fold that is sharp and clear, and this area is a showplace for geological visitors (Kupfer and Morgan, 1976, p. 56–57). If the beds at G-24 are examined in detail, however, it is seen that individual beds, up to 10 centimeters thick, wedge out and disappear within 5 meters in one direction and join together in the other direction. These black beds probably represent an original sediment-rich internal shear zone that has been remobilized, recrystallized, and folded. If this is true, then the Weeks' CAZ is much older than similar zones found at the other Five-Island mines. It represents an older boundary shear zone that formed at some lower stratigraphic level and has since been mobilized and brought into its present position (Kupfer, 1976, p. 1439).

Fractures. Fractures in salt may be natural or induced by the works of man. The following table (Table 1) shows the principal types of fractures. These openings, along with natural and artificial openings, form the only porosity and permeability to be observed in salt. The only natural openings are those filled with fluids or gases, as already described. The artificial openings, including mine workings and borings, are important as they induce most of the fractures observed in salt stocks. As most of these fractures are ubiquitous, they are not of importance in this report. The exfoliation fractures, although not anomalous, will be described in somewhat more detail because of their importance to mining safety; and because one special type, ceiling slabbing, appears to be more strongly developed and therefore more dangerous in and near anomalous zones.

Exfoliation joints. Exfoliation joints, also called expansion joints, form when any homogeneous rock, such as salt, expands. As the salt in salt domes was originally buried several thousands of meters deeper than it is now, the salt was compressed and recrystallized under a high confining pressure (stress). Given an opportunity, the salt will expand, commonly causing jointing and fracturing.

Exfoliation joints in mines form parallel to the walls, ceilings, and floors of the mine openings as the salt creeps inward (Fig. 3). This movement can extend into the salt for at least 15 meters, and open joints have been observed 7 meters back of the mine face. One "rule of thumb" states that this distance is half the width of the opening (i.e., over 10 meters in most Gulf Coast mines). The joints are most obvious at corners where two sets intersect and cause the corners to spall and become rounded. The size of the joints, distance back into the walls, and rapidity with which they open are controlled by many factors such as salt purity, temperature, depth, and speed of mining. Figure 4 shows diagrammatically some of the relationships involved.

Exfoliation joints mainly develop in the first month after a mine room has been opened up, but they continue to develop for at least a year. It is not known if they always develop; very pure salt may flow outward without the development of open joints. Salt flow is very rapid for the first six months, but gradually decreases to a slow and barely

TABLE 1

Fractures in Salt

1. Joints and other subparallel fractures.
   a. Blast fractures—created at the time of mining
   b. Exfoliation joints—created by release of pressure (strain)
      aa. Natural
      bb. Artificial
2. Cracks and other irregular fractures
   a. Intergranular fractures—friability
   b. Miscellaneous—various origins

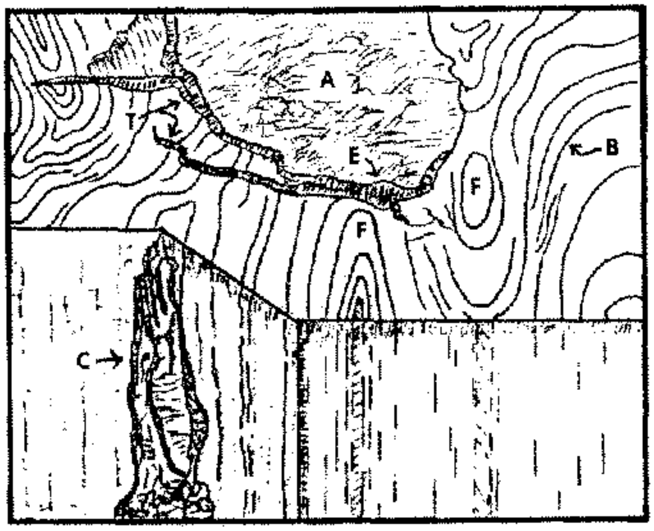

Figure 3. Ceiling slabbing occurs on exfoliation joints (E and T) that parallel the flat roof. As the slabs fall away, broad expanses of very smooth, black ceiling are exposed (A). Locally the joints (T) may form at two or more levels. Ceiling slabbing is independent of bedding (B). Corner spalling (C) is more irregular and partially influenced by both bedding and mining direction. The potential for ceiling slabbing is greater in areas of folds (F), especially in black, impure salt.

perceptible rate that probably continues indefinitely; jointing may do the same.

The importance of this gradual development of intergranular fractures and of joints, at first rapidly and later slowly, to the mine-leak problem cannot be over-emphasized. Mine management is continually trying to seal off leaks, only to have them reopen in a few months or a few years. The reason is that the contact between salt and cement is the most vulnerable place for differential movement, thus tight seals are broken with time and leaking starts again. Similarly, joints can be dry for months, but as they gradually develop they eventually tap liquid pockets or brine passageways.

Two experimental approaches are suggested. First, try to develop cements that match the properties of the salt as nearly as possible, and that remain flexible rather than brittle as they "set". Second, experiment with nature's own remedy—the expanding clay. An expanding clay, like montmorillonite, bentonite or attapulgite, never "sets". When dry it moves into fractures and compacts; and when wet it expands and swells, forming a seal.

Ceiling Slabbing. Exfoliation joints that form in the roof (ceiling) of the mine form horizontal slabs that are difficult to detect until they fall (Figs. 3 and 4). Slabbing can be very dangerous, especially if the joint forms several tens of

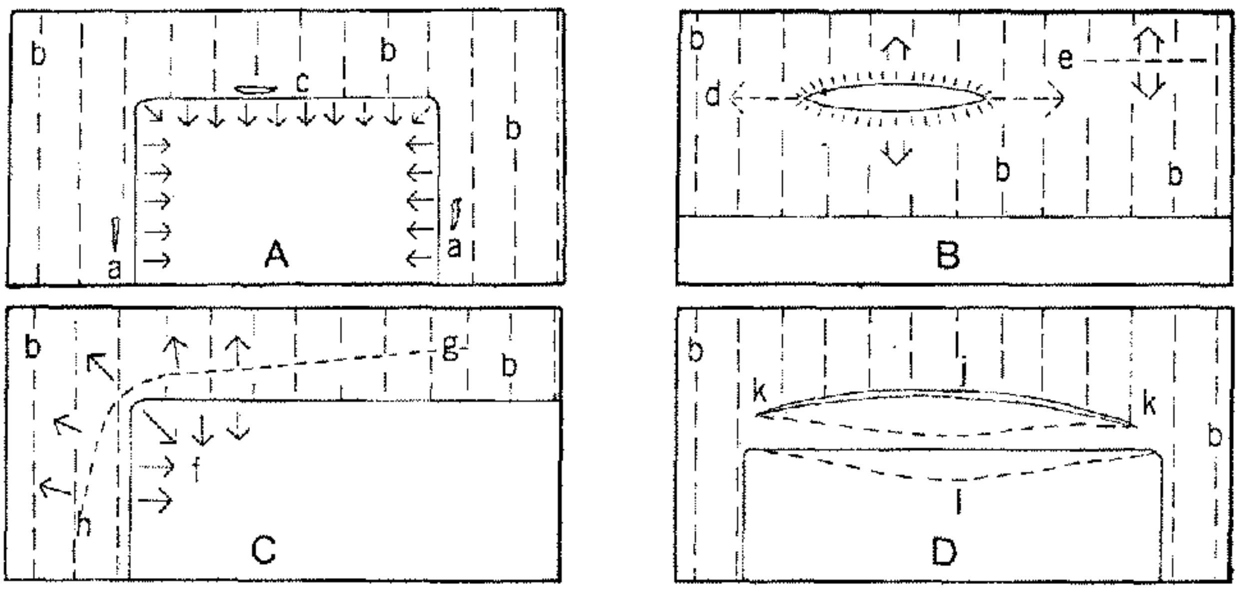

Figure 4. Diagrammatic cross section of typical salt working shows development of exfoliation joints and ceiling slabbing. Openings are greatly exaggerated. Both bedding (b) and joints (a, c, d, e, g, h) develop perpendicular to the plane of the sketch.

A) Arrows indicate tendency of salt to expand inward upon release of confining pressure by mine opening. Exfoliation joints develop at *a* and *c*. Vertical bedding shown by dashed line *b*. B) Stresses, wide arrow in roof can be released by development of exfoliation joints (short dashed lines *d* and *e*) that parallel the roof face. Once joint *d* forms it expands laterally (arrows), developing smooth, horizontal joint plane. Because it is easier for stresses to be released by continued development of *d* than for a new joint *e* to form, one joint dominates a large area. C) At corners, radial stress release *f* is at right angles to face. Exfoliation joints *g* and *h* curve inward and intersect. Thus exfoliation slabs are thicker at the center of walls and ceilings than at the sides. D) Slightly arcuate exfoliation joint in ceiling (k-j-k) allows the roof to sag for a few centimeters to position *l*, shown greatly exaggerated by short dashed lines; this results in failure of the slab and roof-fall.

centimeters above the ceiling face, so that the slab is thick and extensive. When large slabs fall, they can crush both men and machinery. Investigation of these "roof falls", or "ceiling slabbing", indicates that they are larger, more common, and more dangerous as workings go deeper and rooms become wider.

Typical slabs in normal salt are only 10 to 30 centimeters thick and cover areas about 3 to 5 meters in diameter. In black, folded salt, the slabs are up to 1.5 meters thick and cover areas of up to 30 meters in length. After slabbing, the ceiling is very flat and smooth, and reflects light uniformly over the whole surface. Commonly the surface is black and clearly shows the large arch-bends of the folds. The folds seem to have localized the joint and the later "roof-fall". Slabbing is controlled, in part, by the type of salt and its fold structure.

Ceiling slabbing is most frequent in dark, anhydrite-rich beds of salt, and particularly in black salt of the type associated with anomalous zones. Most slabs occur at the arch-bend of these black folds. The reason for this occurrence has not yet been fully explained, but is probably related to the additional strength imparted to the salt by the impurities. Thus, ceiling slabbing, particularly the thick and extensive slabs that are most dangerous, commonly occurs in the area of other anomalies such as interbedded sediments, pressure pockets, and black salt.

In addition to width of arch and salt composition, some other factors that may affect ceiling slabbing are time, speed of mining, temperature, and orientation. Slabbing commonly occurs soon after a mining area has been opened; if slabbing does not occur within a few months, it is much less likely to occur at all. But areas that have slabbed in the past may do so again, even after rock bolts (roof bolts) have been installed. Speed of mining and sequence of mining are possible factors, including the length of time a face is left unblasted. The orientation of rooms to each other also influences the jointing. Corner spalling (Fig. 3) is universal, and increases in importance with the height of the rooms and the depth of the mine opening below sea level. A marked change in roof level, overhangs, lips, and other angular changes in roof shape inevitably cause spalling.

A sudden change in temperature causes differential expansion, and may cause a slab that has already formed to fall. Several cases of ceiling slabbing have occurred when diesel equipment (with exhaust pointed upward) have been left standing at one place with the engine running.

PRESSURE POCKETS

Size and shape. Pressure pocket is a name I am using for a particular type of "blowout" or gas "burst" that occurs in all but one of the salt mines of Louisiana, the exception being the Avery Island mine, which is still being mined at a relatively shallow depth. A pressure pocket is an opening that develops in the roof of a mine-working during blasting. More salt breaks out than was planned; and a rounded, conical, or vertically elongate opening develops in the roof or, sometimes, in the upper part of the wall of the mine opening. Even though an initial opening may start out at a low angle, in a meter or so it will turn upward. Most are from 0.5 to 10 meters high, but they range from just barely observable to some that are so high the tops have not yet been seen or measured (Fig. 5), but are estimated to be over 50 meters. The large ones are cornucopia-shaped openings that twist upward into the roof for 10 to 30 meters, are 3 to 10 meters wide at the base, and look somewhat like a solution-cavity in limestone—a conical, twisting opening that gradually decreases in size upward. When they form, large volumes of granulated salt are blown as far as 40 meters into the workings.

There is every gradation, from the large openings that displace tons of salt, to small pockets that are difficult to distinguish from the pockets left by slightly erratic blast holes or "overbreaks". The small ones are mostly confined to the corners between walls and ceiling, and are 10 to 50 centimeters in diameter. These small openings are ordinarily overlooked; but they occur in the same anomalous zones as the large pressure pockets and are characterized by the same distinctive joint pattern (next section).

Pressure pockets occur in pipe-like zones of salt. These "pipes" have a long vertical dimension and are somewhat cylindrical, tapering toward the top (and also probably toward the bottom in the natural state, although this is a surmise).

In the larger and better exposed pipes, the long (vertical) axis appears to be at least five times as long as the diameter, and may be more than that. In cross-section some pipes are elliptical, and the longer axis more or less parallels the direction of bedding or is perpendicular to it.

Jointing. The walls of most pressure pockets have a distinctive, concentric, shingle-like joint pattern that does not occur in normal blast openings, but does have some resemblance to blast fractures. As one looks into the circular opening, the walls are covered by joint-bounded slabs of salt. The joint spacing is about 1 to 3 centimeters and the

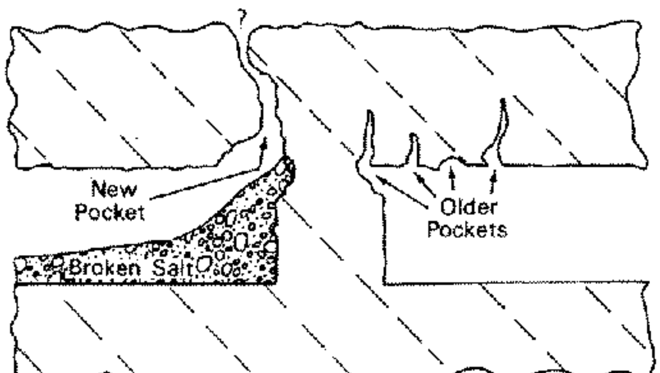

Figure 5. Cross section of pressure pockets in 25-foot (7.62 m) high mine workings. Note large volume of salt "exploded" out of the new pocket.

joints are inclined at a low angle to the surface of the working and at right-angles to the axis of the "pocket". The wall appears to be covered by "shingles" of salt in a concentric pattern. Concentric jointing may be absent, vague, or well-developed; but, if present, it helps to identify the opening as a pressure pocket and not just a blast opening or "overbreak".

Location. Commonly a series of pressure pockets are aligned along a single black bed (Fig. 6) or a thin zone of beds. The pressure pockets, especially the larger ones, occur with other anomalous features such as black salt, shearing, and inclusions. They are not always confined to the sediment part of the CAZ, but are common there. At the Belle Isle mine they occur in a parallel zone about 200 to 400 meters from the CAZ (Fig. 7). At the Weeks Island mine one set occurs at the inner edge of the sheared salt sheath (EAZ) which surrounds the stock and is in pure white salt. At Jefferson Island mine the main line of pressure pockets is vaguely parallel to the EAZ, but is 300 meters away from it.

There is some indication that pressure pockets increase in size and abundance with greater depth, although this is not firmly established (Table 3). Not enough mining has been done yet at various levels within any one mine. One relatively large pressure pocket (5 m in diameter) is located as shallow as 200 meters below the ground surface; smaller pockets along strike are 120 meters below. The largest ones are in the deepest (400 m) mine levels.

Upward only. Another unusual feature of the occurrence of pressure pockets is their location only in the roofs of workings and not in the floors. After the rooms have been cleared of broken salt and mining has continued into a new area, pockets extend tens of meters into the roof (Table 2), but the floor is the flat surface made by the original undercutting operation (Fig. 5). Whatever is being released (pressure, gas, stress) must extend into the floor as well as the roof as mining cuts the "pipe" of salt at an arbitrary level, yet only the salt in the roof is released explosively. Is this because of gravity or mining method? Probably it is both. The undercutting operation, which is done slowly over a period of hours probably allows the slow release of the stress for a meter or two into the salt. Then more time elapses as powder holes are drilled, loaded, and finally blasted (sometimes several shifts later). By this time all of the stress in the lower half of the workings and for a distance into the floor has had an opportunity to be released slowly. The salt in the upper half, however, is still confined and the stress is suddenly released by the blast. A pressure pocket forms and travels with high speed up the "pipe" of still unreleased stress as gravity aids in the removal of the salt. This hypothesis is confirmed by the fact that the large pressure pockets occur at the forward end of a block of salt removed by blasting, and commonly curve horizontally into the newly opened face before curving upward into the "pipe". If the original "pipe" is too close to the previous

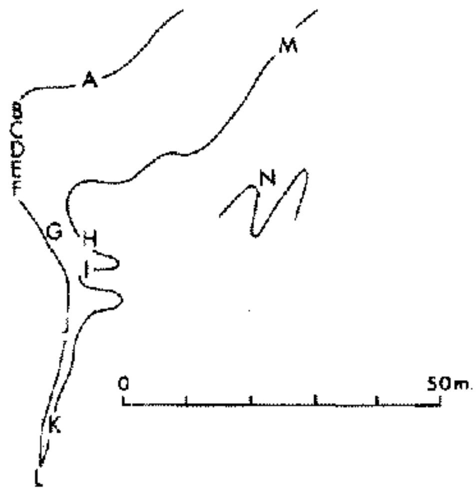

Figure 6. Map view of pressure pockets (A–M) that have developed along a single, black, clay-bearing, popcorn-type, salt bed at the Cote Blanche mine. Pocket N may be on a sheared-out part of the same bed. See Table 2.

TABLE 2

Pressure Pockets, Cote Blanche Mine

Letters correspond to Figure 6. Length, width, and height of pockets in meters; plunge and azimuth of long-axis of pockets in degrees.

	L	W	H	Plunge	Comment
A.	0.3	0.2	0.2	Hemisphere	Small pocket in roof
B.	0.5	0.3	8	80 @ 090	Tiny chute
C.	0.3	0.3	1	Vertical	Part of pocket C-D-E-F
D.	2	1	3	70 @ 020	As above
E.	1	1	5	50 @ 355	As above
F.	2	1	3	55 @ 000	As above
G.	5	2	10	65 @ 160	Large, south-plunging cavity
H.	3	1.2	1.5	45 @ 290	Large, horizontal elongation
I.	2.5	1.3	2	75 @ 350	Upper part of G and H
GH&I.	6	4	7	60 @ 340	Large, complex pocket of three parts
J.	7	3	12+	Vertical	Twists upward, base plunges 200 azimuth
K.	0.4	0.3	1	? @ 020	In roof, since mined away
L.	1.3	0.7	0.3	60 @ 020	In corner
M.	8	5	6	Hemisphere	Black bed forks northward
N.	10	6	8	65 @ 330	Large, high pocket; same bed???

working face most of the stress is released before blasting—a pocket may not form, or if it does it is much smaller.

An unanswered problem is why the holes drilled for blasting do not release the stress. Possibly the holes are not large enough or extensive enough.

After most of the stress in the "pipe" has been released, either upward by explosion (blowout) or by gradual release downward, the "pipe" stabilizes. Any residual stresses or pressures are probably gradually released with time.

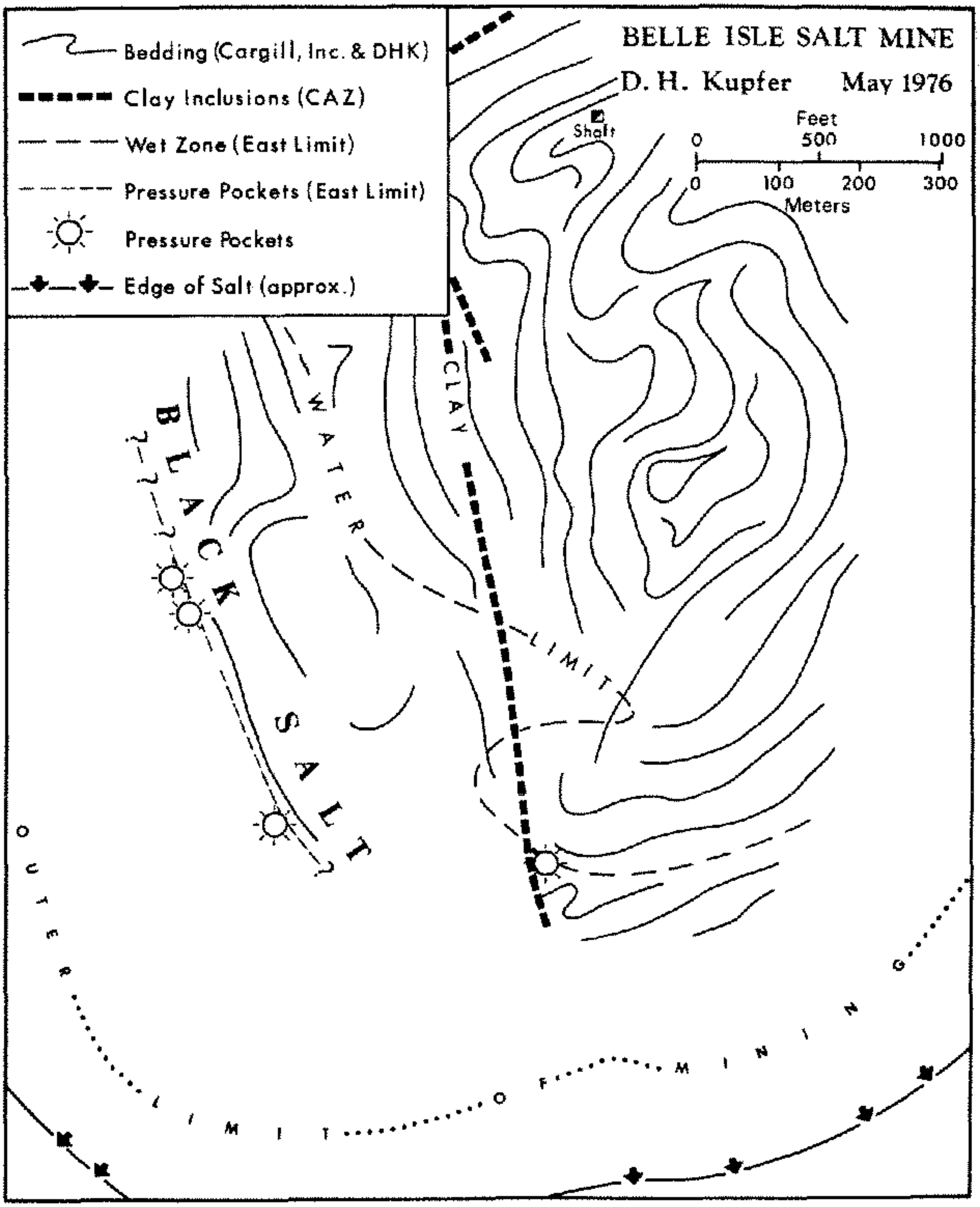

Figure 7. Sub-parallel arrangement of anomalous features away from the central, boundary-shear, anomalous zone as marked by clay inclusions, Belle Isle mine. Water drips, followed by darker salt, and then pressure pockets extend southwest away from the clay zone and to the center of the older spine. The location of the southwestern edge of the salt stock is approximate. Some of the bedding is taken from Cargill mine maps.

TABLE 3

Louisiana Salt Mines

CAZ = central anomalous zone; EAZ = edge anomalous zone; OZ = other zone; PP = pressure pocket; CS = ceiling slabbing. Table lists only prominent anomalous characteristics of the six Louisiana salt mines; continued mining may add to the list.

Jefferson Island

Northernmost island; Diamond Crystal Salt Co.; mined since 1922, four levels, deepest at 450 m.

Top of salt at two levels, lowest and oldest has caprock and sulfur (mined 1930s); CAZ between the two spines.

Inclusions: Some sediment, minor brine (including $CaCl_2$), gas.

- CAZ: Wide, dry, sediment, much dark folded salt, slabbing, $CaCl_2$ brine.
- EAZ: Penetrated in one area, strong shearing, sediment, leaks.
- CS: Most independent of anomalous zones; also in dark folded salt of CAZ, EAZ.
- PP: 350–400 m deep, several large, independent of CAZ, near EAZ.

Avery Island

North central island; International Salt Co.; first mined 1862, early flooding, current mining at three levels, deepest at 275 m.

Top of salt highly irregular, cut by 'valleys' that reflect the anomalous zones, no caprock; several spines.

Inclusions: Several zones of sandstone and brine.

- CAZ: Wide, abundant sediment, sheared, very wet: pierced in several places.
- EAZ: Not penetrated.
- OZ: Two or more, unexplored, wet.
- CS: None
- PP: None

Weeks Island

Central island; Morton Salt Co.; mined since 1900, two levels (150 & 250 m), upper dry and without anomalies.

Top of salt irregular, no caprock, two spines with large physiographic valley east of main CAZ.

Inclusions: Mixed sediment, oil, minor brine, gas.

- CAZ: Width unknown, sheared clay and sand, folded black salt, PP, oil and grease; probably a refolded zone, locally recrystallized.
- EAZ: Wide shear zone, then PP zone, traces of sandstone, generally dry.
- OZ: Branches from CAZ, one thin sandstone bed, light oil, PP.
- CS: Most in dark, folded salt, independent of CAZ and EAZ.
- PP: 220–240 m deep: small to medium size, in all three zones.

Cote Blanche Island

South central island; Domtar Salt Co.; mined since 1961, one level (375 m).

Top of salt poorly known, no cap rock; one large spine, poikiloblastic salt.

Inclusions: Thin beds of sandstone with K-Mg (primary ?), gas, black clay.

CAZ and EAZ undetected

- OZ: Two zones, sandstone, potash, slabbing, PP, unusual jointing.
- PP: 360–370 m depth, moderate size; follow black, clay-bearing salt bed.

Belle Isle

Southernmost island, geographically separate from others; Cargill Inc.; mined since 1960, one level (425 m); early mining attempt in 1898 at 30 m, flooded.

Top of salt inclined, patchy caprock and sulfur on lowest part; two spines, youngest is highest with overhang and no caprock.

Inclusions: Clay-lime sediment, brine, gas.

- CAZ: Narrow, clay balls dated Oligo-Miocene. Dry with minor CS and PP near edges, but toward center of dome the black salt zone with large PP and moisture branches away.
- EAZ: CAZ zone curves tangentially into EAZ, gas, black salt, clay balls.
- CS: Most in black, folded salt independent of main CAZ; also in CAZ.
- PP: 420–390 m deep, several large near center of stock, on both CAZ and in the associated black, moist salt area near it.

Winnfield

Central Louisiana, northern salt-dome province: Carey Salt Co.; mined 1930–65, one level (250 m deep; 190 m subsea), flooded; caprock quarry on surface; one spine with simple internal structure, salt rose from 8000 m, salt less pure (90% NaCl).

Inclusions: Brine and CO_2 gas, much anhydrite (10%) in salt.

- CAZ: None
- EAZ: Possibly not penetrated.
- CS: None recorded, but floor-heaving noted.
- PP: 200–240 m deep; one large PP that may have exploded during the night.

Gas. Pressure pocket "pipes" contain gas under pressure, which may or may not be the cause of the stress. This gas is disseminated throughout the salt of the "pipe". Holes drilled into the pipe release gas, and sometimes brine, both under high pressure. Even the grains of salt expelled by the explosion contain bubbles of gas under pressure. As one walks over the broken salt a "popping" sound can be heard as bubbles of gas are released. Pieces of salt dropped into water release gas as the salt is dissolved, again with a popping noise. This type of salt has been called "crackle" or "popcorn" salt. A salt analysis at the Winnfield mine (Hoy, Foose, and O'Neill, 1962, p. 1458) showed the gas to be 50 percent carbon dioxide and 22 percent water under 500 to 1000 atmospheres pressure.

Winnfield. A large pressure pocket occurred at Winnfield mine (Fig. 1) in central Louisiana in the 1950's has been described by Belchic (1960, p. 38–39). Because of the inaccessibility of the original publication, the complete description is repeated here:

"*Carbon dioxide gas and brine:* Carbon dioxide gas is very abundant in the dome, occurring not only as inclusions in the halite crystals, but also in large pockets. Such a pocket was tapped during the course of mining operations, resulting in the violent release of dry gas under high pressure, which filled the room with fine salt, blown down from a pocket over 100 feet above the roof of the mine. This pressure surge forced the belt off the ventilating fan at the surface. In other instances gas has heaved the floor up with great force. This gas is frequently associated with saturated brine, and together they are observed in most sections of the mine. Their most common occurrence is in the porous and permeable bands, and through small crevices and joints, escaping into various low-pressure areas, such as mine rooms, mine wells, drill holes, etc.

"During the early years of mining operations, nine exploration holes were drilled in the floor of the northwestern part of the mine to an average depth of 600 feet below that datum. Several of these holes flowed saturated brine and gas under high pressure, and mine well No. 8 still produces a small amount of gas and brine. Evidently, the brine comes from the deeper interior of the dome, for it has never freshened, and has progressively sealed the holes rather than enlarged them.

"In several mine rooms may be observed hundreds of small craters or stalagmite-like mounds of salt. They are formed by gas which, escaping upward through the floor under pressure, brings with it brine that upon evaporation leaves small mounds of salt, ranging in height and diameter from a few millimeters to several inches. In the sections of the mine which recently have been opened, these features are small and very active. The gas may be plainly heard as it bubbles up through the brine. In most of the older rooms, however, either the gas supply in the immediate vicinity has been exhausted, or more probably, the brine has sealed off the vents, for the craters are no longer active and the floor of the rooms is comparatively dry.

"Generally when a low room (25-foot roof) is opened in a "wet" area, brine drips from the roof for days to months, forming iron oxide stained "salt stalactites" of all sizes. Later, when these low rooms are enlarged to approximately 90 feet by blasting down the roof, the stalactites do not form, or are very small. This indicates that the source of brine and gas is cut off when a low room is mined; the brine above the room, no longer under pressure from below, percolates slowly downward, forming these features as it drips from the roof. When mining operations are renewed in these rooms and higher roofs cut, the water from above has been exhausted and stalactites no longer form. If a low room stands for several years, the stalactites, having apparently exhausted their source of brine, cease to form.

"Usually there is little or no brine or gas flow from the walls, although on several occasions when blast holes were drilled into the walls, small gas pockets were tapped which violently ejected tools or dynamite. From several of these holes there developed a considerable flow of brine, which soon diminished and generally ceased entirely within a few hours. However, in the walls of certain rooms are holes drilled a number of years ago. From several of these hang large "stalactites" of deeply stained salt, still actively forming. These long-active stalactites occur almost without exception in the corners or on the back walls of the rooms. Holes drilled in the pillars between rooms, on the other hand, do not remain active for any length of time.

"In some rooms, no gas or brine activity has ever been observed. In other rooms, "stalactites" have been forming steadily on the roof for years. Invariably these latter rooms are located in the extreme western end of the mine, where the occurrence of very coarsely crystalline salt and much carbon dioxide gas suggest the close proximity of the edge of the dome."

Several features of the Winnfield mine occurrences should be noted. Although the main pressure-pocket explosion did not penetrate the floor, other instances "heaved the floor up". Also, according to one report that I have from one of the miners of the area, the main explosion occurred at night, and not during blasting. Also, the force of this explosion appears to have been greater than that at other mines. It should also be noted that several of the features described by Belchic are more descriptive of typical mine leaks than of pressure pockets, even though these two may be related.

Origin. In summary, the principal characteristics of pressure pockets are that they are gaseous, pipe-like, and occur along linear zones that are associated with clastic, liquid, and gaseous inclusions, shearing, and abnormally dark salt. The pressure or stress can be released slowly, but if released suddenly causes a violent explosion. Pockets are of various sizes and appear to increase in size and pressure with depth.

Most suggested origins imply that pressure pockets are related to pressurized gases (and/or liquids), but another hypothesis is that they are related to salt in super-stressed condition (personal communication, M.B. Mirza, Mining Engineer, Weeks Island mine, 1977). Mirza suggests that when mining allows a release of pressure, the salt undergoes a phase change and resulting volume expansion, which causes the explosive ejection of the salt. This hypothesis places the stress in the solid salt, rather than in the associated confined liquids or gases. The fact that the pressure appears to be dissipated somewhat by small openings, such as drill holes, and over a long period of time, would suggest that this is not the principal cause of pressure pockets, but might be a contributing factor.

If the pressure pockets are caused by confined gases under pressure, the question arises as to when the gases were introduced—primary or secondary? Both may occur, and this has been considered elsewhere in this report.

At Belle Isle mine, however, the origin appears to be definitely secondary (Fig. 7). The boundary shear zone has been mapped southeastward for over 1000 meters (Kupfer, 1976) from the northwest edge of the salt stock and well into the center of the stock. The solid, liquid, and gaseous phases of the inclusions appear to separate as the CAZ is traced into the center of the stock (Fig. 7), and the intensity of the liquid leaks and gaseous explosions also increase. This suggests that although all three (solid, liquid, and gas) may have originally been introduced into the salt along the boundary shear zone that is now incorporated into the center of the stock, differential movements have occurred. The solid materials are the least mobile, and the sediments are still plastered against the same salt as they were when they were on the outside of the salt stock. Movement has caused shearing, lensing, boudinage, and intimate recrystallization of salt into the sediment, but transfer distances are probably measured in centimeters, not meters. Liquids have proved more mobile, being found as much as 100 meters into the surrounding and older salt, indicating that at the time of intrusion of the adjacent new spine of salt, the old spine was apparently highly fractured and porous, and this edge-salt contained liquids. Gases could penetrate even farther, over 200 meters.

After the gas and liquid penetrated the salt, the salt started moving (spine or movement) and much of the porosity/permeability of the CAZ was destroyed. The gases in the original boundary zone were able to escape because of the greater permeability caused by the sediments in this zone. The gases that penetrated well into the more massive salt became permanently sealed there by recrystallization and maintained their pressure through later movements. This would explain the parallelism of separate pressure-pocket zones with the zones of sedimentary inclusions (Belle Isle, Jefferson Island) and the increase in size of the pressure pockets toward the center of the stock in all mines.

Mines, like the Weeks mine, where the pressure pockets are more intimately associated with the sediments, probably had a different history. The sediment zone may have been incorporated into the salt stock (by spine motion) when it was at a greater depth, and the more plastic nature of the salt and sediment prevented the escape of the gas associated with this zone. Greater depth would also mean that the edge zone (before spine motion) was less brittle, narrower, and almost confined to the sheared clay gouge zone (shale sheath). Thus the EAZ, which later became a CAZ, was narrower and the separation of gas and liquids from the solid sediments did not occur.

Pressure pockets are caused by gases of various compositions, hydrogen sulfide, methane, carbon dioxide, and probably others, and probably various origins. The gases are incorporated into the massive salt, and as the salt moves during salt dome formation, the gas pockets are subdivided, stretched vertically, and disseminated through the individual crystals and into the boundaries around the grains. The gas in the pipes is in tiny bubbles, cracks, and other small openings. The "popcorn" salt that results is confined to pipe-like, cylindrical zones of vertical orientation. The pipes are aligned horizontally along the bedding.

As mine works penetrate an area of pipes the geopressured salt tends to expand outward into the workings. Salt grains separate and intergranular fractures form that connect the "popcorn" gas pockets, and gas is released into the new fractures. If exfoliation joints form, these cause even greater release of inter- and intra-granular gas into the open joints. The release extends back into the salt for as much as 7 to 10 meters. If preliminary drilling and undercutting does not allow the escape of these gases, sudden release occurs during blasting and a pressure pocket starts to form. As the pocket grows, more gas is released. Gravity, combined with the expanding gas, hurls the salt downward and out into the workings. The pocket grows until the pressure is released, or the pocket becomes so filled with salt that no more instantaneous release is possible. Further release is gradual and the size of the pocket is stabilized.

INTERRELATIONSHIPS

The characteristics of the various types of anomalies have been described, and their typical occurrences have been noted. Most tend to be associated either with exterior shear zones that formed at the edge of the salt stock (EAZ, edge anomalous zones), or with EAZ that were later included into the salt as a boundary shear zone (CAZ, central anomalous zone). The CAZ at Weeks Island appears to have been later remobilized and refolded.

Sediment and black salt are found at the outer edge of the EAZ and in the core of the CAZ. Other types of anomalies may occur with the sediment or in zones around it. Liquid drips, for example, commonly occur in the next zone outward, while gas, especially in pressure pockets commonly occurs still farther out. But both liquids and gases also occur intimately mixed with the sediments. Shearing is all-pervasive, and some shearing is very widespread in its occurrence and may have a separate origin. Shearing is probably a necessary prerequisite of both the CAZ and the EAZ, even if later recrystallization sometimes makes the shearing less obvious. Slabbing is controlled more by depth and by mine width than by position with respect to other anomalous features, but slabs are thicker, larger, and more abundant in the black sediment-bearing salt associated with the CAZ.

In the Cote Blanche Island mine the sediment-bearing zones are very thin and lenticular, but persist over great distances. A series of exposures of red to orange-brown sandstone appear to be part of a single bed that can be traced throughout the entire mine in a giant, discontinuous, and highly irregular loop. The loop is about 550 meters long (north-south) by 200 meters wide. It has not been followed continuously because it is lenticular, and because much of the mine is now covered by a layer of dust and soot that prevents easy observation. This long, discontinuous, and quite narrow bed (commonly only 10–100 cm thick) appears to be folded rather than faulted into its present position. It seems probable that this orange sandstone was an original bed in the salt sequence that has been domed up into the salt stock sequence in the same way that the salt was. The individual sand grains are very rounded, well-sorted, and frosted and represent a wind-blown sand deposited into the salt basin by an unusually strong and long-continued wind storm. This was also a time of great aridity, as the sand is associated with carnolite and K/Mg brines. The other sand zone at Cote Blanche is a similar, thinner, and equally widespread sandstone bed, but the sand is not wind-blown. The second bed (which could even be part of the first bed, though not likely) is only 3 to 10 centimeters thick, dark red-brown, and poorly sorted. At present it is best explained as primary also, but there is still much to be learned about these occurrences. They appear to present many problems.

Table 3 summarizes some of the observations made thus far, and shows the high degree of variability involved. Probably the only thing clear is that a single origin cannot be used to explain all of the anomalous features; yet their consistent occurrence together suggests some kind of a common background. Most appear to represent either present day edge shear zones (EAZ) around salt stocks or older zones that have been incorporated into the stock as boundary shear zones (CAZ). The boundary shear zones may have formed near the surface, in which case they are wide and diverse; or at great depth, in which case they are narrow and all the anomalous features occur together. Some zones may have been further folded and recrystallized after they formed. Some anomalous features are suggested to have been caused by primary solids, liquids, or gases, but this is quite speculative.

CONCLUSIONS

Typical Gulf Coast domal salt is pure, uniform in grain size, and folded into vertically-plunging complex folds of flowage origin. A salt stock consists of separate masses of salt called spines, that appear to have been individually emplaced into the surrounding sediments. Each spine is bounded by a shear zone of lenticular salt and sediment of a more anomalous nature.

Anomalous features in salt include various kinds of exotic materials such as lenses of sediment and pockets of liquids and gases. These appear to be concentrated into zones of various types that are characterized by shearing, recrystallization, ceiling-slabbing, leaks of various sizes and duration, and a special kind of gas "blowout" called a pressure-pocket. Most of the foreign materials appear to have been ground into the salt by shearing at the edges of the spines, and have been further redistributed within these edge-zones by later movements. The more mobile gases sometimes move several hundreds of meters into the salt from the original edge-zones; the liquids migrate only a hundred meters or so.

Thus, most of the anomalous occurrences can be explained as secondary in origin and as introduced into the salt during its domal rise. But this is not true of all the anomalies; some of the materials (solid, liquid, and gaseous) are better explained as having originated with the salt at the time of its original precipitation or soon thereafter.

In general, the various anomalous features found in salt are detrimental to the mining industry and to the use of salt domes for storage and other purposes; some features present dangerous hazards. Pressure pockets and ceiling slabbing can cause loss of life and material; leaks commonly flood mines or introduce dangerous gases. In a way, it is fortunte that all these deleterious features are commonly closely associated. This means that when one is encountered in the mining process, management can be on the lookout for others. It also means that the major dangers are concentrated into zones that can, in many cases, be left unmined.

Several problems are presented by the use of these data. In general, each anomalous feature can occur alone and under harmless conditions; thus the presence of a single feature is not sufficient to justify the abandonment of a mining area. Also, some of the features are very widespread, so that abandonment of every area where any anomalous feature occurs would leave almost no usable salt. Clearly, discretion should be exercised, and mining regulations must be tempered with judgment and understanding of the causes, which are multiple and complex.

Our present knowledge of the various factors involved is still minimal. Much can and will be learned concerning distribution, structure, texture, mineralogy, chemistry, and physical properties of the various features. Cooperation among investigators is essential for safety and to fulfill modern environmental requirements.

Meanwhile, some positive results can be stated. If several of the anomalous features are found in a particular area of a mine and mining is mandatory, this area should be mined with caution. If it can be circumvented, it should be. In some cases, the passage of time eases the problem and makes mining less hazardous. In dangerous areas, probing ahead by drilling can help to detect problems before they become insurmountable. Careful mapping of the character of the salt that has already been mined is very helpful. Highly sheared salt is generally encountered before the main anomalous zone is reached. Most of the anomalous zones either parallel the overall bedding trends, or are at least sub-parallel to them. The mine opening itself is the greatest cause of problems. Salt expands into the opening and the wave of disruption extends for long distances into the walls, ceiling, and floors. This disruption, in turn, connects pockets of liquids and gases that were previously isolated.

My advice, which is that of a structural geologist, not an engineer nor a rock mechanic specialist, is as follows. Anomalous zones can commonly be detected before dangerous problems arise. If possible, avoid them. Never penetrate closer than 100 meters to the edge of the salt stock, and stay even farther away from the top of the salt stock. External leaks, once started, are almost impossible to stop permanently with present technology. Central anomalous zones are less dangerous, but still should be avoided if possible. If they must be penetrated, keep the openings as small as possible, and proceed with caution. An exploratory drilling program is advisable.

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