MASTER

GEOLOGY - HYDROLOGY OF AVERY ISLAND SALT DOME

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Part I
Geology

1. Review of the Geology of the Gulf Coast Salt Domes

The source rock in the formation of the Gulf Coast salt domes is the Louann salt of the Eagle Mills formation. There are continued questions as to the exact age of the Louann. The Eagle Mills is overlain by the Smackover formation of the Upper Jurassic. It is generally believed that the Eagle Mills is younger than the Pennsylvanian. Thus, the Eagle Mills could fall into the category of Upper Permian, Triassic, Lower or Middle Jurassic.

The uppermost tops of the Louann beds occur at depths of approximately 5,500 feet in southern Arkansas. Similarly, the tops of the Louann are encountered at depths of about 5,900 to 6,000 feet in Union County, Alabama. These depths seem to be the shallowest depths recorded for the Louann beds. The Louann formation has a sharp dip toward the Gulf Coast so that just south of the Arkansas border, we find the first domal structures of the Louann. These are in Webster and Beinville Parrishes, Louisiana with the axis of the Gulf geosyncline roughly paralleling the coast of Louisiana and Texas.

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Salt being a visco-plastic material, flows readily with high pressures and temperatures. Gussow states that salt becomes plastic in all three axial directions at a temperature of 662°F. At depths of 14,000 to 15,000 feet in salt, temperatures of 450° to 470°F have been recorded. As the salt experiences burial, it is heated and pressurized to a point where it begins to flow plastically. Seeking a pressure relief, it has a tendency to flow toward areas of less pressure which are structural anomalies or ruptures. As the salt flows to a structural discontinuity or weakness, it continues to receive a flow of heat energy by virtue of its thermal conductivity. The average heat flow for the Gulf Coast area is 1.2×10^{-6} cal/cm²sec. whereas the geothermal flow rate in salt domes has been found to range between 6.2×10^{-6} cal/cm²sec. to 10.1×10^{-6} cal/cm² sec. Thus, it may be assumed that the low density salt will form a temperature anomaly in the more dense cooler rocks that it penetrates. A salt dome may be considered as a bottomless intrusive or laccolith with a cooling of the outer shell as the plastic core continued to move vertically.

Many of the Gulf Coast salt domes have cap rocks. A number of reasons have been suggested as to the origin of the cap rock. Basically, the cap rock is an accumulation of insoluble residue which results from the dissolving

of the salt. Ground water circulating against the mass of salt dissolves the salt leaving the sand, anhydrite, iron and other insolubles as residue. Gulf Coast domes exhibit caps from 0 or only a few feet to over 1,100 feet. Insolubles form a bottom layer of anhydrite which may be subsequently altered to gypsum and an upper layer of calcite or limestone. On occasion sufficient free sulphur is present to form an economic deposit. These deposits of sulphur are believed to be formed by bacteria which reduce the calcium sulphate.

As the salt pillow develops, depletion of the salt from the Louann begins with the formation of peripheral sinks. Halbouty has divided these sinks into two classes. The primary sink is characterized by a thinning of the rim sediments as the dome's mass is approached. A secondary sink is developed in conjunction with subsidence that occurs around the periphery of the dome.

Classification of salt domes has been made with respect to several sets of criteria. One is with respect to depth where an arbitrary "top of salt" of less than 4,000 feet separates the Shallow Domes from the Intermediate Domes. Again, an arbitrary depth of 10,000 to 12,000 feet differentiates between the Intermediate Domes and the Deep Seated Domes. An alternate method of

classification relates to the structural form of the dome. These include massifs or ridges; Piercement Domes which may be a segment of a massif; spines and non-piercements. A number of subclassifications have been proposed by various authors.

The salt domes of the Gulf Coast can be separated into two tiers. The northern tier is composed of three basins or that of East Texas, Northern Louisiana Basin and the East Central Basin covering a portion of northeastern Louisiana and most of south central Mississippi. The southern tier extends eastward from the San Marcos Arch in Texas and roughly parallels the Gulf Coast to the proximity of the eastern border of Mississippi. This southern tier of domes is bounded on the northeastern section by the Wiggins Arch and influenced by the Lasalle Arch in Louisiana conforming to Gulf Coast geosyncline.

Part I

2. Geology of the Avery Island Dome

(a) Introduction

The Avery Island Dome is located ten miles south - southwest of New Iberia, Louisiana. Avery is the second island of the "Five Islands" which form a chain of salt across the southern part of Iberia Parish, more specifically in T13S, R5 and 6E. The 2,500 acres comprising Avery rise from the marsh and swamp land to a height of 167 feet above Mean Gulf Level. After thousands of years of brine consumption by animals, Indians and the first settlers, rock salt was discovered at Avery Island in 1862.

These first salt workings were an open pit which was serviced from the mainland by a corduroy road. On April 17, 1863, these workings were destroyed by Federal troops. After the close of the Civil War, the first shaft was sunk in 1867 to a depth of 90 feet. Headings were turned off this shaft and, as reported in old documents, they penetrated the side of the dome. From the location of the "Blue Hole" which constitutes the old mine workings, it is the opinion of the author that they penetrated the south side of the major fault zone.

The Avery Rock Salt Mining Company was organized in 1898 and the sinking of a shaft was begun. This shaft which is still active as a facility for the current mining operation, was sunk to a depth of 500 feet. In 1962 an inclined slope was driven downward and across what constitutes the major fault.

This tunnel terminated at the 700 foot level on the north side of the dome. Again, faced with dirty salt and a series of what appeared to be minor faults, management drove a second set of inclined tunnels downward penetrating the south side of the dome at the 880 level.

Part I

2. Geology of the Avery Island Dome

(b) Geomorphology

Avery Island is a metamorphic deposit of tectonic origin that has been uplifted through the coastal marshes by the almost vertical, batholithic type intrusion of early Jurassic salt. This salt has penetrated several miles of overlying younger sediments to an elevation above sea level. Some masses of foreign sandstone, clay and gravel were carried upward on top of the salt. A portion of the unconsolidated sands resting on top of the salt is actually a collection of insolubles which are remnants of the dissolving of the top of the salt dome as it moves upward through the soft sedimentary aquifers. Recent drilling on the northern flanks of the dome have found small isolated masses of cap rock although no cap rock has ever been encountered on the top or southern flanks.

From the lithological-mineralogical standpoint, the dome is obviously predominantly composed of rock salt which by itself, a polymineral rock, is mainly

composed of halite and anhydrite. Besides halite and anhydrite, R. E. Taylor (1938) specified dolomite, calcite, pyrite, quartz, limonite, hauerite, sulphur, hematite and kaolinite as mineral components of the water insoluble residue of the rock salt (in order of abundance).

During recent explorations of the dome, continuous channel samples were taken across the 500' level of the Avery Island Mine in the east-west direction perpendicular to the strike of the isoclines. One sample was collected from Avery every 10 feet of the channel. All samples were oven dried for 18 hours and weighed. After that they were dissolved in 200 cc of demineralized water, allowed to stand for two hours at 30°C, filtered through a millipore membrane, dried and weighed. The weight of the remaining insoluble residue was determined and expressed in percent.

Also analyses for such trace elements as barium, bromine, strontium, lithium, magnesium, calcium and potassium were run on the same samples. Bromine was analyzed by the orthotolidine method whereas the heavy metals by atomic absorption. In general, the

analyses indicate that the water insolubles taken from composite samples are extremely low in this cross-section through the mine, and vary from several hundreds to over one tenth of one percent only. Calcium is the dominant element; lithium even in traces does not exist; the level of bromine is extremely low, and small quantities of potassium are distributed throughout the dome with sharp increases being noted close to the main fault. This increase may be due to the original fluids entrapped in the sandstone breccia in that area. R. E. Taylor (1938) found that the salt cement of the sandstone inclusions from Avery Island showed high concentrations of potassium. In the following analyses, the samples from number 1000 - 1120 are from the area of the new shaft, where large fragments of brecciated sandstone are present.

Trace Elements and Water Insolubles in Composite Salt Samples

Avery Island Dome

<u>Sample</u> <u>B</u>	<u>% water insol.</u> <u>material</u>	<u>pH</u>	<u>Ba</u> <u>ug/gm</u>	<u>Br</u> <u>ug/gm</u>	<u>Sr</u> <u>ug/gm</u>	<u>Li*</u> <u>ug/gm</u>	<u>Mg</u> <u>ug/gm</u>	<u>Ca</u> <u>ug/gm</u>	<u>K</u> <u>ug/gm</u>
10	0.0817	6.0	23.85	0.40	8.83	0	4.82	2930	28.90
20	0.0727	6.4	39.87	0.80	8.37	0	8.37	3189	29.5
30	0.1275	6.0	19.88	0.39	8.70	0	18.37	2767	31.6
40	0.0787	6.1	9.94	0.41	6.76	0	5.57	2505	24.6
50	0.2532	6.1	17.41	0.39	5.58	0	2.99	1872	24.6
60	0.0707	6.6	19.91	0.40	6.37	0	9.16	2469	28.6
70	0.0866	6.0	20.00	0.80	6.40	0	19.40	2040	34.4
80	0.1265	6.5	9.93	0.79	6.75	0	6.36	2543	29.4
90	0.2204	6.2	20.02	0.40	11.14	0	3.78	3979	26.3
100	0.0966	6.1	20.17	0.40	5.67	0	7.26	1544	29.0
110	0.0663	6.3	20.34	0.75	6.51	0	6.10	2098	24.4
120	0.1675	6.3	30.61	0.41	3.67	0	6.94	1184	35.1
130	0.0694	6.0	29.75	0.39	4.76	0	5.16	1825	30.1
140	0.2695	6.2	19.82	0.40	5.55	0	6.34	2141	28.9
150	0.1042	5.9	17.56	0.40	8.83	0	2.21	2971	27.3
160	0.0725	6.1	19.97	0.40	6.79	0	6.99	2756	31.9
170	0.0671	6.6	29.96	0.45	7.59	0	7.59	2716	31.9
180	0.0599	6.4	13.99	0.40	6.80	0	8.00	2320	30.4

Sample B	% water insol. material	pH	Ba ug/gm	Br ug/gm	Sr ug/gm	Li* ug/gm	Mg ug/gm	Ca ug/gm	K ug/gm
190	0.0608	6.4	19.95	0.39	6.38	0	6.38	2114	35.9
200	0.0665	6.0	19.85	0.59	5.56	0	5.68	1826	30.2
210	0.0683	5.9	17.50	0.39	7.92	0	2.38	2059	27.7
220	0.1047	6.2	19.79	0.29	5.54	0	1.98	1781	26.9
230	0.0575	6.0	29.75	0.39	3.97	0	4.17	1507	30.1
240	0.0579	6.5	19.84	0.39	4.76	0	6.75	1746	27.0
250	0.0639	5.9	19.89	0.40	4.77	0	6.55	1751	30.2
260	0.0798	6.0	29.72	0.39	3.96	0	2.58	1625	22.2
270	0.1829	6.0	24.00	0.29	5.54	0	2.18	2532	30.9
280	0.0963	6.0	20.19	0.75	7.67	0	6.66	26.65	27.5
290	0.0567	6.5	20.12	0.71	6.84	0	4.83	2776	26.5
300	0.0581	6.0	20.12	0.41	6.81	0	5.61	2244	26.4
310	0.1041	6.5	30.42	0.41	7.70	0	5.27	2515	12.2
320	0.0829	6.5	19.97	0.80	6.39	0	4.59	2157	22.3
330	0.1115	6.1	13.82	0.40	6.71	0	4.15	2488	24.5
340	0.1073	6.2	20.00	0.29	8.76	0	2.39	28.67	26.3
350	0.0838	6.0	15.20	0.31	7.94	0	3.57	2701	29.4
360	0.1119	6.1	19.91	0.32	7.61	0	3.20	2564	29.6
370	0.1917	6.0	24.04	0.29	5.61	0	2.40	1882	29.6
380	0.1755	6.0	17.46	0.40	5.57	0	2.59	2070	27.1

Sample	% water insol. material	pH	Ba ug/gm	Br ug/gm	Sr ug/gm	Li* ug/gm	Mg ug/gm	Ca ug/gm	K ug/gm
390	0.0948	6.0	13.18	0.40	4.39	0	2.40	1878	23.2
400	0.0555	6.0	13.16	0.39	6.76	0	2.39	2467	24.7
410	0.1634	6.0	27.82	0.28	7.97	0	3.78	2668	27.1
420	0.1216	6.0	17.49	0.39	5.58	0	2.59	2389	23.1
430	0.1330	5.7	20.08	0.65	5.59	0	5.59	1878	24.8
440	0.0354	6.0	27.85	0.29	5.54	0	4.75	1901	26.9
450	0.1045	6.1	17.49	0.41	4.35	0	3.95	1660	29.25
460	0.1533	6.0	17.70	0.29	6.72	0	3.56	2609	35.6
470	0.1439	5.9	24.14	0.38	5.54	0	3.16	2294	27.7
480	0.1579	5.9	30.14	0.65	8.03	0	6.63	3018	24.8
490	0.0795	6.0	17.46	0.71	6.74	0	7.34	2142	24.6
500	0.0892	6.1	29.92	0.30	5.59	0	2.39	1956	27.2
510	0.1255	5.6	30.16	0.68	9.24	0	8.44	3501	28.9
520	0.1125	6.1	15.11	0.39	10.33	0	3.38	3101	23.0
530	0.1223	6.1	27.91	0.65	8.77	0	4.38	2871	31.1
540	0.0763	6.2	29.82	0.39	9.16	0	5.37	3102	33.4
550	0.0999	6.1	19.79	0.28	13.46	0	6.93	2772	23.8
560	0.0638	6.2	31.74	0.38	8.73	0	6.15	2499	28.57
570	0.1874	6.1	19.80	0.38	6.73	0	4.95	3049	24.5
580	0.1300	5.8	19.89	0.66	5.17	0	4.77	2231	23.8

Sample B	% water insol. material	pH	Ba ug/gm	Br ug/gm	Sr ug/gm	Li* ug/gm	Mg ug/gm	Ca ug/gm	K ug/gm
590	0.1045	6.1	19.92	0.40	7.96	0	3.784	3107	25.5
600	0.1661	6.1	23.85	0.64	6.76	0	3.38	1908	27.8
610	0.1380	5.9	19.95	0.71	6.00	0	4.18	2234	23.2
620	0.1315	6.0	30.13	0.60	8.04	0	4.02	3134	24.9
630	0.0847	6.1	17.67	0.38	8.29	0	4.73	2844	24.5
640	0.0864	6.2	23.71	0.42	10.03	0	4.62	3210	26.5
650	0.0760	6.5	19.95	0.65	7.98	0	8.58	2594	28.7
660	0.0734	5.8	19.79	0.39	6.73	0	13.06	2652	31.7
670	0.0868	5.9	30.02	0.71	6.01	0	10.41	2482	39.2
680	0.1031	5.8	30.03	0.68	5.20	0	4.00	2162	34.4
690	0.0198	6.1	27.81	0.39	4.37	0	4.37	1708	27.0
700	0.0330	6.0	20.00	0.28	8.00	0	4.80	3046	25.6
710	0.0326	5.9	25.08	0.62	7.35	0	6.35	2809	24.1
720	0.0198	6.0	19.86	0.65	8.74	0	6.16	3059	23.8
730	0.0637	6.1	15.90	0.39	8.73	0	4.76	2897	40.5
740	0.0835	6.1	23.95	0.54	8.37	0	3.99	2871	27.9
750	0.1578	5.8	15.90	0.66	5.96	0	3.18	2385	26.2
760	0.0532	5.7	19.81	0.75	7.13	0	13.87	2536	27.7
770	0.0350	6.0	27.98	0.40	3.19	0	3.79	1279	28.0

Sample B	% water insol. material	pH	Ba ug/gm	Br ug/gm	Sr ug/gm	Li* ug/gm	Mg ug/gm	Ca ug/gm	K ug/gm
780	0.0148	6.2	30.12	0.55	8.03	0	7.63	2611	41.8
790	0.0159	6.0	20.01	0.67	8.00	0	3.60	3202	28.8
800	0.0253	6.1	29.95	0.78	6.39	0	8.79	2117	47.1
810	0.1325	5.9	19.78	0.73	7.12	0	7.71	2730	34.8
820	0.0299	6.1	30.14	0.68	7.23	0	4.62	2331	28.9
830	0.0218	6.2	29.81	0.59	5.57	0	3.58	2147	26.2
840	0.0691	6.2	29.87	0.67	7.97	0	7.77	2350	33.6
850	0.0378	6.0	30.14	0.75	4.09	0	4.02	1407	22.5
860	0.1200	6.3	30.16	0.67	6.03	0	5.03	2333	37.8
870	0.1186	6.2	29.80	0.74	5.56	0	3.77	2464	26.2
880	0.0991	6.1	19.78	0.40	6.73	0	3.36	2453	24.5
900	0.1199	5.8	30.08	0.85	8.82	0	7.02	3095	23.3
910	0.1367	5.9	19.98	0.65	7.99	0	5.39	3237	31.9
920	0.0596	5.9	19.84	0.95	5.16	0	5.35	2222	23.8
930	0.0212	5.9	19.92	0.74	3.98	0	4.98	1713	23.9
940	0.0359	6.1	13.98	0.40	5.59	0	7.19	1438	39.9
950	0.0947	6.0	19.90	0.55	7.56	0	7.36	2905	31.8
960	0.0712	6.0	20.02	0.40	9.60	0	11.21	3203	32.0
970	0.0908	6.1	29.68	0.54	8.31	0	6.92	3127	34.8

Sample B	% water insol. material	pH	Ba ug/gm	Br ug/gm	Sr ug/gm	Li* ug/gm	Mg ug/gm	Ca ug/gm	K ug/gm
980	0.0451	6.2	20.00	0.29	2.80	0	8.40	1040	34.5
990	0.1075	6.1	20.17	0.41	8.47	0	9.09	3188	29.9
1000	0.1075	6.3	29.68	0.55	8.31	0	6.53	3048	30.1
1010	0.1147	6.2	20.34	0.42	2.85	0	7.73	936	27.7
1020	0.0484	6.3	20.26	0.54	3.65	0	7.09	1297	30.8
1030	0.0881	6.0	29.90	0.40	8.37	0	7.57	3150	41.5
1040	0.1090	6.4	20.00	0.75	9.20	0	10.40	3481	80.0
1050	0.1455	5.8	19.96	0.74	6.38	0	8.584	2795	43.9
1060	0.0931	5.7	20.61	0.43	7.00	0	11.95	1525	50.3
1070	0.1591	6.3	19.87	0.55	9.53	0	27.82	3219	112.9
1080	0.0715	6.4	20.10	0.42	6.83	0	12.06	2493	49.1
1090	0.0766	6.2	20.00	0.40	9.60	0	76.00	3280	62.4
1100	0.1130	6.4	29.76	0.40	11.90	0	67.46	3849	1190.5
1110	0.0229	6.4	29.84	0.47	10.74	0	41.82	3780	501.4
1120	0.0289	5.9	13.78	0.40	25.55	0	35.38	5031	931.6

* 0 ug/gm is < 0.1 ug/gm

Aside from the red sandstones that were described by R. E. Taylor (1938), more recent workings of the mine have shown material of a similar texture but deviating somewhat in color. Sandstone and sandstone breccias are in abundance as thin seams and a scattering of small fragments. Most of these sandstone inclusions are found either at the parameter of the mine or in the main fault zone. In general, the sandstone associated with the parameter is a rusty yellow limonitic material while that included as fault gouge is a grayish blue to light buff. This material seems not to have been oxidized or less oxidized with the double valent ferrous ion. In the fault zone associated with the sandstone is a black sandstone that is sometimes referred to by the miners as "coal". This material is massive, highly argillaceous and in some areas has a petroliferous odor.

The island is oval shaped with a long axis trending in a NW-SE direction for a distance of approximately 2.2 miles. The minor axis of the oval is about 1.4 miles. As is shown on the accompanying United States Geological Survey topographical map of the island, the outer edge is a series of terraces. These terraces

JACOBY & COMPANY

DRAWN BY R.J.D.

CHECK BY S.S.

APPROVED BY:

SCALE AS NOTED

DATE JAN. 25, 1977

OUTLINES OF THE MINE
AGAINST THE TOPOGRAPHY
OF THE ISLAND

SURFACE RELIEF OF AVERY ISLAND

AFTER U.S.G.S. DELCAMBRE QUADRANGLE
1963

are the out wash sediments of the "hills" which form the interior of the island. A valley running north and south in which the railroad has been built, cuts off approximately 1/3 of the island.

The western "hills", which form about one third of the island, start in the area adjacent to the old hoist shaft of the International Salt Company and gradually rise to over 100 feet in the northern section or the Jungle Garden. The north and south valley is relatively narrow in the north; broadening and becoming flat in the center; again, narrowing prior to its broadening as it intersects the swamp.

Drilling on the northern side of the island shows that the salt is some 200 feet deeper than on the south side of the island, yet the elevations on the north side of the island, both east and west of the valley, are considerably higher than on the south side. As shown in the Sediment Isopach (Isopach Map #1) of sediments on top of the salt, two areas of sediment thinning are to be observed. One is the north near the Jungle Gardens and underlying the high elevations of that area; and a second mass with an epicenter is due east of the main or old hoist shaft. It appears that the surface morphology may be closely

LEGEND

- WELL LOCATION
- *50 WELL NUMBER
- 131 THICKNESS OF SEDIMENTS OVERLYING THE 3034 ELEVATION TOP OF SALT

ISOPACH MAP "1" THICKNESS OF SEDIMENTS

related to the quantity of insolubles carried either as "drag" in the faults or as granular fragments of the Louann. As the salt is dissolved by meteoric waters, the build of "hills" of insolubles occurs as the dome continues to move upward. These hills of insolubles are gradually eroded into the terrace which form the periphery.

The sharp erosional valley which trends across the island in a west-southwest to east-northeast direction overlies what has been termed the "main" fault. Meteoric water has preferentially dissolved the fault gouge which is the secondary deposition of the halite. This sharp ravine on the east side contains sand pits which are periodically mined. These small pits show a variegated layering of sand with colors of white, buff, brown, lavender and yellow. This feature is clearly outlined on the structural map on the top of salt. Near the center of the island, wells were drilled where split spoon samples were taken in connection with the sinking of a new hoist shaft. Three simulated logs showing soil conditions which one might encounter have been included as X, Y and Z. A "Summary of Laboratory Test Results" has also been simulated for the same borings.

LOG OF BORING

Boring No. **X**

Ground Elev. _____ Datum _____ Gr. Water Depth **6.0'**

Sample No.	SAMPLE Depth — Feet		DEPTH STRATUM Feet		VISUAL CLASSIFICATION	*STANDARD PENETRATION TEST	
	From	To	From	To			
			0.0	0.5	Loose gray & tan clayey sand		
1	2.5	3.0	0.5	4.0	Very soft gray clay w/sand pockets & trace of organic matter		
2	5.5	6.0	4.0	8.0	Medium stiff dark gray silty clay w/sand lenses & gravel pockets		
3	8.5	9.0	8.0	10.0	Medium stiff to stiff tan & gray sandy clay		
4	10.0	10.5	10.0		Loose gray fine sand		
5	10.5	12.0		13.0	Ditto	7	9
6	13.5	15.0	13.0		Soft dark gray silty clay w/sand layers & organic matter	1	4
7	19.5	20.0		21.0	Ditto		
8	24.5	25.0	21.0	26.0	Medium stiff dark gray silty clay with organic matter		
9	29.5	30.0	26.0	33.0	Medium stiff gray organic clay		
10	34.5	35.0	33.0	35.0	Very loose gray sand w/pea gravel & clay		
11	39.5	40.0	35.0	41.0	Medium stiff gray sandy clay w/organic matter & sand pockets		
12	44.5	45.0	41.0	47.0	Stiff black organic clay w/decayed wood		
13	49.5	50.0	47.0	52.0	Medium stiff black organic clay with decayed wood		
14	54.5	55.0	52.0	57.5	Stiff black organic clay w/decayed wood		
15	59.5	60.0	57.5	62.0	Stiff greenish-gray sandy clay		
16	64.5	65.0	62.0	67.0	Very stiff greenish-gray sandy clay		
					(Continued)		

Number in first column indicates number of blows of 140-lb. hammer dropped 30 in. required to seat 2-in. O. D. splitspoon sampler 6 in. Number in second column indicates number of blows of 140-lb. hammer dropped 30 in. required to drive 2-in. O. D. splitspoon sampler 1 ft. after seating 6 in.

Remarks: Boring located approximately 40' S.E. of canal.

Predominant type shown heavy. Modifying type shown light.

100

Ground Elev. _____ Datum _____ Gr. Water Depth 6.0' 120

17 DEPTH IN FT.

Remarks: Boring located approximately 40' S.E. of
canal.

22
(Sheet #2)

SUMMARY OF LABORATORY TEST RESULTS

BORING X

Sheet 1 of 2

Sam- ple No.	Depth in Ft.	Classification	Water Content Percent	Density Lbs./Cu.Ft.		Unconfined Compressive Strength Lbs./Sq.Ft.	Atterberg Limits		
				Dry	Wet		LL	PL	PI
1	2.5	Very soft gray clay w/trace organic mat- ter & sand pockets	43.5	75.2	107.9	375	55	20	35
2	5.5	Medium stiff dark gray silty clay w/sand lenses	28.9	92.7	119.5	1145	42	20	22
3	8.5	Medium stiff tan & gray sandy clay	24.3	101.1	125.7	1965	34	19	15
7	19.5	Soft dark gray silty clay w/sand layers & organic matter	25.0	101.1	126.3	595*	27	19	8
8	24.5	Med. stiff dark gray silty clay w/organic matter	31.9	89.0	117.4	1885	41	25	16
9	29.5	Medium stiff dark gray organic clay	55.1	67.6	104.8	1150	77	26	51
11	39.5	Med. stiff gray sandy clay w/sand pkts. & org. matter	44.5	74.6	107.8	1065	57	27	30
12	44.5	Stiff black organic clay w/wood	105.9	41.6	85.7	2060	156	74	82
13	49.5	Medium stiff black or- ganic clay w/wood	115.5	38.8	83.6	1030	199	56	143
14	54.5	Stiff black organic clay w/wood	119.1	38.8	85.0	2000	180	65	115
15	59.5	Stiff greenish-gray sandy clay	17.5	113.0	132.8	2590	37	13	24
16	64.5	Very stiff greenish-gray sandy clay	23.9	101.4	125.6	5220	62	20	42
17	69.5	Very stiff greenish-gray clay w/sand pockets	30.7	92.9	121.4	7285	82	24	58
18	74.5	Ditto	31.4	92.2	121.6	6415	72	24	48
20	84.5	Very stiff greenish-gray & tan clay w/sand pockets	28.7	95.2	122.8	6850	62	21	41

*Undrained confined compression shear test;
confined at approximate overburden pressure.

(Sheet #1)

SUMMARY OF LABORATORY TEST RESULTS

BORING X
(Cont'd)

Sheet 2 of 2

Sam- ple No.	Depth in Ft.	Classification	Water Content Percent	Density Lbs./Cu.Ft.		Unconfined Compressive Strength Lbs./Sq.Ft.	Atterberg Limits		
				Dry	Wet		LL	PL	PI
21	89.5	Very stiff tan & gray clay w/concretions	30.3	92.0	119.9	5595	75	22	53
22	94.5	Stiff tan & gray clay w/concretions	38.6	82.5	114.3	3185	96	18	78
23	99.5	Stiff gray sandy clay	10.2	125.3	138.1	2015	38	12	26
24	104.5	Extremely stiff gray sandy clay	16.6	117.3	136.8	9520	26	13	13
25	109.5	Ditto	14.3	115.2	131.6	14110	35	15	20

(Sheet #2)

LOG OF BORING

Boring No. Y

Ground Elev. _____ Datum _____ Gr. Water Depth 1.0'

Sample No.	SAMPLE Depth — Feet		DEPTH STRATUM Feet		VISUAL CLASSIFICATION	*STANDARD PENETRATION TEST	
	From	To	From	To			
			0.0	0.5	Loose gray sand		
1	2.5	3.0	0.5	4.5	Medium dense tan clayey sand w/silty sand layers		
2	5.5	6.0	4.5	6.0	Stiff gray & tan silty clay w/sand layers & organic matter		
3	7.0	7.5	6.0	8.0	Medium dense brown & gray clayey sand w/silty sand layers		
4	9.0	9.5	8.0		Medium stiff gray sandy clay w/organic matter		
5	11.5	12.0		12.5	Medium stiff to stiff gray sandy clay w/organic matter		
6	14.5	15.0	12.5		Soft to medium stiff gray sandy clay w/organic matter & trace of gravel		
7	17.0	17.5		17.5	Ditto		
8	19.5	20.0	17.5	22.5	Dense gray silty sand w/trace of pea gravel		
9	22.5	23.0	22.5		Stiff to very stiff greenish-gray sandy clay w/sand layers		
10	26.0	26.5		28.5	Ditto		
11	29.5	30.0	28.5	31.0	Loose to medium dense gray clayey sand w/trace of pea gravel		
12	34.5	35.0	31.0	35.0	Stiff greenish-gray & tan sandy clay		

*Number in first column indicates number of blows of 140-lb. hammer dropped 30 in. required to seat 2-in. O. D. splitspoon sampler 6 in. Number in second column indicates number of blows of 140-lb. hammer dropped 30 in. required to drive 2-in. O. D. splitspoon sampler 1 ft. after seating 6 in.

Remarks: Boring located approximately 200' S.E. of
canal.

Predominant type shown heavy. Modifying type shown light.

SUMMARY OF LABORATORY TEST RESULTS

BORING : Y

Sam- ple No.	Depth in Ft.	Classification	Water Content Percent	Density Lbs./Cu.Ft.		Unconfined Compressive Strength Lbs./Sq.Ft.	Atterberg Limits		
				Dry	Wet		LL	PL	PI
1	2.5	Medium dense tan clayey sand w/silty sand layers	18.6	105.8	125.5	400*	21	15	6
2	5.5	Stiff tan & gray silty clay	24.5	100.0	124.5	2340	32	22	10
3	7.0	Medium dense brown & gray clayey sand with silty sand layers	17.6	105.0	123.6	1700*	23	16	7
4	9.0	Medium stiff gray sandy clay w/trace organic matter	22.3	104.3	127.6	1280	35	19	16
6	14.5	Soft gray sandy clay w/organic matter	23.8	101.8	126.0	565	23	20	3
7	17.0	Medium stiff gray sandy clay w/organic matter	29.9	94.5	122.9	1875	40	23	17
8	19.5	Dense gray silty sand w/trace of pea gravel	14.4	114.6	131.1	1865*	Non-Plastic		
9	22.5	Stiff greenish-gray sandy clay w/sand layers	12.2	121.4	136.2	3235	20	14	6
10	26.0	Very stiff greenish-gray sandy clay w/sand layers	16.8	115.0	134.3	5900	30	14	16
12	34.5	Stiff greenish-gray & tan sandy clay	14.7	118.9	136.4	2375	29	14	15

*Undrained confined compression shear test;
confined at approximate overburden pressure.

LOG OF BORING

Boring No. **Z**

Ground Elev. _____ Datum _____ Gr. Water Depth 7.0'

[illegible]

*Number in first column indicates number of blows of 140-lb. hammer dropped 30 in. required to seat 2-in. O. D. splitspoon sampler 6 in. Number in second column indicates number of blows of 140-lb. hammer dropped 30 in. required to drive 2-in. O. D. splitspoon sampler 1 ft. after seating 6 in.

Remarks: Boring located approximately 400' S.E. of
canal.

Predominant type shown heavy. Modifying type shown light.

SUMMARY OF LABORATORY TEST RESULTS

BORING Z

Sample No.	Depth in Ft.	Classification	Water Content Percent	Density		Unconfined Compressive Strength Lbs./Sq.Ft.	Atterberg Limits		
				Dry	Wet		LL	PL	PI
1	2.5	Very soft dark gray sandy clay	21.0	100.5	121.6	400	22	18	4
2	4.5	Extremely stiff gray & tan sandy clay	13.9	115.7	131.8	15650	42	17	25
3	7.5	Very stiff gray & tan sandy clay	19.8	109.1	130.7	7105	44	18	26
4	10.5	Soft gray & tan sandy clay w/clayey sand layers	15.5	116.7	134.8	925*	30	19	11
5	14.5	Medium stiff greenish-gray sandy clay with trace of gravel	21.2	108.6	131.6	1125	23	18	5
6	19.5	Hard greenish-gray clay w/silt pockets	24.9	95.8	119.6	1575**	72	22	50

BORING C-600

1	2.5	Very stiff gray & tan sandy clay	20.4	103.9	125.1	4270	40	22	18
2	4.5	Very compact tan & gray clayey silt	9.7	99.4	109.0	5670*	32	23	9
4	10.5	Very soft tan & gray sandy clay w/clay pockets & sand layers	22.4	99.6	121.9	345	21	19	2
5	14.5	Soft gray sandy clay with trace of wood	32.7	88.9	118.0	785	41	25	16
6	19.5	Medium stiff gray clay w/trace of organic matter & silt pockets	41.4	77.4	109.5	1155	62	28	34
8	29.5	Stiff gray silty clay w/trace organic matter	32.1	88.3	116.6	2525	34	23	11
10	39.5	Medium stiff gray silty clay w/trace of gravel	25.4	95.4	119.6	1515	36	23	13

*Undrained confined compression shear test;
confined at approximate overburden pressure.

**Sample disturbed.

Part I

2. Geology of the Avery Island Dome

(c) Tectonics

i External Shape

The external structure of the Avery Island Dome above the 10,000 foot contour is delineated by the structural contour map published by the Geological Society of New Orleans. On the south side of the dome, the contour lines between the 1,000 foot level and the 10,000 level show the top of the salt sloping steeply to the south. Traveling in a clockwise direction around the dome, the gradient to the slope made by the top of salt decreases to a more gentle slope.

Northeast of the center of the dome, an overhang begins with the 8,000 foot contour going under the 6,000 foot contour. Immediately adjacent to this point, all contours of a higher elevation cross over the 9,000 and 10,000 foot contours. This condition of overhang, above the 9,000 foot contour to an elevation of 1,000 feet, exists in an arc of 120° to a point due east of the center of the dome.

From this point through another arc of approximately 30°, the flank of the dome is depicted as being almost vertical. This vertical attitude gradually becomes a steep slope as one approaches the southern side of the dome.

Taking into consideration only that portion of the dome above the 1,000 foot contour, the two factors which have the greatest influence in the post depositional shaping of the dome are the (1) meteoric water which percolates through the alluvium and (2) the fluctuations of the ground water elevation caused by tidal fluctuations. The effectiveness of the tide is enhanced by the high permeability of the layers of gravel which immediately overlie large areas of the salt mass.

The main feature of the salt surface above the 1,000 foot contour is the "main" fault which trends east-northeast. This fault takes a crescent shape and is a typical "spine" type formation where a portion of the dome has undergone a shearing action. Where the fault intersects the periphery of the dome, dissolution of the uncapped salt has been the greatest.

As is illustrated by Figure 1 "Structure Map - Top of Salt", both flanks show contour indentation with a saddle having been formed on the fault. This contour map interprets the data to mean that a sink hole exists in the top of salt and is the source of all mine leaks. It is the author's opinion that while this is true in part, closer drill hole spacing would extend the -200 foot contour and the -300 foot contour into the area represented as a sink hole.

Part I

2. Geology of the Avery Island Dome

(c) Tectonics

ii Metamorphism and Flowage

The Avery Island Dome is similar to other Gulf Coast domes, more specifically to the domes of the "Five Islands". Several of the salt domes housing mines, have had the exposed internal structure mapped by Robert Balk (1949 & 1953) and Muehlberger (1959). In 1961, the internal structure of the Avery Island 500 foot level was mapped by P. J. McMullen & Doxey. Except for one map, this work has been lost. The following is the author's interpretation of this map.

All the available workings in the then active 500 foot level were mapped by virtue of anhydrite laminae. In certain areas bands were masked due to dust and smoke carbon. This masking together with the height of the room roofs made mapping an impossibility. The configuration of the rooms on the north side of the 500 foot level tend to outline the main fault. In a majority of cases, these rooms were abandoned because the face was wet or damp. The flowage lines parallel the curvilinear displacement of the fault. All

LEGEND

MAP OF THE BANDING
 OF
 AVERY IS. AND MINE - AVERY IS. AND LA

MINE FLOOR LEVEL, 500' BELOW SEA LEVEL

BY P. MCWALLEN & HERMAN DICKET
 SEPTEMBER 56

notations of the dips of flowage bands adjacent to this curvilinear surface, show an inclination in a southerly direction away from the fault. These dips vary from a minimum angle of 66° to a maximum of 86° with a predominance of low angle dips along the western side of the fault showing the lower angles of dip. Some 12 measurements at the western edge show an average dip of 69° . In general, these are the northern flanks of isoclinal folds and relate to the main fault. This normal or shear fault has segmented the southern portion of the dome so as to form a so-called "spine" or an ungula of a right circular cylinder or a truncated block. The stock of the dome continued to be fed salt and moved upward. The weight of the truncated block caused the deeper, hotter, more plastic salt to be deflected to the north, thus forming the overhang to the north which begins at a depth of approximately 9,000 feet.

The large irregular masses of unmined salt are areas where the chemical composition in terms of sodium chloride are so low as to be non-commercial.

We would assume that the salt was squeezed horizontally from the Louann mother bed. As it formed, the stock

in the structural anomaly of the overlying rock was folded. In its ascent to the surface, the hot plastic salt cooled on the outer periphery forming a hard ridge shell. It is believed that the hot plastic core of the dome continued to move, shearing the folds as suggested by Balk.¹

Again, it is evident that the axes of the isoclinal folds parallel the curvilinear fault structure where these axes are as distant as 500 feet from the structure. Associated with the main fault are layered sand inclusions. The layered inclusions of sand have flowage characteristics similar to those of salt. This flowage type structure is readily understood since the matrix or cementing material of the sandstone is salt. The variety of colors of sand inclusions found underground is similar to those found in the sand pits on the surface, although in the underground, buff to brown predominates.

In traveling toward the south side of the dome, you find that folding is due primarily to flowage and should be classified as "flow folding" or "ptygmatic folding". The banding shows a complete variety of drag folds, Z drag folding, slip folds and isoclines.

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¹ Balk, Robert, 1949, Structure of Grand Saline Salt Dome, van Zandt County, Texas: Amer. Assoc. Petrol. Geol. Bull. Vol. 33 p 1791-1829.

All faces on the southeast, south and southwest portions of the mine were abandoned due to the dampness in the salt. It is interesting to note that all the recorded dips are to the south and southeast. It is the author's opinion that another macro fault or faults has terminated continued mining operations to the south. It has been estimated that some 10 to 15,000,000 tons of extractable salt may be available on the 500 foot level south of this projected fault zone.

Part I

2. Geology of the Avery Island Dome

(c) Tectonics

iii Faulting and Tension Cracks

Of all the geological phenomena relating to salt domes, perhaps the least understood is faulting.

It is the least understood because it is the most difficult to recognize in the mine openings and more particularly in the core.

There are a large number of micro faults associated with the flowage structure and folding. Macro faults are associated with a large accumulation of differential stresses which have insufficient time for relief by plastic flow. These macro faults are the ones which are of concern in any mining or storage operation. It is these faults that are referred to in this section of the report.

In mines, dampness is generally associated with faulting and thus faults are avoided due to the possible influx of water. Where moisture is not encountered in a fault, the salt is usually so contaminated with insoluble "drag" material that it is unmarketable. Of specific importance is the occurrence of white silica sand and various forms

of anhydrite. All leaks on the 700 foot level of the Avery Island Mine are confined to the main fault zone.

On the accompanying figure, the titled Geologic Map of the Avery Island Mine, this fault referred to previously as the main fault is marked "Southern Coarse Belt" with a second, only partially delineated, fault marked "Northern Coarse Belt". The northernmost of the workings shown on this map are the 700 foot level. In stating that all faults on the 700 foot level were confined to the fault area, reference was made to the rooms T26, T25, P23, Q23, R23, P22 and P21 and more specifically, to the contact between the crystal salt (Secondary Deposition) and the metamorphic salt of the dome.

The rooms which were driven into this fault were all 150 feet wide. These rooms were driven into the fault with full knowledge of the fault's presence. Benchmarking was only completed to the full height in that area outlined by the dotted line due to the development of leaks after the initial headings were driven.

It is the opinion of the author that all the wet faces of salt on the 500 foot level were either directly or indirectly associated with a fault structure and that all moisture encountered was an artificial brine or a solute of meteoric water. No moisture or wet faces have been encountered on the 880 foot level. All mining on the 700 foot level has been abandoned. Again, the abandonment of the 880 foot level was due to wetness in the faces. Thus, it now appears that a system of faults crossed the north and west side of these openings.

Those rooms associated with H6, H7, G6, F6, E6 and D6 are characterized by inclusions in the salt of heavily layered banded anhydrite which includes evidence of flowage due to elongated crystals, slickensides within the layered anhydrite and wetness.

Tension cracks have developed during the depositional history of the Avery Island Dome. I have previously reported these observations which were made some three years ago on the mine's 500 foot level. It was found that by using long wave length ultra-violet light, narrow pink bands could be observed in the pillars and roofs of the old mine workings. As previously

LEGEND

	MAJOR DISLOCATION	W	WATER
	OTHER SHEAR ZONES	H	HYDROCARBONS
	MARGINAL FRACTURES		BRECCIAS
	COARSE CRYSTALLINE SALT		SANDSTONES
	CORES OF ANTICLINES		OVERBURDEN
			CLAYS SANDS AND GRAVELS

AVERY ISLAND DOME
 GEOLOGICAL CROSS SECTION A-A'
 HORIZONTAL SCALE 1" = 400'
 VERTICAL SCALE 1" = 100'

Geologic Map Of The
Avery Island Mine
1" = 400'

- LEGEND**
- Medium crystalline salt (Crystals $\approx 1/4"$)
  - Very coarse salt (Crystals $> 2"$)
  - Dark coarse beds
  - Sandstone and limonitic beds
  - Clay Nodules
  - Major leak, present or past
  - Major leak, grouted
  - Belt boundaries

stated, all recorded dips on flowage structure bands are to the south and southeast. These pink linear bands form acute angles with the flowage bands dipping approximately 70° to 85° to the north and northwest. These bands were not discernible with white light from cap lamps, flash lights or electric light bulbs. Under ultra-violet light these bands have a thickness varying from 1/4 inch to 1 inch.

Crushed salt products from the 700 and 880 foot levels were found, upon examination with ultra-violet light, to contain these same pink particles. A sample of these particles were collected and dissolved in water with a resultant snap, crackle and popping. A sample of the gas evolving was collected and found to be methane with traces of propane and butane.

Part I

2. Geology of the Avery Island Dome

(c) Tectonics

iv Secondary Deposition and Healing

These tension cracks have a radial curvature in plain view and are filled with recrystallized secondary salt. This secondary salt contains appreciable percentages of hydrocarbon gas which is principally methane. It should be noted that this is a characteristic difference between the recrystallized salt of the tension cracks and the recrystallized salt associated with either the flanks of the dome or that which forms the large shear faults of the primary domal mass.

It is the author's opinion that these tension cracks are a result of the difference in the specific gravity of the salt mass and the low density of the soft confining sediments. The density of salt ranges from 2.1 to 2.6 or more, depending in part upon the impurities that it contains. From the soil value densities previously reported for the earthen material on top of the salt, these wet densities ranged from 1.7 to 2.1 with some isolated samples recording values as low

as 1.3 specific gravity. It is apparent that, as the salt intrusion nears the surface of the earth, the confining pressures of the penetrated materials become less. Thus, depending on a number of factors such as heat, degree of compaction and specific gravity of the confining sediments, the structural soundness of the salt and the height to which the salt has been extruded, radial tension cracks will develop.

At Avery Island, these tension cracks were healed by hot methane and other hydrocarbon gases entering these tension fissures at their intersection with the periphery of the dome. Hot compressed gases entered these brine filled fissures with two resultant effects. First, they acted in a manner similar to an air lift causing an upward circulation of hot brine. Secondly, the hot gases expanded as they moved upward to areas of reduced pressure, absorbing the water from the brine. This effect plus the cooling of the brine circulating upward, caused a precipitation of the salt. Gradually the crack was healed.

The mechanics of the healing of the fault zones within the dome involves the development of secondarily deposited or recrystallized salt, but this

salt generally does not contain hydrocarbon gases. This fault filling or replacement, crystal halite is characterized by sand inclusions either as lenses, fragments and/or small granular particles. .

The third point at which one finds secondarily deposited crystal halite is at the periphery or flanks of the dome from the center. In the proximity of the periphery, all banding begins to fade and disappear, indicating that the primary dome salt was dissolved and recrystallized as an outside "shell". This type of deposition might be accounted for by the vertical ascension of hot brines which, as they cooled, deposited crystal halite. This has not been adequately explored at Avery Island so that a valid conclusion can be drawn. On the Bruinsburg Dome, near Port Gibson, Mississippi, the A.E.C. drilled a core hole which was reportedly in the center of the dome. Subsequent drilling and geophysical exploration showed this hole to have penetrated the periphery of the dome. Thousands of vertical feet of clear crystal salt was recovered from this hole together with its whipstock.

Part II

Hydrology

1. External

The most important aspect of mining salt at Avery Island and probably that of any mine built in a salt dome, is the external water of the dome. Since there are only minor remnants of an andy-drite cap rock at isolated points on the flanks, the top of the salt dome is exposed to the percolation of meteoric waters.

The general distribution of ground waters, aside, and within different areas of the salt intrusion is presented in Plate H1.

This systematics of ground waters was based on data collected from many tests of drill holes, drilled from the holes were also utilized for accumulation of water level data for the aquifer on top of the salt dome. Chemical analyses were run to determine the distribution of ions and mainly for location of low salinity "streams" within this aquifer in both horizontal and vertical dimensions. Two cross-sections, C-C' and D-D' show the lithological composition of the unconsolidated sediments occupied by the aquifer within the central canyon area on top of

DISTRIBUTION OF GROUND WATERS IN THE AVERY ISLAND SALT DOME

JACOBY & COMPANY

DRAWN BY R.J.D.	CHECK BY S.S.

APPROVED BY:

SCALE Δ3 NOTED	DATE JAN. 24, 1977

NOTE:

HORIZONTAL PROJECTION NOT TO SCALE

Plate
H1

CROSS-SECTIONS THROUGH THE CENTRAL CANYON

W
C

JACOBY & COMPANY	
DRAWN BY R.D.	CHECK BY S.S.
APPROVED BY:	
SCALE AS NOTED	DATE JAN. 26, 1977

E
C'

SW
D

Plate
H2

STRUCTURE OF THE TOP OF SALT IN THE CENTRAL CANYON

OUTLINES OF THE WORKINGS
AT THE 700' LEVEL

DEEP CREVASSE AND CAVITIES
BELOW THE TOP OF SALT, AND
SEA LEVEL ELEVATION OF PENET-
-RATION

SANDSTONE BRECCIA IN
TOP OF SALT

C — C' CROSS - SECTIONS

D — D'

CENTRAL
CANYON

0 200'

JACOBY & COMPANY	
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APPROVED BY:	
SCALE AS NOTED	DATE JUN. 26, 1977

Plate
H3

the dome, Plate H2.

In a descending order, first ground waters can be encountered already within the surface mantle of sediments on the island. Perched waters were found at different depths within the clays in lenses and layers of sands above the median gulf level elevation, within the eastern hills of the island.

The first aquifer occurs in the sands and gravels within the unconsolidated sediments, on top of the dome. As mentioned before, thickness of this aquifer is greatest in the flanks of the dome, and in the central canyon area where it exceeds 200 feet. The aquifer thins out distinctly in the direction of the high elevated segments of the dome. In these locations you encounter a thickness of 10-15 feet or less. This aquifer is under water table conditions. Its piezometric water level raises from seal level in the periphery of the dome to about 20 feet above sea level in the center of the island. It is constantly being recharged by meteoric waters through outcrops of unconsolidated sediments on the surface. A prime example of this is in the area of the valley where, through the

sand and gravel pits in the center of the island. There is also recharge through several beds of intermittent creeks which cut through the clays, and exposed the high permeability of unconsolidated sediments of the aquifer where it is above the water table. In general, it was found that the many ponds and lakes of the island, do not communicate with the aquifer having, as a base, one of the clay layers. An exception is the Blue Hole, or Blue Pond, which in fact is a flooded old shallow salt mine, and where there is a direct communication between the surface waters, the aquifer and the salt deposit.

It was found that within the central canyon area (Plate H3), the horizontal distribution of chlorides at the bottom of the aquifer was quite diversified. It varied from 8% to 98% NaCl (Plate H4). The distribution of chlorides indicate that there is a stream of relatively low salinity waters close to the bottom of the aquifer which signs itself with the long axis of the canyon, shifting towards its western bank. Specific gravities of those waters oscillate from 1.015 to 1.199. It was interesting to find that most of the water samples from this aquifer

CHLORIDES %

• 1-18 PIEZOMETER HOLES

○ 1-11 GROUT HOLES

— MINE LEAK

— 7505 DRILLING STATIONS - MINE

— 25 — UP HOLES - MINE

S.S.

JACOBY & COMPANY

DRAWN BY R.J.D

CHECK BY SS.

APPROVED BY:

SCALE AS NOTED

DATE JAN. 27, 1977

STRUCTURAL AND LITHOLOGICAL CROSS-SECTION

VERTICAL SCALE 1 : 6,000
HORIZONTAL SCALE 1 : 24,000

CLAYS

SANDS AND GRAVELS

BRECCIATED SANDSTONE

THIN LAYERS OR BRECCIATED FRAGMENTS OF BLACK MUDSTONE

HALITE WITH GRAY TO BLACK BANDS OF ANHYDRITE

FINE TO MEDIUM CRYSTALLINE - CRYSTALS < 0.5 INCH

ERRATIC PATCHES OF GYPSUM - FRAGMENTARY CAP ROCK

ENTRAPPED METHANE IMPREGNATING SPORADICALLY SOME SEQUENCES OF HALITE

COARSE CRYSTALLINE HALITE - CRYSTALS LARGER THAN 0.5 INCH

THICK, BLACK BANDS OF ANHYDRITE

MARGINAL JOINTS - FRACTURES, USUALLY IMPREGNATED WITH HYDROCARBONS

MAJOR DISLOCATION

SHEAR ZONE INDICATING DIRECTION OF SHEAR

displayed an alkaline state with pH values from 6.9, the single lowest, through 7-8 to 10.6, the highest. The vertical distribution of chlorides is more uniform and changes from 0, in the uppermost layers of the aquifer, to 98% or more of sodium chloride saturation at the contact of the salt. The surface recharge by meteoric waters is quite extensive in summer, with the average monthly precipitation of about 5.2 inches per month or 62.4 inches per year. The upper portions of the aquifer constitute a fresh water zone floating on the heavier saline waters below. This floating effect explains the high sea level elevation of the water table in the central areas of the island. Such conditions predominate during the rainy summer seasons. In low precipitation periods the balance between the hydrostatic head within the aquifer and that of the waters outside the island may be reversed, and recharge in the opposite direction, is quite possible. Insufficient data are available to make a positive statement at this time.

Part II

Hydrology

2. Internal

(a) Faults

Below the aquifer, there is a zone of ground waters composed primarily of high salinity brines. These brines occur within crevices and cavities in the top of the salt which in themselves occur in the fault outcrop. Such cavities are known to penetrate deep into the salt dome. In the central canyons area, these crevices have been encountered at depths of -500 feet below gulf level. These crevices are closely related to the structure of the intrusion, because they are elongated with the strike of the structural elements of the dome. These crevices are in an inclined attitude parallel to the strike plane of the fault. They developed in several parallel sequences and appear to be tabular openings.

(b) Faults: Non-Meteoric Fluids

Within the central fault dislocation, in association with the sequences of sandstone breccias, and sandstone seams, there is some seepage into the mine of saturated brines. These brines contain a high accumulations of potassium salts when associated with

these sandstones. The salt associated with the sandstones have some potassium mineralization which is soluble even in saturated brines.

During horizontal coring operations fluid filled cavities have been encountered. Because the cavities were pressurized with methane gas and the fluid at variance to the normal chemical composition of meteoric based brines it is the author's opinion that these are formational waters perhaps associated with the sandstones which were dragged into the fault. A sample collected from one such core hole which produced gas, brine and mud gave the following chemical analysis for the muddy brine:

Barium	340 p.p.m.
Magnesium	3,290 p.p.m.
Calcium	41,664 p.p.m.
Iron	10,313 p.p.m.
Manganese	61 p.p.m.
Silica (as SiO ₂)	231 p.p.m.
Sulphide	666 p.p.m.
Sulphate	124,995 p.p.m.
Chloride	546,018 p.p.m.
Oil & Grease	164 p.p.m.

Meteoric waters seeping from the aquifer above, have a very high, but strongly fluctuating content of iron. Iron content may vary by fractions of one milligram per liter to as much as 6 milligrams per liter or more. The calcium/magnesium ratio for waters related to the ground water aquifer are very high, sometimes as large as 1400. This contrasts markedly with the sample above which was known to be connate in origin and with a Ca/Mg ratio of 13.

Downward migration of brines, even supersaturated with respect to sodium chloride, within sequences of salts above extracted areas is possible. This is due to the development of a system of stress crevices above the mined out areas. Brines within the crevices and above the roof of the mine display unusual hydrostatic pressures which are always lower than the calculated hydrostatic head for the same given depth. Pressures in these crevices oscillate from 0-170 psi at elevations above the 700 foot level.

Temperatures of these percolating meteoric waters are steady, fluctuating between 76.2°F - 76.8°F for the peripheral zones. Areas closer to the center of the dome exhibit brine temperatures in circulating fluids of 78.5°F. In other words, brines recharged

from the aquifer above the dome, are cooler than the formational temperature of salt, and also cooler than the air temperature in the workings.

(c) Intergranular Voids

In zones, where there are no open crevices, migration of brines is possible under existing hydrostatic pressures through micro channel and between the crystals or grains of salt, together with transmissibility along intracrystalline faces. This intracrystalline hydraulic conductivity usually develops above the zone of sag crevices, within the disturbed structurally "chimney of stresses", located usually in the center of gravity for individual extracted areas and above the stress arch associated with the opening. Brines within such zones of loose salt display normal hydrostatic heads that closely approximate calculated hydrostatic values. Pressures from 230-310 psi were encountered within this zone above the 700 foot level.

It was interesting to notice that contrary to the pH values for the aquifer above the dome, waters within the sag crevice zone display much lower pH, as a rule on the acidic side, fluctuating from 4.5 to 5.5.

Some of the brines from within the deep crevices and cavities show distinct traces of hydrogen sulfide and also substantive amounts of gaseous nitrogen. Although many domes have reported the existence of carbon dioxide, none of the gas analyzed from the Avery Island dome have shown any carbon dioxide.

The aquifer above the salt dome extends beyond the periphery of the dome, increasing rapidly in thickness as one departs the dome. Its thickness above the dome reaching maximum of about 200 feet within the central canyon and increases to over 200 feet outside the flanks of the dome. At this level usually a sequence of shale is encountered outside the dome. It is very indicative that wells located very close to the flank of the dome, within this aquifer, can operate on certain limited capacity only or otherwise a surge of saline waters or understaurated brines develops. It is considered that a plume of brines with salinities decreasing away from the dome surrounds the salt intrusion. The shape of the plume must be related to the movement within this aquifer, and in undisturbed conditions would be asymmetrically oval in shape, narrower on the upstream side and wider on the downstream or southeastern side of the dome.

This shape of the plume can be drastically distorted by excessive extraction of ground waters in areas too close to the dome.

Part II

Hydrology

2. Internal

d. Interstitial

In general, the metamorphosed mass of salt that constitutes the Avery dome is very dry with a low inter moisture content. This low moisture content was demonstrated recently when electromagnetic energy was used in an attempt to detect anomalies in the salt. Unlike other domes in the area where the attenuation of electromagnetic energy is halted by interstitial moisture, Avery's salt allows good transmission.

It is difficult to determine surface moisture from interstitial moisture. In general, surface moisture is related to the slight deliquescence of salt and the percent calcium chloride that forms a salt contaminate. It has been postulated that 95% of the moisture found in laboratory testing is surface moisture with only 5% being truly interstitial. Surface moisture is determined by heating a sample of salt at 350° C for 15 minutes. Interstitial moisture is determined as the difference between total moisture when heated at 500° C for 15 minutes and surface moisture.

Part III

Rock Mechanics

1. In Situ Stresses

The in-situ stress field of the Avery Island Dome is very complex. It has been suggested that the dome is moving upward but to the best of the author's knowledge, there is no scientific data to support this allegation. The movement of the old hoist head frame with relationship to the shaft has an undetermined cause but, in all probability, was artificially induced by the underlying mine workings. Factors influencing the in-situ stresses of the dome are:

1. Mine workings
2. Oil & gas production
3. Confining pressures of beds pierced by the salt intrusion
4. Shear faults
5. Domoal cooling and heat flow
6. Flowage planes

Below a depth of 1,000 feet, the primary induced stresses are those associated with the extraction of oil and gas. This effect is not measurable. Down to a depth of 4,000 to 5,000 feet, the outside shell of the dome is believed

to be in tension due to the difference in the specific gravity of the salt in contrast to specific gravity of the penetrated sediments. The periphery tension cracks mentioned previously in this text, have been healed but the conditions which created them are still in existence, although diminished.

A full delineation of the faults and the pattern of faults has not been established but the stress buildup has obviously been relieved. Sections of the dome which have been segmented by the faults occasionally exhibit areas of loose large (1/4" to 1/2") crystals of salt. These crystals have an intergranular void space which was apparently gas filled prior to mining operations. It is believed that these voids are the result of domal cooling from the outside inward to the core.

It may be observed that pillar spalling on occasion occurs along flowage planes indicating an inherent weakness above these planes.

Part III

Rock Mechanics

2. Induced Stresses

Above the depth of 1,000 feet, the prime factor influencing the stress field is the mine workings. As reported previously in the 1976 Rapid Excavation and Tunneling Conference, the first attempt to monitor salt movement in the mine working was in April, 1962. Movement associated with the mine workings are a function of

1. Percentage of extraction
2. Strength of the salt
3. Shape of the openings
4. Size of the pillars
5. Faults and other associated anomalies

As a result of a demonstrated ability to control pillar dilation by controlling the shape of the openings on the 500 foot level, roof spans on the 700 foot level were increased from 100 feet to 150 feet. The first gauges were sag pins set in the roof to measure roof sag and dilation pins set in the rib to measure pillar dilation. During the test period it was demonstrated that a stable roof could be created with spans of 150 feet. Additionally, it was demonstrated that pillars

of the dimensions of 150 feet wide by 150 feet thick had significantly more stability than those of the 100 foot by 100 foot dimensions. Where the percentage of extraction is the same, the larger pillars showed no spalling while those of smaller dimensions exhibited sizeable amounts of scaling of the pillar "shell".

Stresses which have been induced into the salt mass as a result of mining operations have been within acceptable limits except where these openings have penetrated the major fault. This penetration has occurred on the 700 foot level with rooms having roof spans of 150 feet in complete disregard of technical advice. All known leaks into the mine occur in rooms driven into this fault zone. By creating the 500 foot level on one side of the fault zone and the 700 foot level on the opposite side, the induced stresses which form a couple whose fulcrum is positioned within the fault zone. Thus, a force has been created which has the tendency of splitting the fault. This condition has been amplified by the creation of an additional level at a depth of 880 feet across the fault from the 700 foot level and below the 500 foot level. As the aerial extent of the 880 foot level increases, this stress field will become more pronounced.

Measurement of rock movement in rooms of 100 feet by 100 feet or 150 feet by 150 feet is difficult. The initial

heading which is usually 20 feet in height can be easily instrumented with convergence gauges, dilation pins in the ribs, roof pins and pressure cells. During the creation of the first 45 foot bench, the convergence gauges of the headings are destroyed and the installation of 65 foot gauges in the new openings is impractical, if not impossible. Roof pins are only of value if they are instrumented for remote reading. Pressure cells designed for direct reading such as the "horse collar" are of no value. The only practical type of installation thus far employed is the dilation pin set in the pillar just above the floor of the first bench. Extreme care must be taken in the installation of such pins in order to avoid blast damage when the second bench is shot. Such pins are read by the installation of a ladderway or with a "cherry picker". After creation of the second bench, no attempt was made to install any type of instruments.

It has been found that roof conditions at Avery Island are good. These conditions were enhanced by the creation of a fillet with a radius of curvature of 3 feet. This procedure was recommended when the roof spans were increased from 100 feet to 150 feet. The Avery Mine has

experienced only one roof fall in the last twenty years. This was in an area where a sharp variation in room heights created a differential stress.

Because of good roof conditions, very few roof bolts have been installed. Since the anchor seat is in pure salt which will deform plastically, the selection of a suitable anchor has been a problem. At present, resin anchors are under study with pull tests to be conducted by Bethlehem Steel. Some bolting has been conducted on the 700 foot level under the following conditions:

Bolt size	7/8"
Plate size	6" x 6" x 3/8"
Hole size	1-5/8" diameter
Pattern	Random
Anchor	Bethlehem Expansion Shells

Part III

Rock Mechanics

3. Grouts and Grouting Procedures

Until recently, except for work associated with the mine shafts, all grouting operations were conducted by the mine personnel. Shaft grouting is always conducted by a contractor. Grouting operations on the 500 foot level were limited to a few isolated occurrences where fluid filled fractures and faults were encountered during mining operations.

Upon driving the inclined slope from the 500 foot level through the main fault to the 700 foot level, several minor leaks associated with sandstones lenses in the fault were encountered. These leaks were grouted off by drilling vertically through the sandstone and injecting portland sulphate resistant cement. These leaks were sealed during tunnel driving in 1962, but periodically the leaks have been rejuvenated by rock movement and subsequently resealed by grouting.

Only after the mine workings on the 700 foot level had been driven into the main fault zone was water encountered on the 700 foot level. Initially, grouting by mine personnel was conducted by drilling shallow holes into the

roof to the first water or void. Most of these grout holes were less than 40 feet in length, usually terminating in sag crevices. Only in a few isolated cases did the grout holes actually penetrate the stress arch above the mine opening. Over 300 of these unplugged holes have been counted but it has been reported that over 600 exist. After the total combined influx of water into the mine had exceeded to 45 gallons per minute, the problem was submitted to a geological-hydrological analysis.

As a result it was found that all leaks on the 700 foot level were associated with the main fault where it had been penetrated by mine workings. After mapping the fault zone, a series of grout holes ranging between 300 and 700 feet in length were drilled perpendicular to the axis of the fault and in keeping with known hydrological conditions. Crevices filled with sand, gravel, mud and water were encountered.

Previous grouting operations used either straight portland cement grout, brine based cement grout or the chemical grout AM-9. Straight cement grout, as with AM-9, will not bind with the salt. Grouts composed of brine based cement will not only adhere to the salt but will also expand upon setting. Initially, thin slurries of brine and cement were

used with approximately 3-1/2 sacks of cement being mixed with 70 gallons of water. The cement-brine ratio used was a function of conditions encountered in the hole with respect to the porosity and permeability of the brine producing zone.

It was recognized that grout would travel downward or horizontally through the fissures and crevices but little or no vertical placement was accomplished above the point where the bore hole penetrated the crevice. Wetting agents were incorporated with the grout in order to decrease the viscosity and increase the flowability. It was found that some of these materials would increase the crevices' acceptance of grout by a multiple of two. Some of this increased acceptance must be credited to an increase in the setting time particularly where two thousand or more sacks were installed. Additionally, other materials were added as fillers to reduce the cost of grouts.

By way of illustration, the grout holes drilled over the "high roof" area in what was termed the Slope #8 area are shown on the accompanying chart.

Summarizing this chart, one finds that those holes in this location whose angle was 21° - 30° were the only ones which actually encountered the "target" leak or the source of water flowing into the mine as confirmed by dye testing.

CORRELATIVE ANALYSIS OF EFFECTIVENESS OF HOLES DRILLED AGAINST
THE NO. 8 SLOPE LEAK
TOTAL NUMBER OF HOLES - 45

Subject of Analysis	Vertical angles of holes		
	0 - 20°	21 - 30°	31 - 35°
Number of holes	19	18	8
Percent of holes	42%	40%	18%
Holes connected to target = leak	0	4	0
Percent connected	0%	22%	0%
Number of holes with loss zones	2	1	0
Number of holes making water	6	14	7
Percent of holes making water	32%	78%	88%
Dry holes	11	3	1
Percent of dry holes	58%	17%	13%
Water intersected in GPM	29.2	476.6	235.0
Percent of total water intersected	4%	64%	32%
GPM per hole	1.5	26.5	29.4
Volume of grout accepted in sacks of cement	486	5,372	419
Percent of grout accepted	8%	86%	6%

Note:

Ends of holes within the above mentioned groups penetrated the following vertical sequences above the roof of the 700 level in the leak area. This vertical distance above the roof is a function of sea level elevation of the drilling station, angle of hole and course length (T.D.) of hole.

Groups of holes	Vertical distance above the roof	
	Minimal	Maximal
0 - 20	49.6'	265'
20 - 30	127'	388'
30 - 35	289'	476'

This percentage of successful completions was low being only 22%. Where success was achieved, holes were redrilled after grouting and parallel ungrouted crevices were found beyond the initial crevice.

The percentage of holes where water bearing crevices were encountered in the salt was excellent. As depicted on the chart, those holes with angles from 0° to 20° showed 32% successful completions; 21° to 30° angle had 78% success while those holes drilled at angles of 31° to 35° were 88% successful.

Piezometers were set on the surface in the area above the Slope #8 leak. Before adequate data could be collected, more precisely as the last piezometer was set, the situation underground was deemed so critical that surface grout holes were commenced immediately. Underground grout holes from stations 7505, 7506, 7507 and 7508 had encountered flows of water, but the emplacement of grout was too slow and many of the holes while being connected to a water filled crevice were not connected directly to a mine leak.

Before the surface grout hole pattern was fully established it was necessary to begin grouting these holes. The distribution of grout is shown on the accompanying chart of the 11 surface grout holes. This operation began with the

introduction of a 15 pound per gallon cement slurry. After some 160,000 gallons of slurry or 16,000 sacks of cement had been placed in the gravel layer which rests on top of the salt, Dowell's bentonite-polymer formulation was injected. This bentonite-polymer formulation was composed of 590 sacks of bentonite and 36,000 gallons of polymer solution for a total of 160,000 gallons of bentonite-polymer slurry.

During this period of injection underground, grout holes which had not yet received grout were opened so as to aid in carrying the surface grout into the crevices. As shown on the Before and After Table, of the 351 gpm total flow from these holes, their total capacity was reduced to 87 gpm or 76% with S-33⁰ at Station #7505 going from 20 gpm to zero a few days later. Grouting operations were terminated by budgetary conditions and a fluid shut off satisfactory to management.

Many of the leaks which continued after these surface grouting operations had been terminated, showed a change in pH from the ground waters normal acidic conditions to basic pH's. It is believed that this change in pH was due to grout entering the water course of the mine leak but in quantities insufficient to block fluid passage.

SurfaceDISTRIBUTION OF GROUT

HOLE	GEL & POLYMER SACKS	CEMENT SACKS		GEL SACKS
G 1		700		100
G 2	30	2000		
G 3	30	2000		
G 4		1300	3000	
G 5		2000	2000	
G 6				60
G 7				100
G 8				100
G 9				100
G10	30	2000		
G11			1000	40
Total	90	10,000	6,000	500

Total 590 sacks of Bentonite/+36,000 lbs Polymer

16,000 sacks of cement

or

124,000 gallons of bentonite slurry

36,000 gallons of polymer

160,000 gallons of cement slurry

Tl 320,000 gallons of grout slurry

MINE HOLES BEFORE AND AFTER GROUTING

10/23/75

<u>Station</u>	<u>Hole</u>	<u>Original Flow</u>	<u>After Grouting</u>
<u>7505</u>	Q-18°	1 GPM	1/2 GPM
	R-25°	3 GPM pH 5	3 GPM pH 10-12
	S-33°	22 GPM	20 GPM Zero 10/28
	T-32°	15 GPM	1/2 GPM Bentonite
	U-35°	50 GPM	Cement
	V-28°	50 GPM	5 GPM
	W-18°	---	8 GPM
	X-25°	50 GPM	Cement
<u>7506</u>	3-20°	8 GPM (Dye)	5 GPM (Dye)
	4-21°	60 GPM (Mud)	10 GPM (Dye)
<u>7508</u>	3-16°	3 GPM	2 GPM
	4-18°	4 GPM	3 GPM
	5-20°	5 GPM	5 GPM
<u>7507</u>	3-30°	50 GPM	5 GPM
	4-25°	30 GPM	20 GPM
<u>Total</u>	15 Holes	351 GPM	13 Holes 87 GPM