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UNITED STATES DEPARTMENT OF THE INTERIOR

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UNIT OF MEASURE ABBREVIATIONS USED IN THS REPORT

cm	centimeter	g	gram
cm^3	cubic centimeter	in	inch
ft	foot	mm	millimeter
ft^2	square foot	pct	percent
ft^3	cubic foot	yr	year
ft^3/d	cubic foot per day		

INVESTIGATION OF METHANE OCCURRENCE AND OUTBURSTS IN THE COTE BLANCHE DOMAL SALT MINE, LOUISIANA

By Gregory M. Molinda[1]

ABSTRACT

The Bureau of Mines conducted an investigation into the occurrence of outbursts of salt known to be responsible for explosions, fatalities, and damage in domal salt mines. The purpose of the investigation was to develop a basis for predicting these outbursts based on geologic and associated physical properties of salt.

The investigation was conducted at the Cote Blanche salt mine in southern Louisiana. Because outbursts are the primary mode of methane emission into the mine, more than 80 outbursts, ranging in size from 1 to 50 ft in diameter have been mapped. These outbursts generally are aligned and elongate parallel to the direction of salt layering. More than 200 salt samples, both random and selected, were tested for methane content. It was found that outburst zones are well correlated with high methane content. Detailed mapping also revealed that the zones are well defined, with salt crystal size abruptly increasing upon entry into the zone. The intensity of folding and kinking of the salt layering within the outburst zone also appears to increase. An interbedded sand layer occurring throughout the mine does not appear to be a significant source of methane. However, fine-grained salt may be related to outburst occurrence.

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INTRODUCTION

The Bureau of Mines has developed a laboratory test for determining methane content in rock salt samples, and has evaluated emission characteristics of various forms of salt. This Bureau report assesses the usefulness of these tests, various geologic parameters, and rock salt properties in predicting the potential for occurence of outbursts in domal salt deposits.

The occurrence of hydrocarbons within salt structures has been observed for many years from exploration drill holes into these structures by both the oil and gas and salt mining industries (1).[2] Many gas occurrences have been encountered, but mostly during underground mining. In one domal salt mine, more than 90 pct of the gas contained in a recovered sample is methane (2). The remainder consists of higher hydrocarbons, O_2, N_2, and CO_2.

The character of methane emission in salt mines is different than in coal mines. Instead of the continuous bleed of gas from the face, roof, and rib as in coal mines, methane in domal salt is emitted mainly as an instantaneous release of gas from salt broken during blasting of production faces. Gas has also been known to bleed from natural fractures in salt, from blast drill holes, or from undercutting a face in preparation for blasting. In at least one instance where a continuous miner was used, gas was emitted (1,000-8,000 ft^3/d) through the face and ribs, migrating primarily along layering within the salt (3). When compared with coal mines, some of which routinely emit several million cubic feet of methane per day, it is seen that methane sources in salt mines rarely amount to a significant volume of methane and are readily diluted by the ventilation system. This has led to the belief that rock salt is essentially impermeable, and that hazardous methane emissions generally occur only during face blasting (1).

Hazardous emissions of methane occur infrequently during production blasting. These emissions characteristically take the form of outbursts. An outburst, as it applies to rock salt mining, can be defined as an unexpected, nearly instantaneous expulsion of gas and rock salt from a production face. The results of outbursts, normally conical cavities, are created by the expulsion of broken rock salt and gas into the previously mined opening. These conical or cylindrical cavities generally range in size from 1 ft to tens of feet in diameter, and can be more than 270 ft high. Average outburst cavity heights may be 10 to 20 ft, and they are almost always propagated upward. They commonly occur at either the rib-roof junction or strictly into the roof. Only rarely has a cavity extended into the floor.

It is thought that most outbursts are at least partly the result of rapid release of high-pressure gas. In the gulf coast region the gas is mainly methane. Methane, hydrogen sulfide, and carbon dioxide have been noted in Polish salt mines for centuries (4). Outbursts at the now-flooded Winnfield salt mine in Louisiana were thought to be driven by pressurized CO_2, as were occurrences in several European salt mines. The fatal mine disaster at the Belle Isle Mine in 1979 proved that high-pressure methane in large quantities could be emitted (1, 4-5). It is estimated that more than 600,000 ft^3 of methane was emitted instantaneously from the outburst that caused that disaster (1).

How methane was incorporated in salt domes is uncertain. Methane may have been entrained in the salt mass shortly after it became mobile, or gas under high pressure from deeply buried organic sediments overlying the evaporite sequence may have been incorporated into the rising salt plume. This gas may have

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[2] Underlined numbers in parentheses refer to items in the list of references at the end of this report.

become isolated in pressurized zones and was carried within the salt stock towards the surface.

Previous work has shown a relationship between anomalous salt zones and gas occurence (2-3, 6). Kupfer describes internal anomalous zones as the area between adjacent salt stocks where rock has been included (7). Another anomalous zone is the contact of salt stocks with bordering strata. When mining approaches these large internal or boundary areas, the methane content of salt increases as well as does outburst frequency. Not all gulf coast salt mines intersect these anomalous zones, and the composition, structure, and gas history may vary greatly from one dome to the next.

Geologic factors that caused changes in crystal texture, structure of the distorted strata, and geochemical characteristics are probably responsible for the occurrence of high-pressure zones, as well as the actual outbursts. Mechanical deformation related to cavern development may also play a role, but is beyond the scope of this report. This report presents the results of detailed geologic mapping and sampling of rock salt for methane content and applies these results to aid in the prediction of outbursts.

NATURE OF OUTBURSTS AT THE COTE BLANCHE MINE

The Cote Blanche Mine, one of five remaining domal salt mines in the gulf coast region, is located approximately 30 miles south of New Iberia, in southern Louisiana (fig. 1). This mine has been in operation since 1961, using a room-and-pillar scheme. Rooms are normally 55 ft wide, square pillars are 100 ft on a side, with a first-cut room height of 25 ft. A second or bench cut is then removed by blasting out the floor, making a total room height of 80 ft. The mining plan is nearly a perfect gridwork and has not changed since the mine opened. Faces are extracted by undercutting and blasting. The salt is then screened and crushed underground and brought to the surface on a skip, where it is loaded on barges by a conveyor belt system.

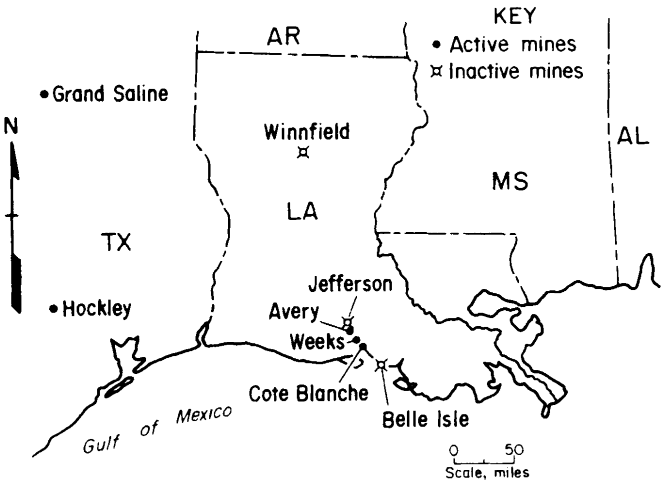

FIGURE 1.–Location of study area showing active and inactive domal salt mines in gulf coast area.

More than 80 outbursts have been observed at the Cote Blanche Mine. They occur throughout the 1,365-ft mine level, but they tend to be concentrated in relatively small areas. Most outbursts and the largest in size are clustered in the northeast quadrant and the southern half of the mine (fig. 2). Outbursts can be identified by a characteristic conical shape with concentric fracturing or onionskin texture (fig. 3). They range in size from 1 ft in diameter to the largest observed outburst, which was over 50 ft in diameter and reached a height of over 50 ft. In one benched area of the mine (22 LS), outbursts occur diagonally on either side of an entry.[3] If these two cavities are from the same outburst occurrence, as is expected, the total outburst length would be over 100 ft.

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[3] Mine location is designated by a grid work system as shown in figure 2. Crosscuts or entries separated by a hyphen (e.g., I-JN) indicate a location between the crosscut or entry; N and S indicate northern and southern part of the mine.

It is difficult to estimate the size of some outbursts, and also the number of outbursts involved because of the nature of their occurrence. Several outbursts can combine to form what appears to be one large outburst cavity. A detailed inspection may show the characteristic bull's-eye pattern at the termination of each outburst, indicating two simultaneous occurrences (fig. 3). Close observation of fracture patterns shows that many outbursts are larger in diameter than the final cavity left in the wall or roof would indicate. Further advance of the face by mining can remove much of the outburst cavity (fig. 4).

Outbursts occur in a number of shapes. Almost always the outburst cavity will have a conical or cylindrical shape, but minor variations on this shape are numerous (8).

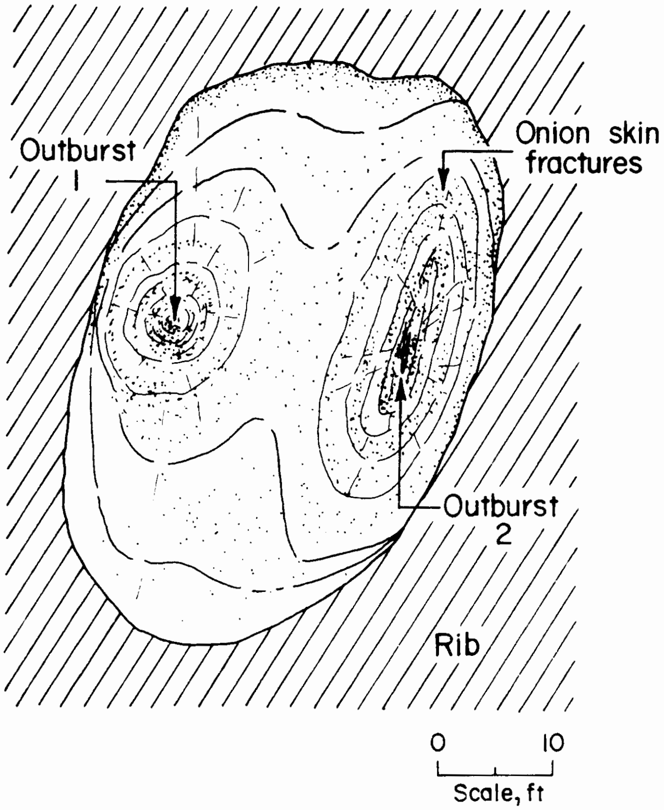

FIGURE 3.—Multiple outbursts showing concentric fracturing known as onionskin texture and bull's-eye termination.

Most outbursts at Cote Blanche Mine propagate vertically, following the near vertical domal structure, but two outbursts were observed to propagate downward into the floor. One example appears to be the termination of an outburst (8-ft diam, 5 ft deep), which seems to plunge approximately 20° below horizontal into the floor (east face of the intersection of 22 LS) (fig. 2). Another example occurs in the bench (north face of 21 NS). Extensive down-plunging outbursts could present serious hazards to multiple level mining.

Previously, it was believed that outburst occurrence in bench areas was rare. However, mapping has shown that outbursts do occur in benches at Cote Blanche (fig. 5). In fact, some of the largest outbursts were observed in bench cuts (22 LS). It was previously believed that face mining above benched areas would relieve gas pressure and prevent outbursting in the bench. But normal salt is so impermeable that it will continue to hold gas under pressure even when mine openings are close. An example is the outburst-prone area at mine location 25-26 GN (fig. 2). Mining was proceeding east between entries 25 and 26 when outbursts were encountered. Mining was halted at this point. Ten years later mining was resumed and outbursts were immediately encountered. Gas pressure had not been substantially relieved during a 10-yr period.

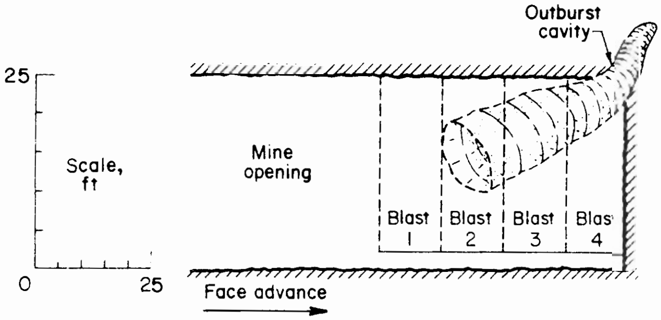

FIGURE 4.— Cross section of mining advance showing outburst cavity removal by successive production blasts.

GEOLOGY OF THE COTE BLANCHE SALT DOME

The Cote Blanche salt dome is one of the famous five island salt domes. These domes form a line trending roughly NW-SE for 60 miles just south of New Iberia, LA (fig. 1). They are diapiric salt structures originating in the Louann Formation of Permian-Jurassic age (9). It has been thought that the Cote Blanche dome is formed from at least two salt spines that moved relative to each other, leaving a marked overhang to the north (10). In contrast to the other four island salt domes, there is no underground evidence of an *internal* boundary zone at the Cote Blanche Mine that would indicate the convergence of two or more salt plumes. Kupfer reports bedding parallel to the domal margin in the southeastern part of the mine (10). This appears to be the only indication of a possible *boundary* zone within the mine limits. This type of zone is caused by vertical dome movement and results in drag of adjacent rock and salt layers.

As in all of the other Louisiana five island salt domes, the internal structure is nearly vertical, although locally salt beds have been observed to roll over to nearly 45° from horizontal. Mapping shows internal structure to be extremely complex (figs. 6-7). The alternating bands of light and dark salt are considered to be original bedding from the evaporite sequence (10). Sediment inclusions occur mainly in the form of an interbedded sand, as opposed to the massive incorporation of clastic and organic debris in anomalous zones. These sandy beds are considered original bedding for several reasons. First, they follow closely the trend of salt layering in occurrences throughout the mine; second, they maintain a fairly constant thickness (1-6 ft); third, the contact between the sand and the adjacent salt is very sharp; and fourth, the sand has a fairly consistent mineralogic composition. This sand unit is one of the few marker beds in the complexly folded salt strata. Another marker bed is a black, carbonaceous silt clay member (fig. 8).

Figure 9 shows the distribution of sand throughout the mine. Based on these marker beds and structural mapping, it appears that although local folding is complex, the axis of a large fold runs from the northwest to the center of the mine and turns southward. Since the strata are nearly vertical, the best description of the structure may be as a vertical, elliptical cylinder, open to the northwest. Folding in the northern half of the mine appears to be broader and more open with the fold limbs approaching each other and tightening as the axis is followed southward (fig. 10). This interpretation is supported by previous mapping (10).

The interbedded sand occurs discontinuously. It may be persistent over several crosscuts then disappears and reappears after skipping a crosscut. It occurs as a sequence of up to two closely spaced thin exposures from 1 to 6 ft thick (6 LN). It is possible the exposures are from the same complexly folded bed (6 LN) (fig. 11). It is possible that *all* of the sandstone in the mine is from the same

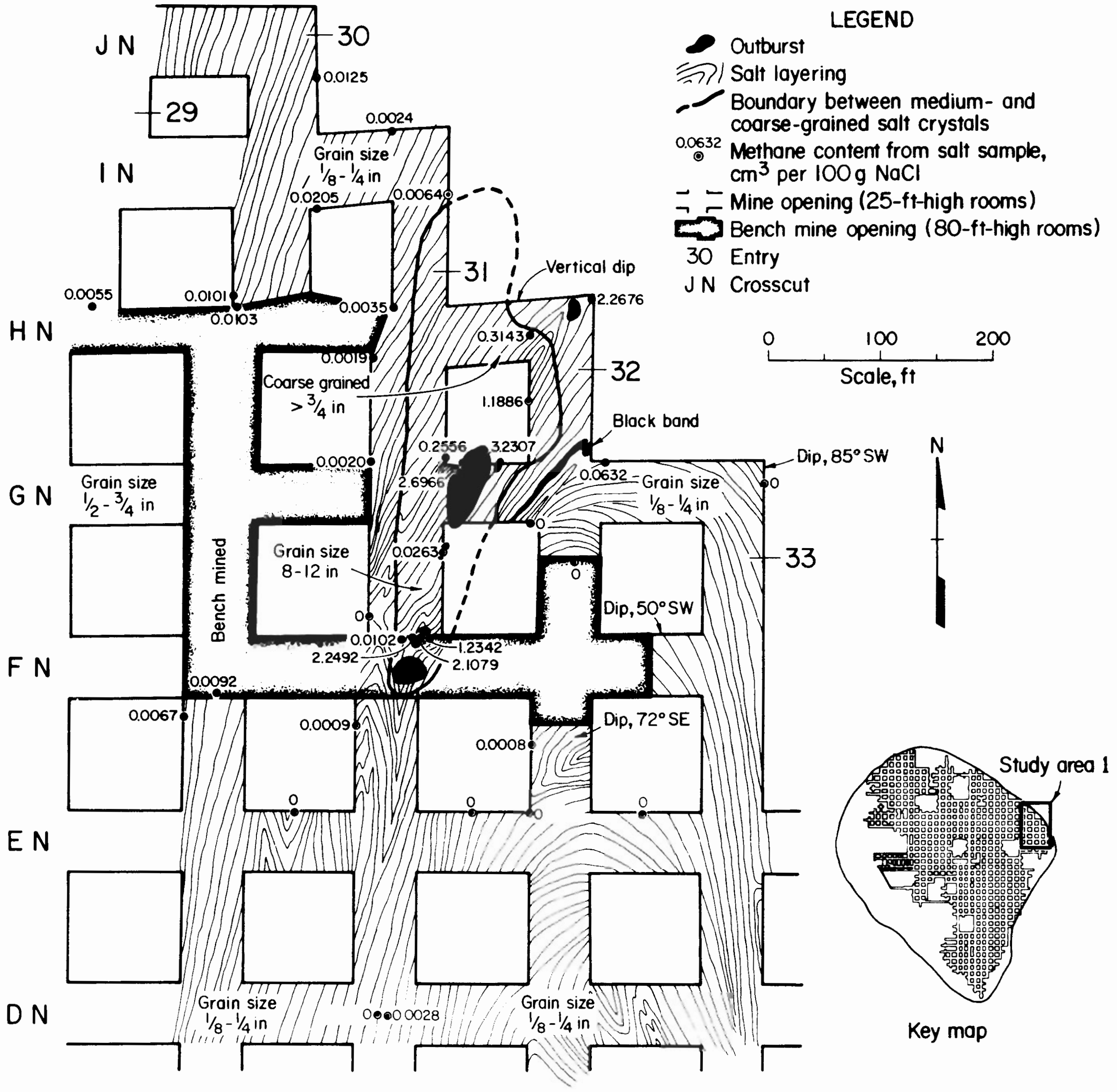

FIGURE 6.–Mine map showing outbursts and their relationship to layering structure, salt crystal size, and methane content, study area 1.

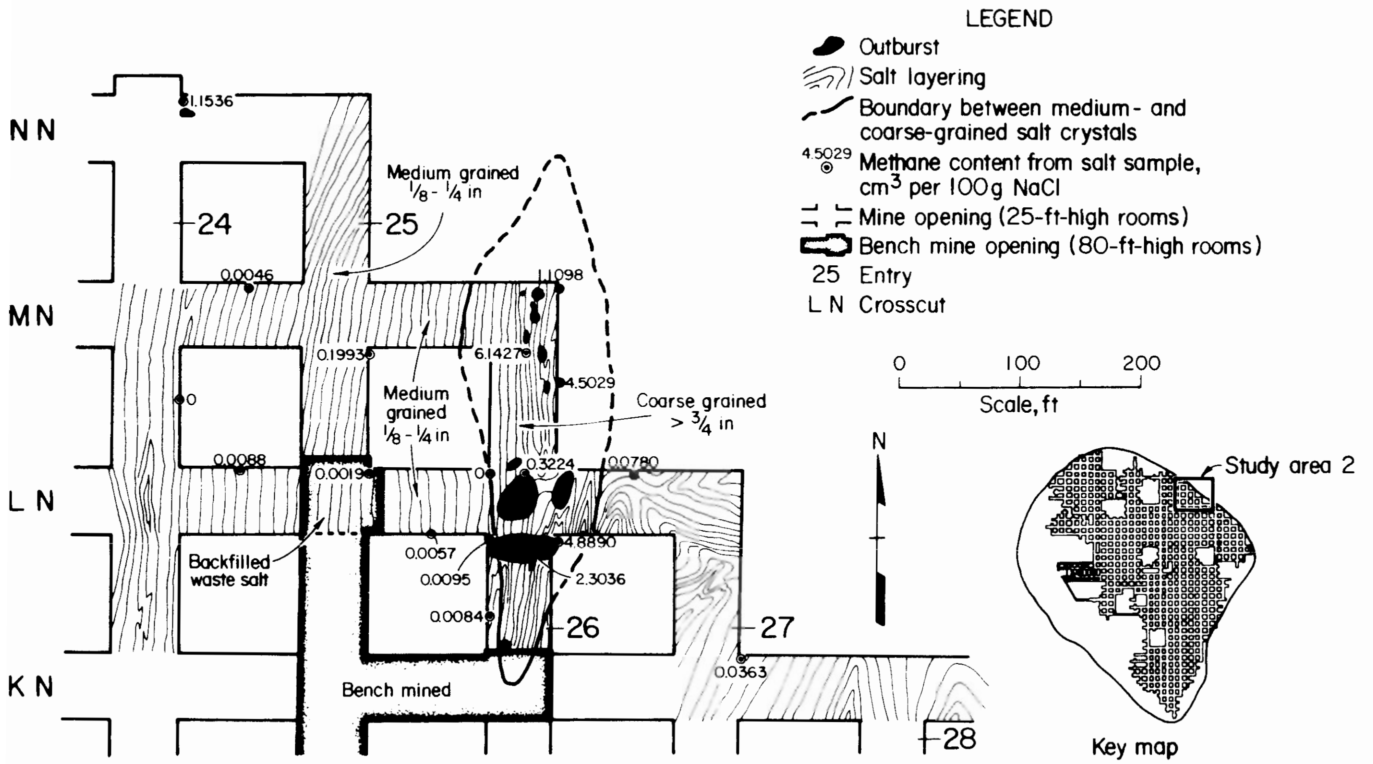

FIGURE 7.–Mine map showing outbursts and their relationship to layering structure, salt crystal size, and methane content, study area 2.

stratigraphic horizon. Because of the complex folding of domal strata, the bed could have folded back on itself in the area around 22 ON and continued south through the center of the dome. The sandstone bed should be continuous but it is absent probably because of vertical shearing, which may leave the sheared portion of the bed either above or below the mined horizon.

The sandy beds, in many instances, occur as blocky cobbles up to 4 ft in diameter. These blocks sometimes form a collapse breccia. At 8-9 PN it appears that the potash matrix was partially dissolved, allowing the sand bed to collapse and brecciate. A boudinage structure also commonly occurs (fig. 12). Boudinage structure is characterized by sausagelike shapes caused by pinching and swelling deformation. These rolled and stretched blocks are a result of vertical transport. In one instance, a thin (2-in thick) continuous clay band parallels the boudinage structure, attesting to the coherency of the clay layer relative to the rigid, discontinuous sandstone. With vertical flowage the clay grains flattened out and stretched, maintaining the strata continuity. The nonplastic quartz grains separated and formed the boudinage structure.

The sand occurs as both unconsolidated sediment and as sandstone blocks with KCl as the cement for both blocks and grains. The amount of sand within the layer varies from 60 pct to only a few percent. The sediment is sometimes replaced by a pinkish-orange sylvinite, a mixture of halite and KCl minerals. The amount of KCl is approximately 7 to 10 pct. Kupfer states that this association of KCl and sand is not unexpected in the original environment of deposition if it is assumed that the sand and KCl are both primary bedding (7). The potash mineral, sylvite, is quite common and is precipitated from a brine solution when evaporation rates are high, possibly because of high winds. In such an arid climate, large amounts of sand and silt could be blown into the evaporite basin.

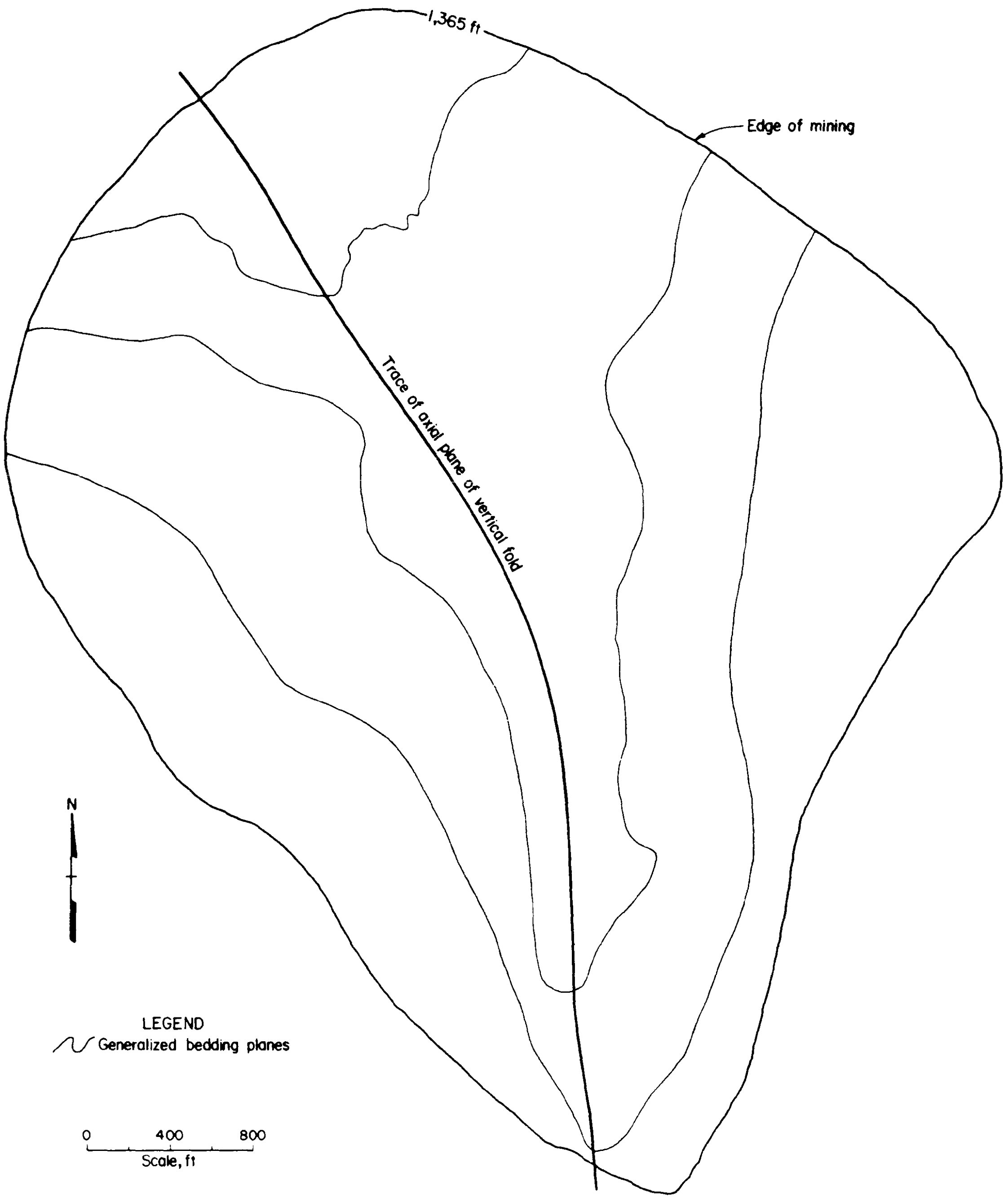

FIGURE 10.–Generalized structure map of Cote Blanche Mine.

Table 1 shows the mineralogic composition of dissolved-out (salt-free) clastics from seven sediment samples. Quartz is the predominant mineral, with up to 25 pct rock fragments as the next most frequent component. Rock fragments are generally sandstone or siltstone with a small percentage of metamorphic fragments. Other components include mica, aragonite, calcite, dolomite, and chert. Some anhydrite is found, but although an insoluble, it is not a detrital mineral.

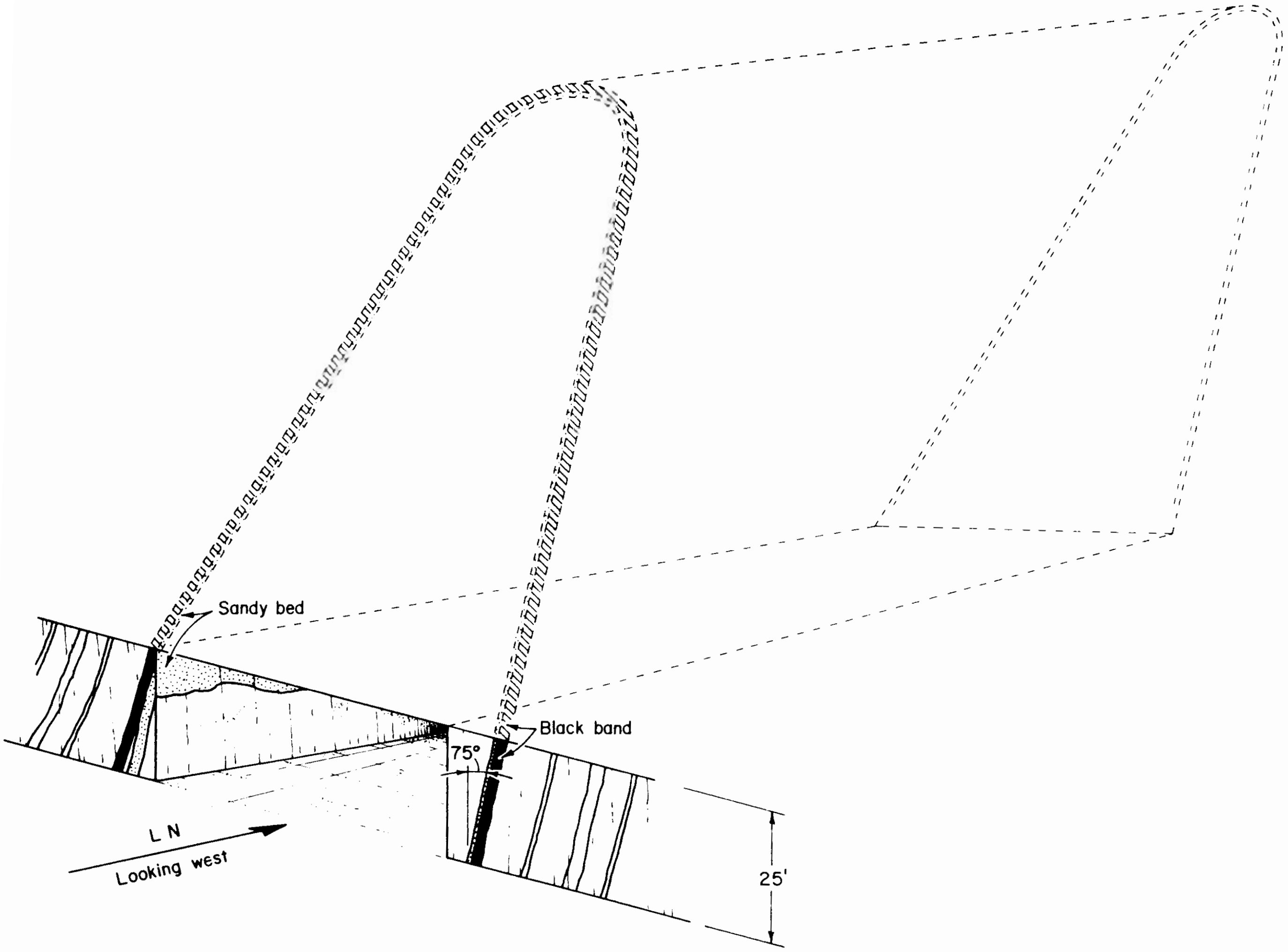

FIGURE 11.–Overturned beds at Cote Blanche Mine.

TABLE 1. - Mineralogic composition of salt-free sediment from selected samples, Cote Blanche salt mine, percent

Sample	Quartz	Feldspar	Rock fragment[1]	Other	Location
1........................	74	0	25	1	10 I-JN
2........................	62	9	19	10	8 MN
3........................	76	3	21	0	15 LN
4........................	78	1	19	2	8- 9 CS
5........................	68	14	16	2	27 JS
6........................	78	1	19	3	8- 9 CS
7........................	78	6	15	1	7- 8 KN

[1] Shale, siltstone, sandstone, metasediments.

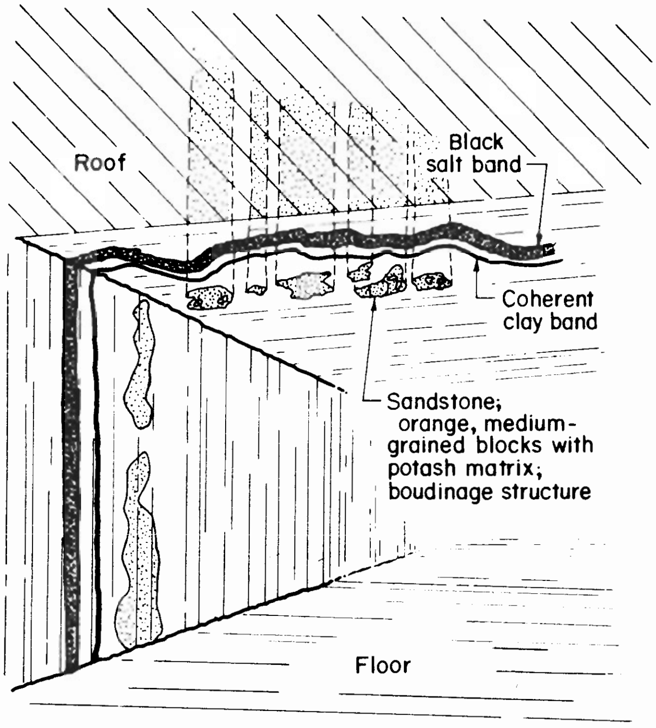

FIGURE 12.–Vertical sandstone unit showing typical pinch and swell boudinage structure.

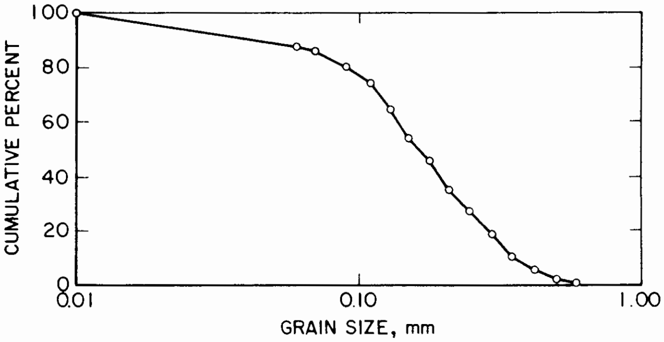

FIGURE 13.–Grain size distribution plot of sediment dissolved out of included sandstone.

The average grain size is fine to very fine sand with many grains being rounded to well rounded. Figure 13 is an average grain size distribution plot developed from standard sieve analysis for the sandstone. The samples average 10 to 15 pct of sediment in the silt size or smaller range. The extreme rounding, sphericity, and frosting of the quartz grains, and the grain size distribution, support the theory of aeolian transport into the evaporite basin. These parameters were evaluated by standard petrographic methods. This sandstone, when exposed, weathers easily in the mine atmosphere, because the KCl minerals readily absorb moisture and swell, disrupting bedding integrity.

Sandy beds with varying amounts of KCl are the most frequently observed clastic occurrence. But at 26 JS another type of sediment is observed; a reddish-brown sandstone, much harder than the first example (fig. 8). This exposure is a true sandstone, while most of the other sediment is unconsolidated. It appears that this is an individual bed separated stratigraphically by several hundred feet from the KCl-rich sand unit. It is impossible to determine the relative stratigraphic age because of complicated folding. The individual quartz grains are stained reddish, and there is a higher percentage of feldspar (sample 5 in table 1). In the northern half of the mine there is a thin bed of black, carbonaceous silt clay. It is seen in four exposures (8 KN, 17 MN, 22 ON, 21 NN) (fig. 8). The assumed continuity of this layer across the mine is based entirely on these exposures. Kupfer observed black clay in small balls in the southern part of the mine associated with outbursts (10). No such association was observed with this clay layer.

Occurring principally in the southern part of the mine is a zone of hard, fine-grained salt (fig. 8). This salt is extremely fine-grained and brittle and has a characteristic ringing sound when struck. Kupfer described the zone as "yellow massive salt" (10). This zone can be traced from 14 DS to 18 PS. It is best exposed in the ventilation tunnel at ES, where it is associated with brine seepage and chemical impurities. This salt is particularly difficult to mine because of its hardness. It is difficult to drill and blast as well as to crush. The salt occurs in a zone as an interbedded normal salt and fine-grained salt. The zone appears to be over 300 ft wide at its northern termination at 14 DS, and tapers to 20 ft at 18 PS. It is also known sporadically in the northern part of the mine at 15 ON, 18 QN.

There is a distinctive jointing pattern associated with this fine-grained salt, which is not found in any other part of the mine. At 18-1/2 JS there is an opening that appears to be a natural cavity. It is approximately 13 in high by 30 in wide and at least 30 ft deep. When this opening was first encountered by mining, gas pressure was observed during undercutting. There is a sequence of closely spaced joints trending N 50° E both above and below the cavity. The joints dip 23° SW, paralleling the open fracture. The same joint pattern occurs in the next room at 19 IS. These are the most prominent joints, although they occur elsewhere in the fine-grained salt zone.

METHANE CONTENT OF THE COTE BLANCHE SALT DOME

Gases physically occur in salt in several ways. The gas can exist on the crystal boundaries or between grains. Methane that exists in this way would be most likely to escape upon production blasting or fracturing due to blasting. Methane can also occur entrained within the salt crystal matrix itself (fig. 14). Entrained bubbles, several millimeters across, can be seen with the unaided eye. These bubbles, which occasionally contain brine, are best seen in very methane-rich salt. Gases can also occur in more permeable zones usually associated with sediment-rich anomalous zones (2). When these zones are penetrated by mining or drilling, small amounts of gas can bleed off. Gases rarely occur in open cavities or pockets. The plastic nature of salt, especially mobile salt, is to close all openings. Evidence that outburst gases are not contained in a cavity is seen by the amount of salt expelled by the outburst. The volume of salt

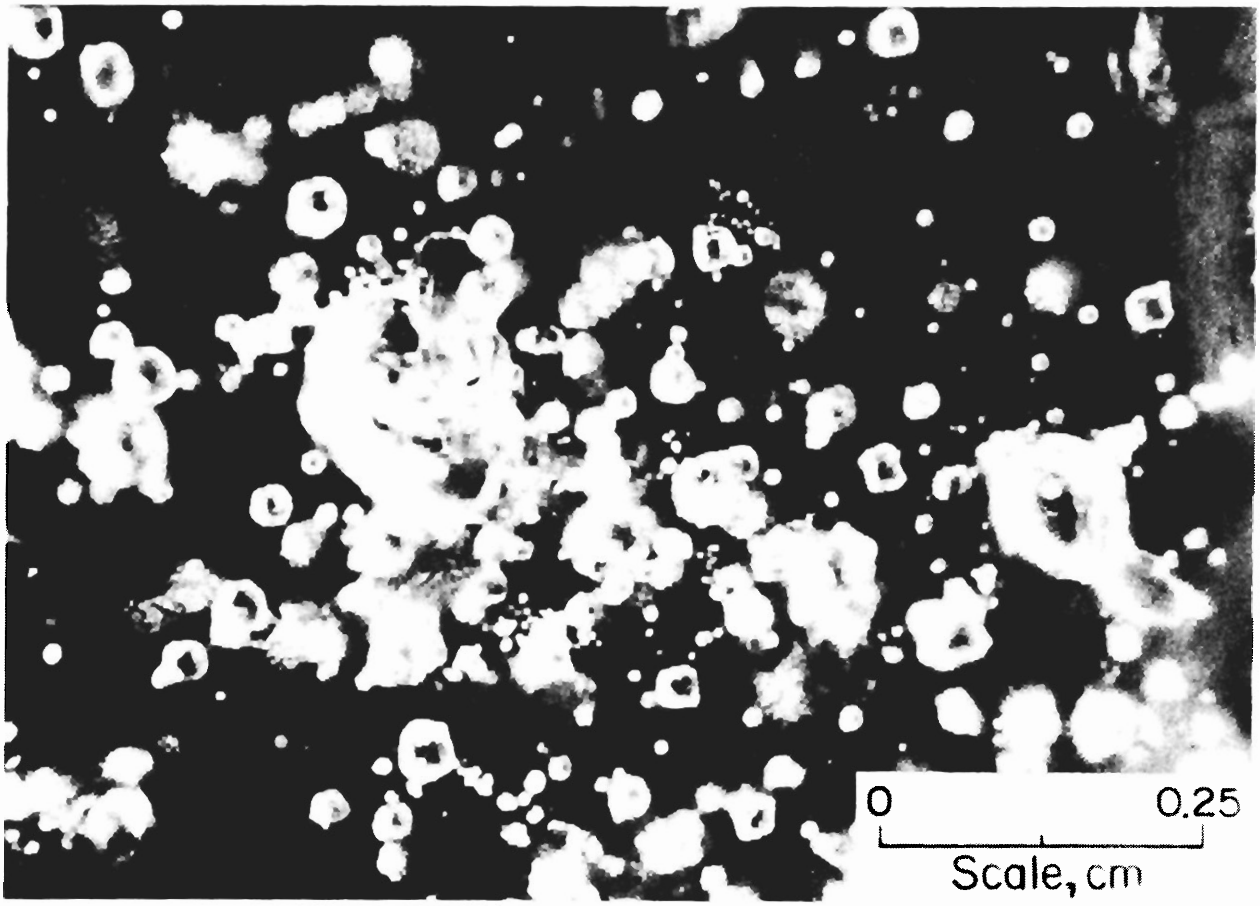

FIGURE 14.–Photomicrograph of salt crystal showing entrained gas bubbles.

expelled is generally enough to fill the cavity.

Previous Bureau work has shown that high methane content and outburst occurrence in domal salt are related (11). Even though outbursts are not exclusively related to methane content, this property can be used as an early warning device. The Cote Blanche Mine currently uses a field-adapted dissolution test for methane. This test was developed by the Bureau and relates noise levels given off by the salt when methane is released to methane content. Salt is dissolved in fresh water and a microphone records the popping sound generated by the pressurized methane. These noise levels have been calibrated to methane content using the standard dissolution test also developed by the Bureau (12). The test has been shown to be useful in alerting mine personnel to gassy conditions. At Cote Blanche, a new level is being planned above the present level. Since strata continuity is near vertical in salt domes, methane-enriched zones can be projected vertically. So by charting methane content on one level, this same information may be used as an aid to reducing hazards on another level.

Salt samples from Cote Blanche Mine have been tested for methane content in order to characterize the nature of methane occurrence. Two hundred nineteen salt samples have been tested for methane content at Cote Blanche. Many of the gassy areas of the mine have been sampled as well as a random sampling for control. Methane content ranged from 0.0 to 8.7 cm^3 CH_4 per 100 g NaCl. A salt sample is considered methane enriched when more than 0.30 cm^3 CH_4 per 100 g NaCl is measured (11). Some of the methane contents at Cote Blanche are among the highest measured in the Gulf Coast basin. Table 2 shows some of the methane content samples at Cote Blanche, their locations, and salt type. It can be seen that most of the highest methane contents are taken directly from outburst cavities or from salt ejected from those cavities. The lower methane concentrations are mainly taken from normal or run-of-mine salt. In addition, the frequency of higher hydrocarbons increases with methane content. This relationship was also indicated by Schatzel (11).

Figure 15 shows the distribution of salt samples and their associated methane contents over the mine area. The major outburst areas (26 MN, 25 GN, 31 GN, and 21 MS) all have high methane contents associated with samples drawn from the outbursts themselves or the broken salt ejected from the outburst cavity. This observation is consistent with findings at other domal salt mines in the area (11). This relationship indicates that routine sampling for methane content can be an effective way of indicating outburst potential.

Schatzel (11) determined that there is a relationship between the type of salt and volume of associated methane. There are three types of rock salt; normal, anomalous, and outburst. Normal salt is pure halite with rare inclusions. This salt normally has no methane associated with it. Anomalous salt contains sediment, organic, or chemical impurities. This type of salt normally is more likely to be methane enriched, but this is not true of anomalous salt tested at Cote Blanche. Outburst salt is rock salt collected directly from an outburst cavity, or from broken salt ejected from such a cavity. Most samples of this salt type show methane enrichment; as do outburst samples from Cote Blanche. Most normal salt samples from Cote Blanche have a low methane content. Samples were also collected systematically across the mine along entries BN, CN, and HN; two grab samples per pillar (fig. 15). Most of these samples show little methane enrichment, supporting the observation that methane occurs in discrete zones, rather than being disseminated uniformly.

At Cote Blanche, methane enrichment in salt samples has occurred in areas where no outbursts occur. Examples include the decline from the face mined level to the bench level (13-18 AN). Methane was encountered continuously during the development of this slope. Methane was emitted during face drilling and undercutting operations. Another area of methane enrichment is the ventilation tunnel between 16 and 18 ES. Here, brine and methane were encountered during

TABLE 2. - Methane content and location of selected salt samples, Cote Blanche salt mine

Sample	Salt type	Ch_4 per 100 g NaCl, cm^3	Higher hydrocarbons	Mine location
8	Normal	2.029	C_2H_6	22 HN
9	..do	2.048	C_2H_6, C_3H_8, C_4H_{10}, C_5H_{12}	26 EN
10	NA	2.107	C_2H_6	31 FN
11	NA	2.249	C_2H_6	31 FN
12	Anomalous	2.267	C_2H_6	32 HN
13	NA	2.303	C_2H_6, C_3H_8, C_4H_{10}, C_5H_{12}	26 LN
14	NA	2.369	C_2H_6	20 GN
15	Outburst	2.379	C_2H_6	25 GN
16	Normal	2.657	C_2H_6	23 HN
17	Outburst	2.696	C_2H_6, C_3H_8	31 GN
18	NA	2.757	C_2H_6, C_3H_8, C_4H_{10}, C_5H_{12}	25 EN
19	Outburst	3.230	C_2H_6, C_3H_8	31 GN
20	..do	3.470	C_2H_6, C_3H_8, C_4H_{10}	31 CN
21	..do	3.595	C_2H_6, C_3H_8, C_4H_{10}	25-26 GN
22	..do	3.758	C_2H_6	25 GN
23	Normal	4.502	C_2H_6, C_3H_8, C_4H_{10}	26 L-MN
24	Outburst	4.663	C_2H_6	25 GN
25	NA	4.687	C_2H_6, C_3H_8, C_4H_{10}, C_5H_{12}	18 GN
26	Normal	4.889	C_2H_6, C_3H_8, C_4H_{10}	26 LN
27	..do	5.635	C_2H_6, C_3H_8, C_4H_{10}, C_5H_{12}	18-19 GS
28	NA	5.711	C_2H_6	21 NS
29	Outburst	5.719	C_2H_6, C_3H_8, C_4H_{10}, C_5H_{12}	26 GN
30	..do	6.128	C_2H_6, C_3H_8, C_4H_{10}, C_5H_{12}	26 GN
31	NA	6.142	C_2H_6, C_3H_8, C_4H_{10}, C_5H_{12}	26 MN
32	Outburst	6.502	C_2H_6, C_3H_8, C_4H_{10}, C_5H_{12}	21 NS
33	..do	7.424	C_2H_6, C_3H_8, C_4H_{10}, C_5H_{12}	26 GN
34	NA	7.561	C_2H_6, C_3H_8, C_4H_{10}, C_5H_{12}	21 DN
35	NA	8.204	C_2H_6, C_3H_8, C_4H_{10}, C_5H_{12}	22 LS
36	NA	8.603	C_2H_6	26 GN
37	Normal	8.783	C_2H_6, C_3H_8, C_4H_{10}, C_5H_{12}	22 LS

NA Not available.

tunnel advancement through impure, dark-banded salt. The presence of methane is indicated by popping salt, large crystal size, and actual emissions in a number of areas devoid of outbursts. While methane under pressure appears necessary to outburst occurrence in the gulf coast, it appears that this is not the only important factor. Other factors may include rock strength, or strata weakening due to geologic or mechanical events. Inherently weak salt (folded or sheared), or salt weakened mechanically because of overloading of undersized pillars, may be more susceptible to blowouts in high-gas-pressure zones.

RELATIONSHIP OF GEOLOGIC PROPERTIES OF SALT DOMES TO OUTBURSTS

Three other geologic associations of salt were investigated to determine if they could be used to predict outburst potential. These include large-scale and local structural layering, salt crystal size, and salt composition. Two outburst areas at Cote Blanche Mine were mapped in detail. Mapped features include outburst size, shape, and location; salt crystal size and the variation of that crystal size with proximity to outbursts; and salt banding direction and disturbance related to outbursts. Salt samples were collected in the study areas and tested for methane content to determine relative gassiness.

SALT LAYERING AND STRUCTURE

Large geologic structures in the mine are indicated by the orientation of alternating light and dark salt layers. This layering trends northwest on the west side of the mine and northeast on the east side and ranges from 45° to vertical and overturned (fig. 8). An example of overturned beds occurs at 5-6 LN (fig. 11). Here, the layers overturned in the roof and give the false impression of multiple sandy beds, which are actually one bed. Dips average 75° to 85° from horizontal. Outbursts tend to occur along linear trends that parallel large-scale layering. In the southern part of the mine a series of outbursts follow a linear trend approximately N 30° E, from JS to NS. This direction parallels the salt layering. In the east-central part of the mine, from EN to HN, another series of outbursts also parallels layering that trends N 10° E. At 17-18 MS three outbursts (ellipsoid shaped; 15 by 7 ft, combination of two; 15 by 5 ft) parallel fine-grained salt beds that trend N 20° W. In study area 1, the series of outbursts also parallel local layering, which trends almost N 30° E (fig. 6). Finally, in study area 2, from FN to HN, the line of outbursts closely parallels layering that runs approximately due north (fig. 7).

The intensity of layering disturbance appears to increase near an outburst occurrence. Two outburst areas were mapped in detail. These indicate the complexity of local layering, and show the location of outbursts up to 50 ft wide (figs. 6-7). Figure 6 shows the structural detail that can be seen in the roof in study area 1. The tight isoclinal folding increases in complexity nearest the outburst area and immediately around it. Study area 2 also exhibits complex folding and shearing nearest the outburst area, as well as salt beds that dip to nearly 45°. These zones of complex folding extend 100 to 150 ft beyond the outburst area in all directions. Although outbursts may occur related to folding intensity in some areas, there are numerous examples of complexly folded beds where no outbursts occur. Therefore, the use of folding and folding intensity as a predictive tool is not supported.

Locally two situations appear to show structural control of layering over outburst occurrence. In the southern part of the mine (21 MS), several outbursts are confined between two black anhydrite layers. The location and direction of propagation of these outbursts is probably controlled by the vertical anhydrite layers (fig. 16). In one instance a 3- to 4-ft-diam outburst is confined between two anhydrite-rich layers, and forms a pipe extending into the roof to an unknown height. In another instance, at 18-1/2 FS, a small outburst (2- to 3-ft diam) is confined between two fine-grained salt bands. These layers appear to be confining the gas and acting as barriers.

SALT CRYSTAL SIZE

It is widely suspected by the Gulf Coast mining industry that large salt crystals are related to high methane content. At Cote Blanche, where the decline

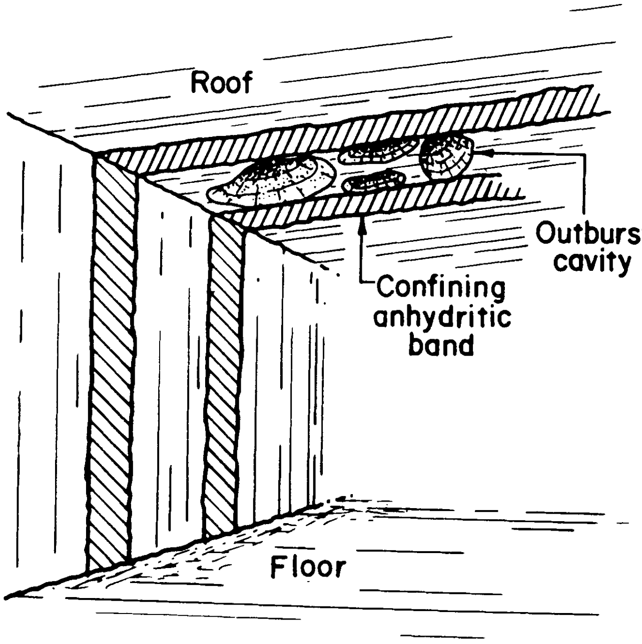

FIGURE 16.–Outbursts confined between anhydrite (black salt) layers.

to the bench level produced gas during drilling and undercutting, salt crystals more than 12 in long are common. Other areas of unusually large cyrstal size often are characterized by popping salt (24 LN, 17 LN) (fig. 8). The texture of salt crystals within Cote Blanche Mine has been described as poikiloblastic (10). This is a metamorphic rock texture in which large crystals form in a matrix of finer grained material and also include smaller crystals within the large crystals. The average salt crystal size in the mine is 1/8 to 1/4 in with a normal even-grained texture. The poikiloblastic texture is common to approximately one quarter of the mine. Individual recrystallized grains can range up to tens of feet across in extreme cases.

Additionally, salt grain size does not appear to be related to layering. Zones of coarse crystals cross layering and fold trends without being influenced. Layering, which represents primary bedding, has persisted from the evaporite basin and subsequent recrystallization has overprinted the coarse crystal zones.

Figure 17 shows the distribution of salt crystal size versus methane content for 219 samples from all over the Cote Blanche Mine. The middle axis of individual grains was measured and an average grain size was estimated for each sample. The grain size was then plotted versus methane content, which was obtained for each sample. The normal grain size at Cote Blanche is approximately 1/8 to 1/4 in. Most samples in this size range had little variation in grain size. This grain size is characterized by low methane content with the relative proportion of normal size samples decreasing as methane content increases. The larger grain sizes (>0.50 in) showed much more variation in the range of grain sizes. These size ranges also were related to increasing methane content.

In both study areas located in the northeastern part of the mine, salt crystal size was mapped in proximity to the outburst zone. There is a noticeable increase in crystal size in a zone that parallels the trend of the outburst zone in both study areas (figs. 6-7). Salt crystal size changes abruptly adjacent to the zone. Crystals within the zone

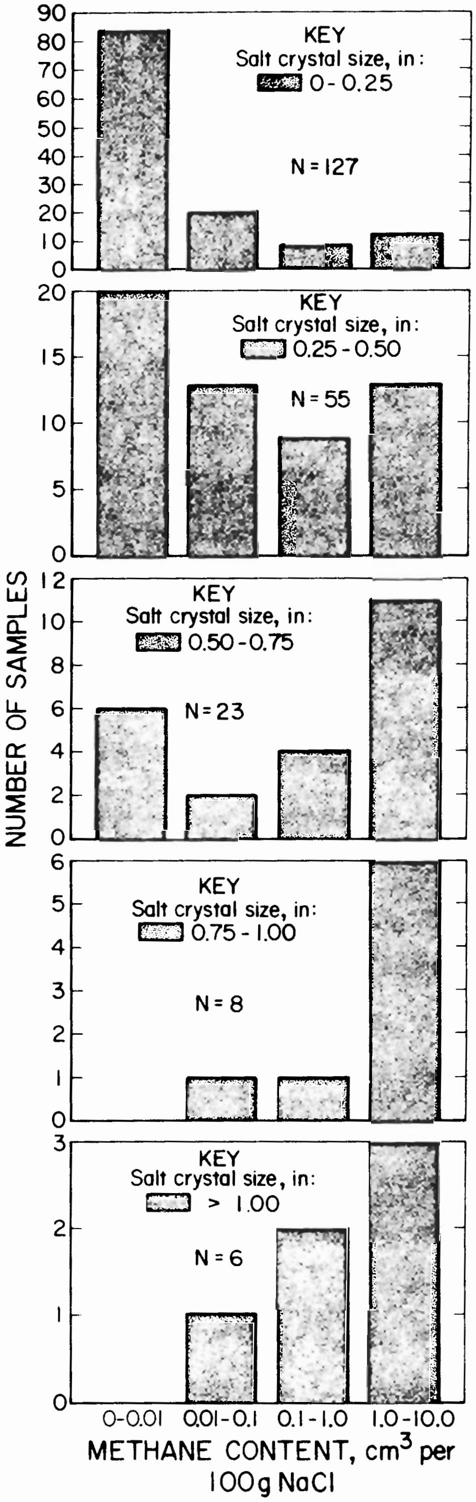

FIGURE 17.–Distribution of salt crystal size versus methane content at Cote Blanche Mine.

commonly reach 6 to 8 in, compared with the normal crystal size of 1/8 to 1/4 in. The texture is poikiloblastic, with smaller grains serving as matrix for the oversized salt grains. The zone is well defined and appears as a vertical envelope around the linear outburst trend. In study area 2, the zone includes all the outbursts and a region up to 50 ft away. In study area 1, all but one of the mapped outbursts are included within the coarse crystal zone. The boundary between coarse and normal salt crystals extends up to 50 ft from the line of outbursts.

The occurrence of methane in bench holes drilled in the floor along entry GN generally coincides with the boundary of the coarse crystal-gassy zone. Methane concentrations of over 1 pct were measured at the bench floor hole collars 125 ft from the outburst zone. A concentration of nearly 5 pct was measured emitting from a hole drilled 1 h earlier at a site 100 ft from the outburst zone.

This well-defined zone of large crystals is not unusual in this salt mine or others in the area. Muehlberger reports a similar zone with halite crystals up to 100 ft long at the Grand Saline Mine (13). Salt purity is also well correlated with crystal size. Generally, the larger the crystal the purer the salt. It is possible that these areas are zones of recrystallization due to permeating brine in anomalous zones. Methane, as well as brine, may be entrapped within large crystals, and on the crystal boundaries. These pods then become isolated by differential movement.

Most of the areas in which outbursts occur have larger than normal crystal sizes. In addition, most of the areas in which high methane contents have been measured also have large salt crystals.

In study areas 1 and 2, salt samples have been tested for methane content and these values plotted along with salt crystal size (figs. 6-7). Study area 1 shows that seven samples within the coarse crystal zone were enriched in methane, with the highest methane content being 3.2 cm^3 per 100 g NaCl. Only one sample outside the coarse-normal crystal boundary was shown to be enriched in methane, and this value is associated with an outburst. Methane contents within the coarse crystal boundary range are more than 150 times those outside the zone. Study area 2 shows six samples within the coarse crystal zone that were enriched in methane, with the highest being over 6.1 cm^3 per 100 g NaCl. This concentration is also more than 150 times that of a sample just outside the zone (0.0363 cm^3 CH_4 per 100 g NaCl). These methane enrichments correlate very well with the occurrence of coarse crystal salt and outbursts. Such detailed mapping and sampling is necessary in order to document the abrupt changes in crystal texture and methane content that take place in the complexly folded salt dome.

The use of salt crystal size along with routine methane content testing can be valuable in predicting the approach to a gassy area. But it must be realized that even if all the criteria indicate the approach to a gassy area, mining may already be very close to an outburst-prone area. Face advance could be as close as 50 ft to a high-pressure zone before changes in methane content and texture indicate a potential hazardous situation.

SALT COMPOSITION

There are several instances where included sediment, fine-grained salt, and outbursts occur together. At 23 JS, a sandy KCl bed (6-12 in thick) bends sharply (fig. 9). On the inside of this bend an outburst occurred. The outburst cavity, approximately 15 ft in diameter and 5 ft high, appears to be confined by the sandy bed on one side. Another outburst, approximately the same size, occurred along this same sandy bed at 23 KS. At 22 ON an outburst (15- to 20-ft in diam, 8 ft deep) occurred on the inside of tight fold of a sandy bed (6 in thick). Parallel to the sandy bed is a thin (6 in) carbonaceous silt clay layer and a bed of fine-grained salt (6 in). There are other instances (18-19 ON, 24 MN-NN) where outbursts and sandstone occur in proximity to each other (within 100 ft), but in none of these cases does it appear that the sandstone, in many instances merely unconsolidated sediment, acts as a significant source or conduit for methane. Most of the outbursts and outburst areas occurred where there is no sign of bedded sediment.

The fine-grained salt trend, extending from ES to OS in the southeastern portion of the mine, is associated with hydrocarbons in several locations. At 18 MS, four outbursts, three approximately 15 by 8 by 5 ft and one approximately 3 ft in diameter, occurred in the roof and rib. These outbursts are aligned parallel to the fine-grained salt layering. Another outburst at 18-1/2 FS is confined between two glassy salt layers. At 18 ES, there is a petroleum seep in the rib. At 17 DS a fracture that bled methane occurred at the roof-rib junction. The mine operators flared gas from the bleeder for more than 1 yr to avoid a hazardous accumulation (10). This gas vent exits the northern boundary of the fine-grained salt trend. The ventilation tunnel (16-18 ES), in which wet, gassy conditions occur, also cuts through the zone of hard, fine-grained salt.

USING GEOLOGIC MAPPING AND METHANE CONTENT SAMPLING FOR PREDICTION OF GASSY ZONES

The investigation of the geologic properties of the Cote Blanche salt dome is aimed at determining how these properties relate to methane-rich zones and then, using the properties with significant relationships, it is hoped to predict the occurrence of these zones in advance of mining. It was necessary to map the location and trend of existing methane-rich zones in order to realize how methane occurs, and its extent and distribution within the mine. Methane-rich zones can be indicated by outbursts, methane emissions, high methane content, very coarse salt crystals, and wet impure salt zones. At other domal salt mines in southern Louisiana, it has been hypothesized that methane is related to boundary zones of anomalous impure salt, which mark the transition between salt stocks. These zones appear to at least be sources of methane, and could possibly be conduits for gas migration from remote areas, possibly outside the dome. At Cote Blanche no such boundary zones have been exposed by mining. A series of thin sand beds are the only included sediment occurrences and these are determined not to be significant sources of methane.

It was also found that lines of outbursts parallel large and small structural features in the dome. The major structural pattern is a large elliptical fold that has an axis which runs from the northwest to the center of the mine and turns southward along entry 20-21 (fig. 10). The series of sandy beds occurring throughout the mine can be used as marker beds for structural mapping. By documenting the large-scale as well as the small-scale structural trends (study areas 1 and 2), projection of linear trends of gassy zones may be possible. If methane-rich zones do show linear properties they may also be projected vertically, since vertical continuity is consistent in salt domes.

Detailed mapping of salt crystal size has shown that methane-rich zones are indicated by large salt crystals, and possibly distorted and kinked layering. These zones are also linear, can be as narrow as 200 ft wide, and are abruptly separated from normal size salt crystals (1/8-1/4 in). Routine documentation of salt crystal size can also indicate if trends are present, and forecast the approach to a gassy zone. It was also found that methane enrichment and large salt crystals occur commonly in other parts of the mine where no outbursts occur. It appears that some additional parameter is important to outburst occurrence. Possibly, the mehcanical properties of rock salt are important in the generation of outburst conditions.

Geologic mapping should be done shortly after blasting before diesel soot deposits obscures roof and rib structures. Soot buildup occurs within a few months. Field mapping should be done on no smaller than 1 in = 100 ft base maps. This will allow most of the complex structural detail to be included. Accurate *sketches* of roof and rib banding should be made, as well as actual strike

TABLE 3. - Procedures for predicting gassy conditions

Mapping.......	Outbursts (size and shape).
	Banding sketch in roof (1 in = 100 ft base map).
	Bed attitude measure (strike and dip).
	Crystal texture (even grained, poikiloblastic), average crystal size, crystal shape.
	Composition--sediment, inclusions (attitude, bedded, foreign), chemical changes (color, taste).
Sampling......	Methane content of salt--standard dissolution, acoustic field dissolution (several representative samples per face).
	Bottle sample for methane from bleeder or drill hole.
Drilling......	Exploration hole--200-300 ft in advance.
	Core log--crystal texture composition.
	Reservoir tests--methane content of core, methane flow, formation pressure packing, packing intervals, recovery time after shut-in.
	Gas composition analysis.

and dip readings taken. Special attention should be taken to map grain size, disturbed banding, and rapidly changing bed attitude. Several measurements (bed attitude, grain size) per intersection are necessary. Any unusual features, such as sediment inclusions, thick black bands, yellow salt, petroleum or brine seeps, potash trends, or outbursts, should be mapped and appropriate bearing taken. Mapping of salt impurities will also be very useful for production quality.

The mapping of texture includes an overall statement of type of texture; whether the salt is even grained or poikiloblastic. Mapping crystal size usually means estimating since access is limited. It is necessary to make many observations in order to arrive at a representative grain size. This high frequency of observation is also necessary since crystal size changes rapidly.

Methane content of salt should be determined at each production face. At least one sample could be taken from the face on each of four corners and one in the middle. This could be accomplished during the face loading part of the mining cycle when access is available from the jumbo drill platforms. These samples could be processed in as little 5 min each by the acoustic dissolution test. Results from these tests could be used to build a three-dimensional model of methane concentrations.

Information can also be gained from drill hole data. Long exploration coreholes can be logged for salt composition and purity, crystal size, and methane content. Also, the disking of core from exploration holes has been used to indicate high-pressure gas zones. Oriented properly, by knowing existing geologic trends, these holes may delineate potential problem areas. In addition, reservoir properties, such as formation pressure and gas flow may be determined. Table 3 shows the necessary predictive procedures.

Although the existence of any single criterion may not be sufficient to indicate gassiness, it appears that the probability of encountering outbursts is greatly increased when all three of the following criteria are observed:

1. High methane content.
2. Unusually large salt crystal size.
3. Increased tightness of folds and kinking.

METHANE CONTROL STRATEGIES

Once sufficient mapping and sampling data have been obtained to delineate potential methane-rich zones, some strategy must be implemented to control potential emission of methane into the mine. Iannacchione (3) found that boreholes drilled into gassy salt zones built pressures rapidly when shut in, but that these pressures were also rapidly dissipated. Additionally, the holes had relatively low gas flows. Therefore attempts at long-range gas drainage by horizontal holes would fail in the impermeable salt strata. Local drainage might possibly have some success. If long exploration holes identified methane-rich zones, it may be possible to fracture the zone with packed charges, and increase permeability for methane drainage, and possibly allow some stress relief.

If advance warning of the approach to methane-rich zones is provided, then face ventilation can be adjusted to dilute methane emissions. Also, additional methane monitors can be positioned so that adequate gas concentration information will be known before personnel are admitted back into mine. Finally, avoidance of the potentially hazardous area is an option if the hazard is sufficiently great.

SUMMARY

Approximately 75 pct of the Cote Blanche Mine has been mapped for outbursts and sediment inclusions. Approximately 25 pct of the mine has been mapped for salt bedding attitude. Two outburst areas were mapped in detail for outburst size and shape, salt layering, and salt crystal size, and closely sampled for salt methane content. Seven sediment samples were analyzed petrographically and complete grain size distributions were developed for 10 other sediment samples.

The mapping and sampling programs at Cote Blanche salt mine have shown the importance of consistent documentation of methane occurrences in understanding the extent to which methane is distributed. Additionally, several relationships were observed that will aid in the prediction of gassy zones in advance of mining. Methane-rich zones occur as isolated linear trends that contact abruptly with normal nongassy salt. In two instances the zones were approximately 100 to 200 ft wide, and paralleled a line of outbursts. The gassy zones were identified by methane contents more than 150 times those outside the zone. Large salt crystals are also known to be related to gassy zones, and these large crystals delineate the methane-rich zones in the study areas. Local salt layering was more disturbed in the immediate outburst area, and may be diagnostic, but more detailed evidence is needed. By mapping salt lithology it was observed that included sediment did not act as a significant source or conduit for methane into the Cote Blanche Mine, as it had been hypothesized in other domal mines in the area. A zone of hard, fine-grained salt had numerous methane occurrences (outbursts, methane bleeder, petroleum seep), suggesting some genetic relationship. Routine methane content testing and mapping is an effective way of quickly determining the gassiness of a sample and, by projection, a region.

Mapping has revealed the basic geologic structure of the salt dome, as well as provided the first documentation of the complete extent of outbursting in the mine. More than 80 outbursts, ranging in size from 1 ft in diameter to more than 50 ft in diameter have been mapped. They tend to occur along linear trends that parallel salt layering direction. Unlike the other salt mines in the area, outbursts have occurred during bench mining, and possibly two have propagated downward.

The other modes of occurrence of methane at the mine include the bleeding of methane from face and bench blastholes, bleeding from undercuts before blasting, and the infrequent venting of methane from natural or blast-induced fractures.

The prediction of gassy conditions in advance of mining can be accomplished by careful methane testing of blasted faces. Information on the methane content can also identify large-scale trends of gas-bearing salt. Since outbursts tend to follow local structural trends, geologic mapping is necessary to predict the direction of potential outbursts. This mapping must be accomplished shortly after mining, before diesel soot obscures much of the information. Mapping will also show changes in folding intensity, salt crystal size, and methane content information, which can allow prediction of gassy zones.

CONCLUSIONS

1. Methane-rich zones at Cote Blanche occur along linear trends that roughly parallel salt layering. The outbursts that punctuate some of the zones tend to occur in clusters, with small outbursts being important because they indicate favorable conditions for the formation of large outbursts. These linear trends can be projected vertically, which will aid in mine planning on multiple levels.
2. Methane-rich zones were found to occur abruptly; sometimes being delineated by sharp contacts such as salt bands. This means that mining advance can be very near a high-pressure gas zone without the operators being aware.
3. Very large, well-formed salt crystals of widely varying size distribution have been shown to indicate high methane content. These zones of high methane content commonly occur throughout the mine. Most do not have outbursts associated with them. They should be documented for purposes of establishing minewide trends. Run-of-mine salt crystals are normally 1/8 to 1/4 in across and methane free.
4. Measurement of pillar size at one outburst area did not appear to show that this parameter was related to outburst occurrence.
5. The best predictive techniques include consistent mapping and sampling for methane content. Another method is drilling long exploration holes in advance of mining for reservoir properties, core disking, and salt composition.
6. Standard long-hole gas drainage techniques will be ineffective in the naturally impermeable salt. It may be possible to induce local permeability with packed charges.

REFERENCES

1. Plimpton, H. G., R. K. Foster, J. S. Risbeck, R. P. Rutherford, R. F. King, G. L. Buffington, and W. C. Traweek. Final Report of Mine Explosion Disaster, Belle Isle Mine, Cargill, Inc., Franklin, St. Mary Parish, Louisiana. MSHA Accident Invest. Rep., 1980, 156 pp.
2. Iannacchione, A. T., R. H. Grau III, A. Sainato, T. M. Kohler, and S. J. Schatzel. Assessment of Methane Hazards in an Anomalous Zone of a Gulf Coast Salt Dome. BuMines RI 8861, 1984, 26 pp.
3. Iannacchione, A. T., G. L. Finfinger, T. M. Kohler, and D. M. Hyman. Investigation of Methane Emissions From an Advancing Face in the Belle Isle Domal Salt Mine, Louisiana. BuMines RI 8723, 1982, 24 pp.
4. Wiesliczka, M. J. Tourist's Guidebook. Cracow Tourist Information and Advertising Centre, Cracow, 1977, 62 pp.; available upon request from G. Molinda, BuMines, Pittsburgh, PA.
5. Belchic, H. C. The Winnfield Salt Dome, Winn Parish, Louisiana. Sec. in Interior Salt Domes and Tertiary Stratigraphy of Northern Louisiana, Shreveport Geol. Soc. (Shreveport, LA), 1960, pp. 29-47.
6. Thoms, R. L., and J. D. Martinez. Blowouts in Domal Salt. Paper in Fifth Symposium on Salt (Hamburg, West Germany, May 29-June 1, 1978). North. OH Geol. Soc. (Cleveland, OH) v. 1, 1980, pp. 119-134.
7. Kupfer, D. H. Shear Zones Inside Gulf Salt Stocks Help To Delineate Spines of Movement. AAPG Bull., v. 60, 1976, pp. 1434-1447.
8. MSHA Storage Task Force. Fact Finding Investigation of Southern Louisiana Salt Domes-Weeks Island, Cote Blanche Island, Jefferson Island, Belle Isle,

Avery Island. 1978, 40 pp.; available upon request from G. Molinda, BuMines, Pittsburgh, PA.

9. Halbouty, M. T. Salt Domes: Gulf Region, United States and Mexico. Gulf Publ. Co. (Houston, TX), 1967, 425 pp.

10. Golder Associates (Houston, TX). Geotechnical Study of Cote Blanche Island Salt Mine--Summary Volume, New Iberia, Louisiana. Rep. to Gulf Interstate Eng. Co., v. 2, appendix II, Oct. 1977, 62 pp.

11. Schatzel, S. J., and D. M. Hyman. Methane Content of Gulf Coast Domal Rock Salt. BuMines RI 8889, 1984, 18 pp.

12. Hyman, D. M. Methodology for Determining Occluded Gas Contents in Domal Rock Salt. BuMines RI 8700, 1982, 11 pp.

13. Muehlberger, W. R., and P. S. Claybaugh. Internal Structure and Petrofabrics of Gulf Coast Salt Domes. Sec. in Diapirism and Diapirs-A Symposium. AAPG mem., 1968, pp. 90-98.

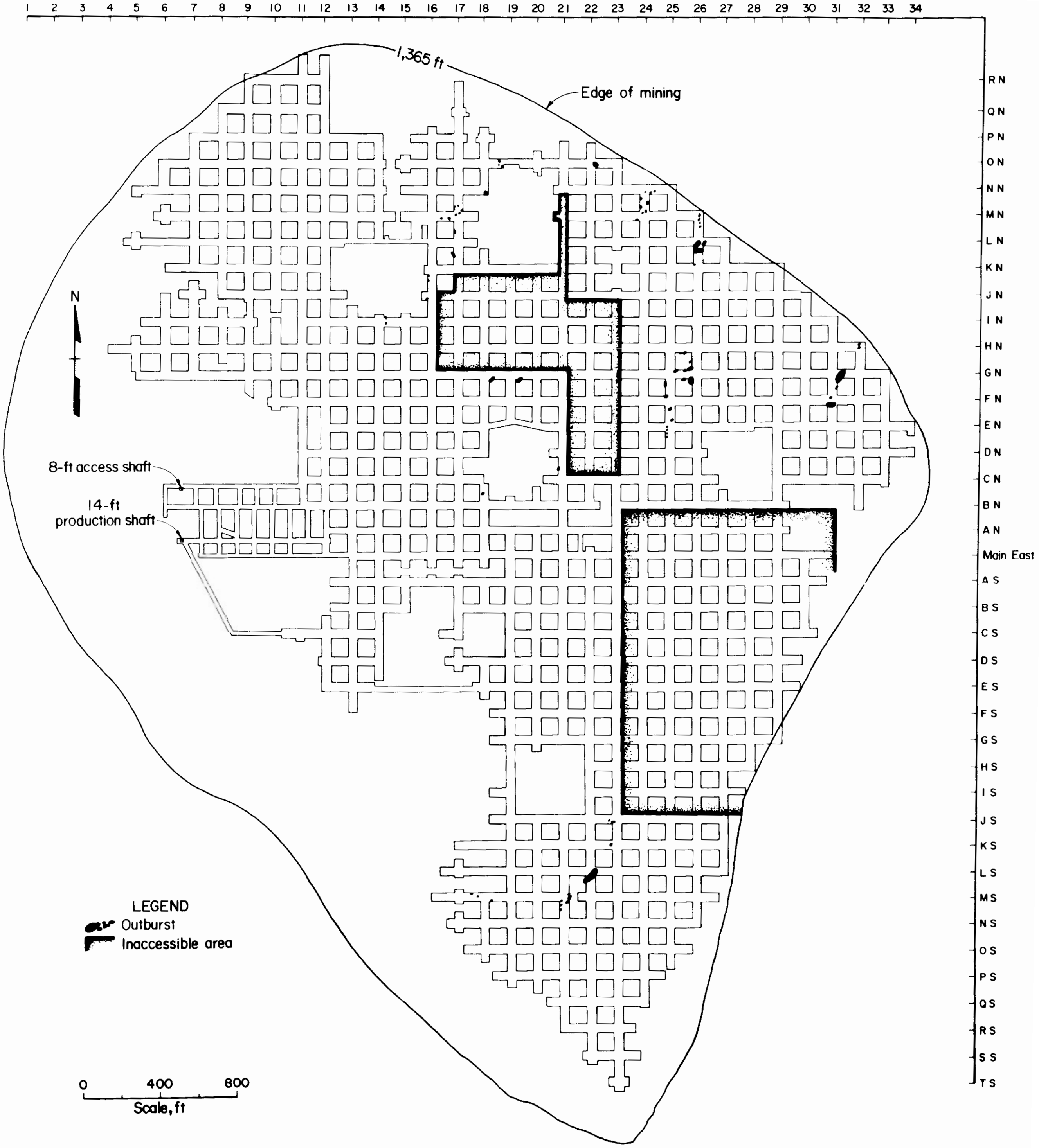

FIGURE 2.–Location of outbursts in Cote Blanche Mine.

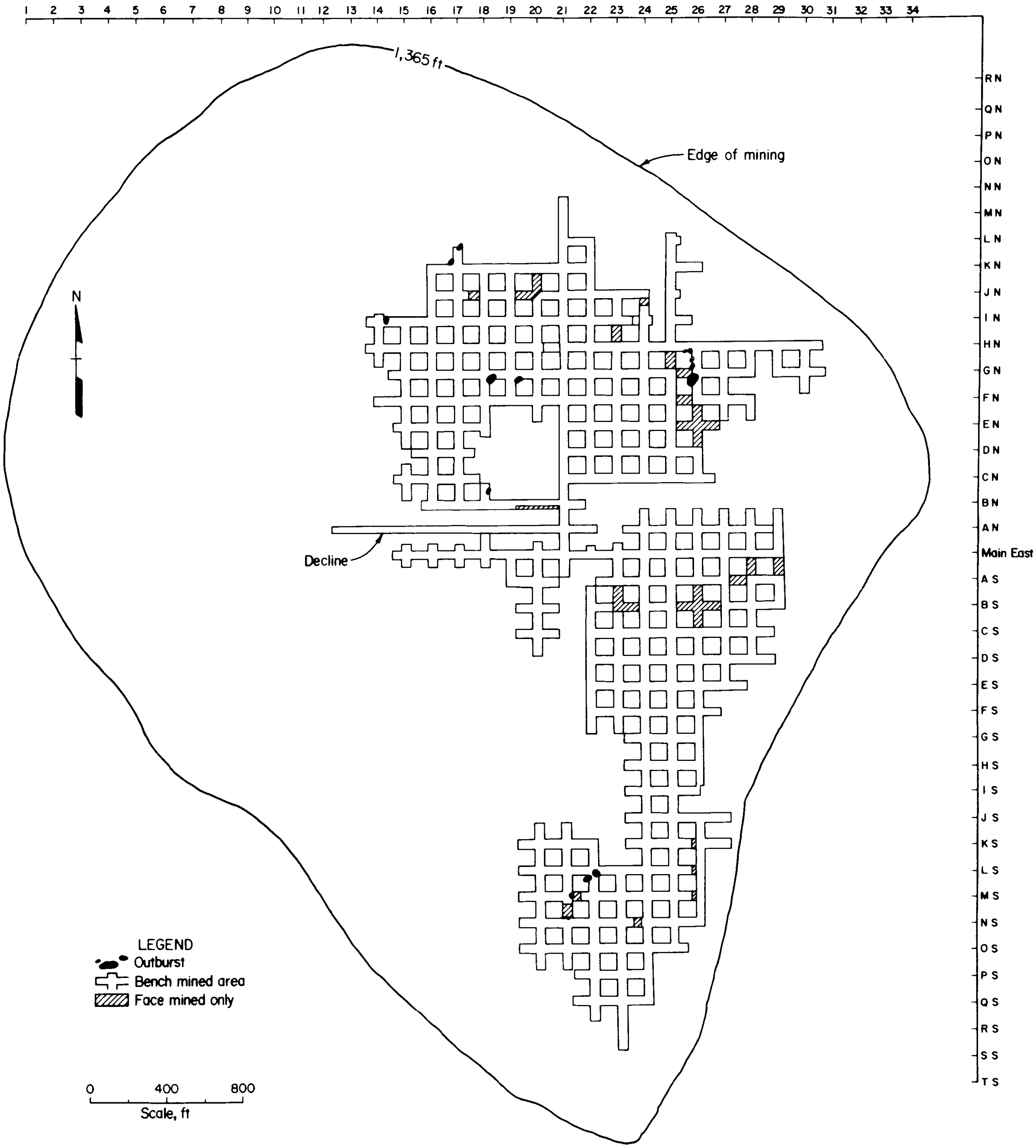

FIGURE 5.–Location of outbursts that occurred during bench mining at Cote Blanche Mine.

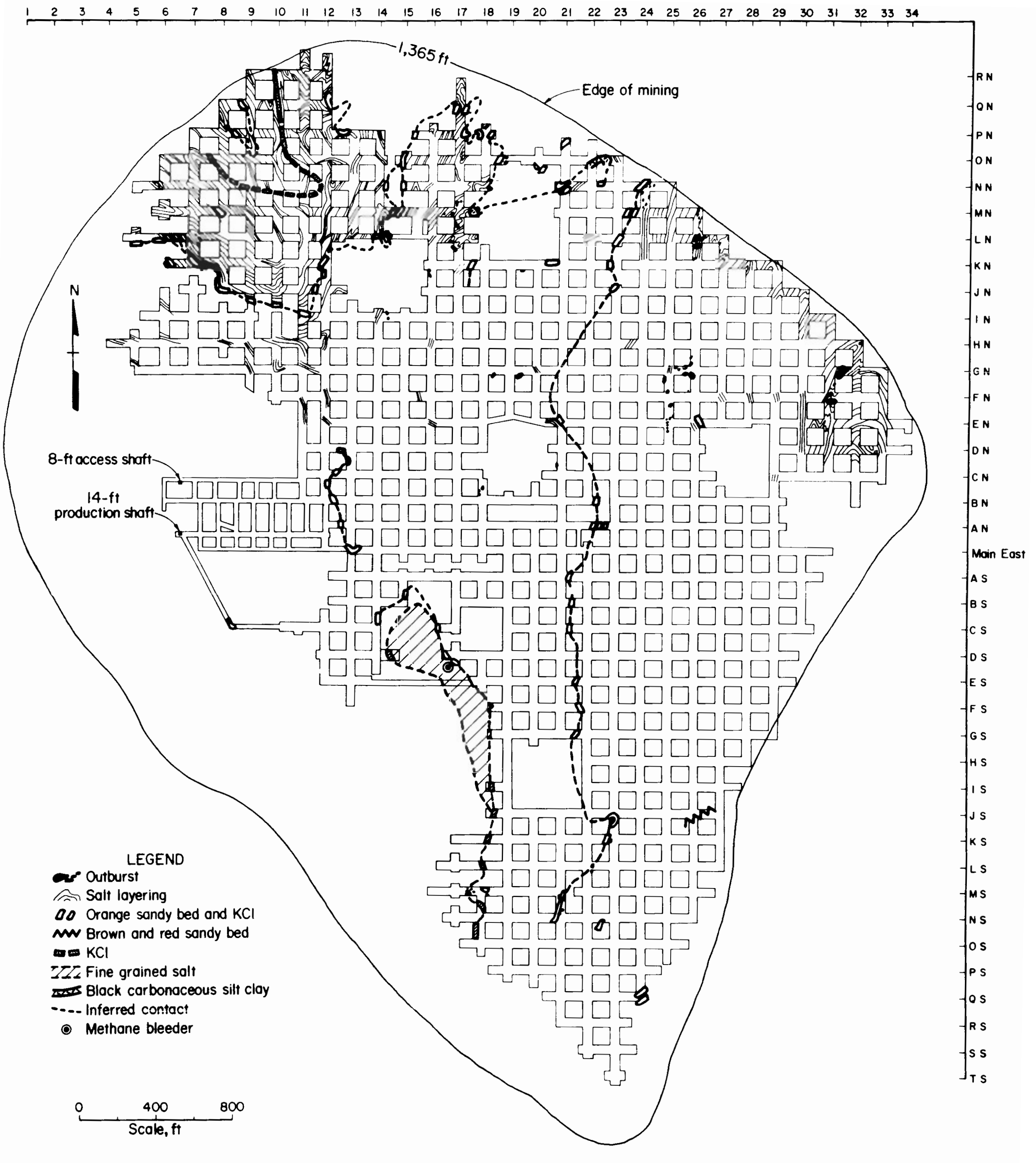

FIGURE 8.—Geologic map of Cote Blanche Mine.

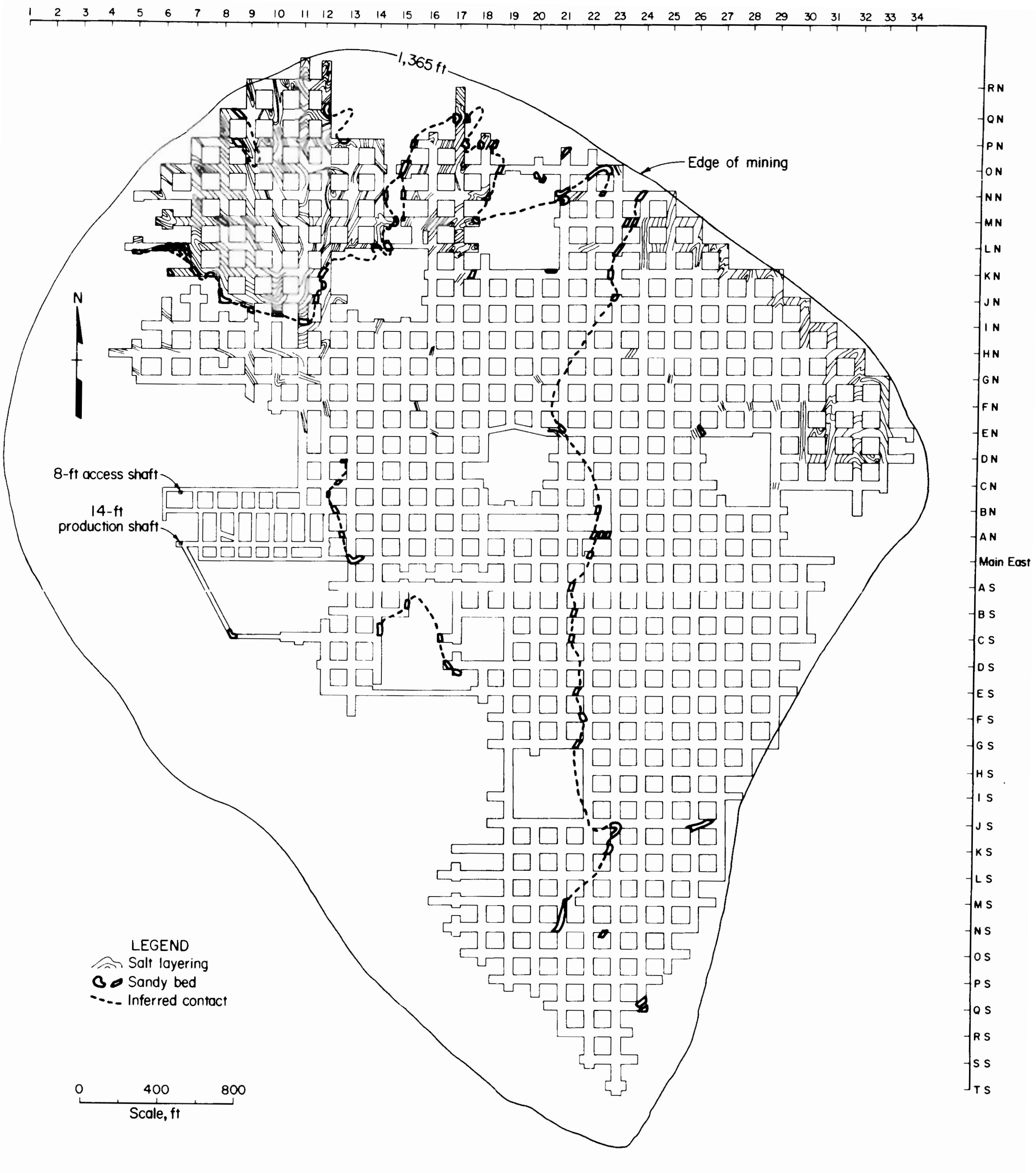

FIGURE 9.–Salt layering and distribution of sandy beds.

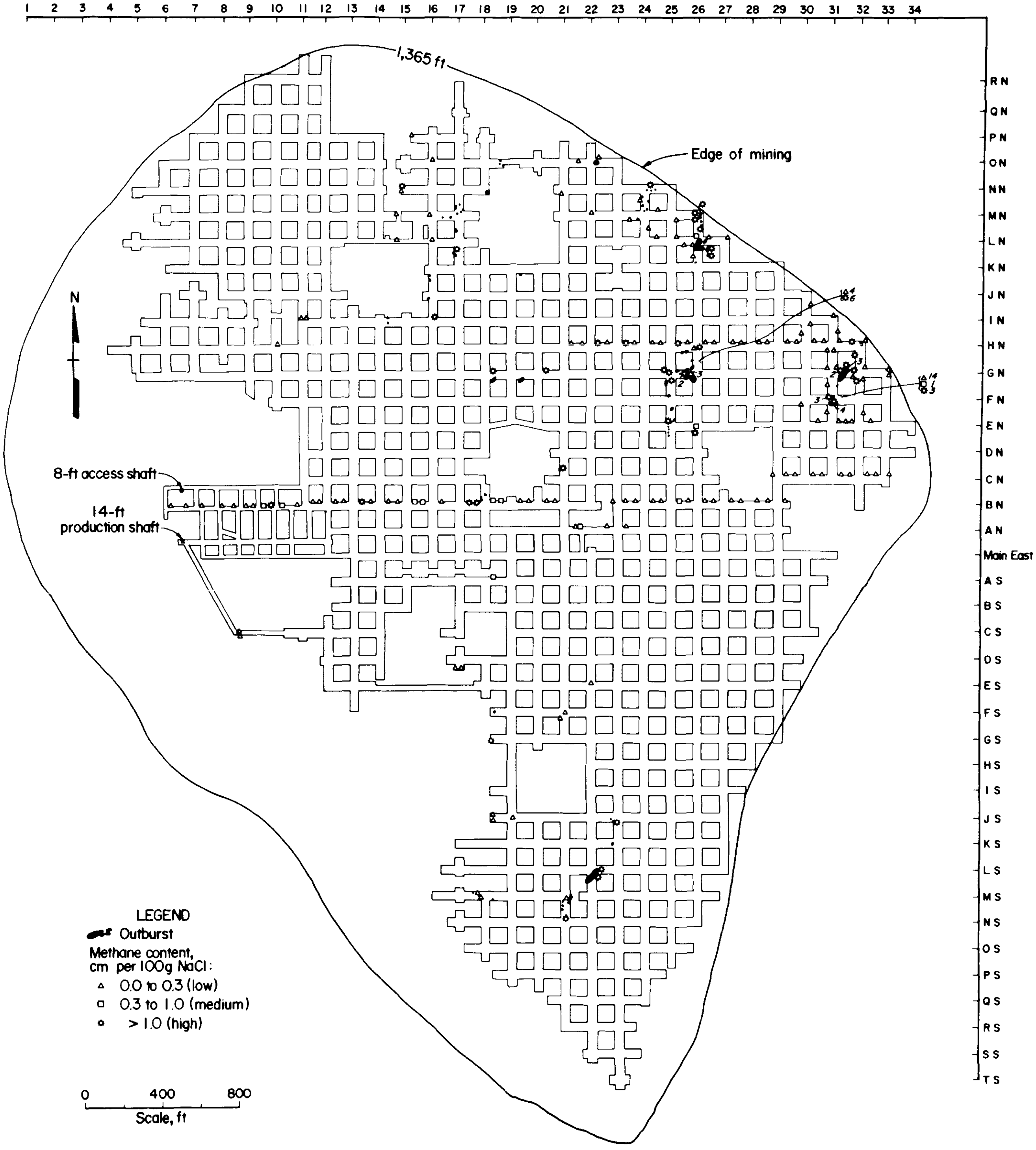

FIGURE 15.—Location of outbursts and salt samples with methane content in Cote Blanche Mine.