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Sulphur Extraction at Bryan Mound

Carolyn L. Kirby and Anna S. Lord

Prepared by
Sandia National Laboratories
Albuquerque, New Mexico 87185 and Livermore, California 94550

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Sandia National Laboratories
P.O. Box 5800
Albuquerque, New Mexico 87185-MS0750

ABSTRACT

The Bryan Mound caprock was subjected to extensive sulphur mining prior to the development of the Strategic Petroleum Reserve. Undoubtedly, the mining has modified the caprock integrity. Cavern wells at Bryan Mound have been subject to a host of well integrity concerns with many likely compromised by the cavernous caprock, surrounding corrosive environment (H_2SO_4), and associated elevated residual temperatures all of which are a product of the mining activities.

The intent of this study was to understand the sulphur mining process and how the mining has affected the stability of the caprock and how the compromised caprock has influenced the integrity of the cavern wells. After an extensive search to collect pertinent information through state agencies, literature searches, and the Sandia SPR library, a better understanding of the caprock can be inferred from the knowledge gained. Specifically, the discovery of the original ore reserve map goes a long way towards modeling caprock stability. In addition the gained knowledge of sulphur mining – subsidence, superheated corrosive waters, and caprock collapse - helps to better predict the post mining effects on wellbore integrity.

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CONTENTS

FIGURES

TABLES

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NOMENCLATURE

DOE	Department of Energy
F	Fahrenheit
LPG	Liquefied petroleum gas
psi	Pounds per square inch
SNL	Sandia National Laboratories
TECQ	Texas Commission on Environmental Quality
TRRC	Texas Railroad Commission

1. INTRODUCTION

The Bryan Mound caprock was subjected to extensive sulphur mining prior to the development of the Strategic Petroleum Reserve. Undoubtedly, the mining has modified the caprock integrity. Cavern wells at Bryan Mound have been subject to a host of well integrity concerns with many likely compromised by the cavernous caprock, surrounding corrosive environment (H_2SO_4), and associated elevated residual temperatures all of which are a product of the mining activities.

The intent of this study was to develop a map that identifies where the bulk of the sulphur extraction occurred, which could be used as an analog to imply the location of the most crumbled and cavernous regions within the caprock. What is known is the location of many of the sulphur wells drilled, but what is not well understood is the production success or ore volume of each well along with an understanding of the geologic sulphur distribution within the caprock. The creation of an ore extraction map would help to improve the Bryan Mound geomechanics model and the cavern well integrity predictions.

This paper presents the geology of caprock sulphur, the sulphur mining process, the sulphur mining history at Bryan Mound, also known as Bryan Heights, as well as a discussion on how the information collected through state agencies, literature searches, and the Sandia SPR library advances our understanding of the Bryan mound caprock structure and environment.

2. APPROACH

The approach to collect pertinent sulphur production data was to (1) search the Texas State agencies records, (2) scour the published literature, and (3) comb through the Sandia Strategic Petroleum Reserve physical library for possible misplaced and/or currently unknown relevant documents.

State agencies contacted were the Texas Railroad Commission (TRRC) and the Texas Commission on Environmental Quality (TCEQ). After contacting the TRRC, the state agency that regulates the oil and gas industry, gas utilities, pipeline safety, safety in the liquefied petroleum gas (LPG) industry, and surface coal and uranium mining, it was discovered that this agency does not have sulphur production records from the 1900's. After 1981 any records of this type were regulated by TCEQ and sulphur wells were classified as Class III wells, which are underground injection wells. The TECQ does not have any information on sulphur wells drilled at Bryan Mound. Although the TCEQ currently is the state agency responsible for permitting injection wells for sulphur recovery, Bryan Mound was mined prior to TECQ's issuance of these permits and over-site. Any actual production records were only required to be held by the operator.

Freeport Sulphur was the main operator on the Bryan Mound dome and has maintained a policy of confidentiality from the very beginning. This has hampered site characterizations in later years. DOE and Freeport were in litigation concerning the condemnation of the site during the 1980's and the outcome of that litigation is unknown at this time, suffice to say that Sandia never received records of sulphur production: tonnage extracted from each well.

Research for this project had to take another direction - contacting retired Sandians, making contact with colleagues at the University of Texas at Austin - Bureau of Economic Geology, looking through old records in the Sandia Strategic Petroleum Reserve Library, and an internet literature search (searching on both spellings of sul<u>ph</u>ur and sul<u>f</u>ur). A number of key publications from the early 1900's describe the history of Bryan Mound and the fundamentals of the sulphur mining that took place.

3. GEOLOGY OF CAPROCK SULPHUR

3.1 Sulphur Formation

Only about 20 percent of the salt domes in the Gulf Coast contain sulphur within their overlying caprocks. A caprock is formed from the dissolution of the underlying salt and consists of the impurities remaining after dissolution. Caprock generally is comprised of anhydrite and layering of its diagenetic products gypsum and limestone, in addition to such compounds as sulfate. Elemental sulphur is formed from the bacterial reduction of sulfate (Kyle, 2002). Sulphur present in caprocks, available for mining, is native sulphur distributed throughout the different strata of the caprock, “occasionally it is in a more or less continuous bed, but it usually fills seams, fissures, and cavities, or is disseminated through the porous limestone” (Baker, 1935). The sulphur associated limestone portion of caprock is naturally honeycombed or vuggy and fractured, but this does not necessarily mean the sulphur deposits are universal throughout the entire caprock. Sulphur also can occur in the anhydrite but cannot be mined because this rock lacks the necessary porosity. The minable sulphur only occurs in the porous limestone (Baker, 1935).

In general, sulphur deposits are found between the anhydrite/gypsum below and the limestone above. Sulphur deposits within the caprock are never uniform. Some salt domes exhibit sulphur across the entire caprock while others have deposits concentrated around the edges of the dome and smaller volumes of ore scattered over the top. The sulphur zones may also be present in one or more horizons. There is no correlation between the thicknesses of the anhydrite/limestone zones to the thickness of the sulphur regions. On some domes, the alteration within the deposit is not complete from gypsum to limestone and sulphur and is a matrix in unequal quantities, both laterally and vertically. This type of mineralization is very prevalent at Bryan Mound, where this can either be noted in all the deposits across the entirety of the caprock or in only along the edges of a deposit (Myers, 1968).

3.2 Bryan Mound Caprock Sulphur

Prior to 1904 seven wells were drilled for petroleum exploration over Bryan Mound. During this exploration for oil and gas, large quantities of sulphur were discovered dispersed through the gypsum and limestone layers at a depth between 700 and 900 feet over 300 acres (Kennedy 1926).

Bryan Mound is considered a medium sized dome with the sulphur ore concentrated around the periphery of the dome with smaller quantities deposited intermittently across the rest of the dome (see Figure 1). Bryan Mound caprock is an example of where the alteration to sulphur is incomplete universally across the dome and quantities of limestone, sulphur, and gypsum are present in unequal distributions both laterally and vertically throughout (Myers, 1968).

The caprock at Bryan Mound is circular in shape, with the shallowest elevation documented at -682 ft located in the northwest region. The greatest thickness of caprock is over the northwest region with a thickness exceeding 400 ft (Lord, 2007). The caprock has been characterized in several reports as having three units (Hogan, 1980; Kennedy, 1926). The three unit division of caprock is very typical in Gulf Coast Salt Domes. Hogan (1980) describes the caprock as follows:

- Unit 1 (uppermost) consists of limestone with water or sulphur-filled pore space.
- Unit 2 (middle) is a transition zone and consists of limestone, gypsum, sulphur and anhydrite.
- Unit 3 (lowermost) consists of anhydrite.

The sulphur deposits are dominant within the middle cavernous unit. Crystalline sulphur is found within these voids, along fractures, and as stalactites and plates. Drilled wells indicate that sulphur is unevenly distributed throughout the unit. No two wells were similar in sulphur content (Kennedy, 1926).

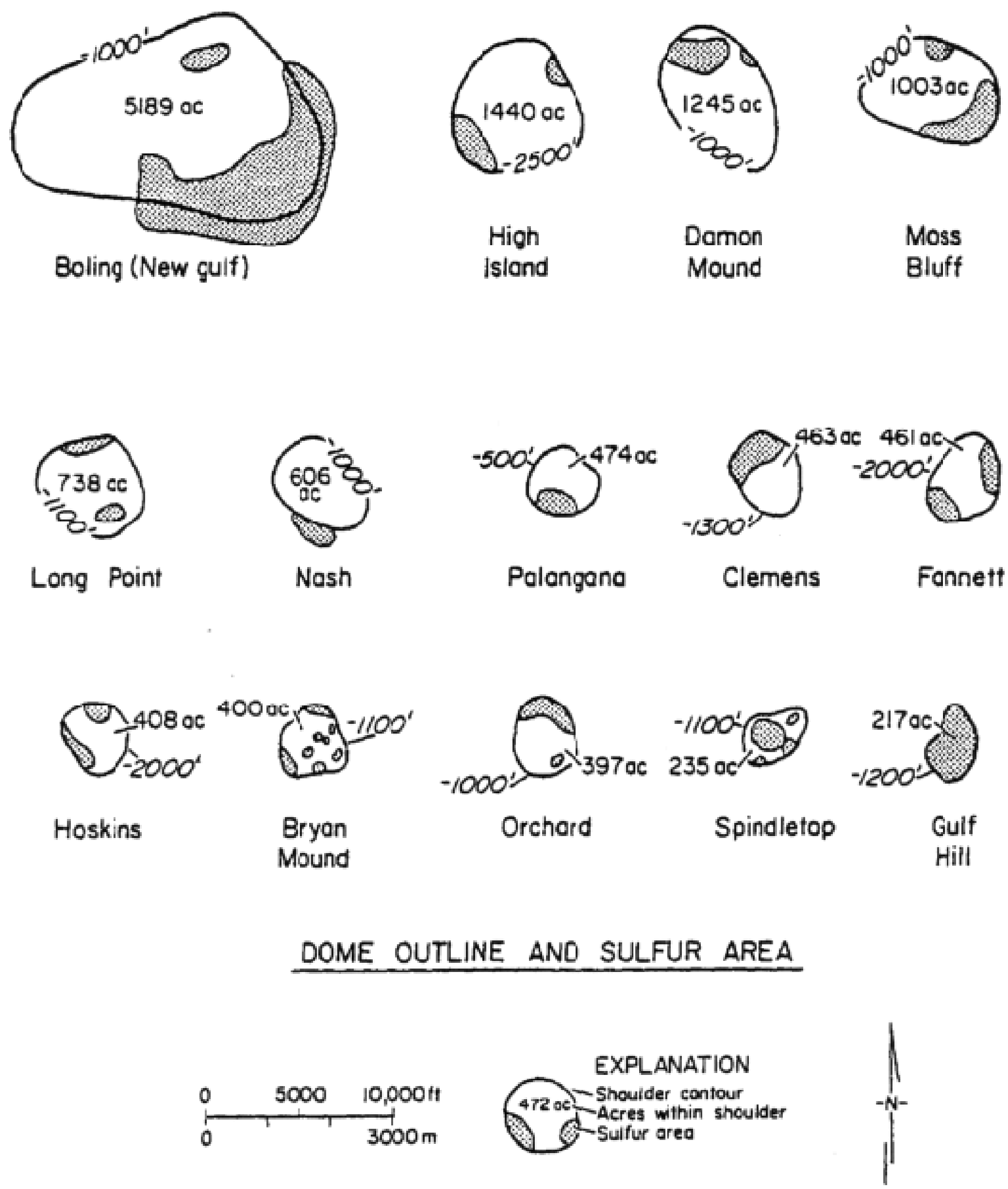

Figure 1. Map of Texas salt domes showing area of sulphur mineralization. (Seni et al, 1985 – with permission from UT-BEG)

4. FRASCH SULPHUR MINING HISTORY

> ***Native sulphur was known to the ancients as brimstone or "the stone that burns" -Warren, 2005***

Sulphur has long been a sought after commodity since the days of early man. Sulphur has been used as a fumigant, in medicine, as a bleaching agent, in incendiary weapons, in gun powder, and as sulphuric acid (Warren, 2005). By the early 1900's with the introduction of the Frasch mining process it became economic to extract sulphur from the caprocks of salt domes along the Gulf Coast. The caprock over the Bryan Mound salt dome was the second dome to be mined for sulphur along the Gulf Coast.

4.1 Conventional Mining Techniques

When sulphur was discovered in the Gulf Coast area in conjunction with the drilling for oil, typical sulphur mining techniques were employed with disastrous results and death. Noxious gases, overlying gumbo and quicksand, petroleum, and flows of underground water charged with hydrogen sulfide prohibited conventional underground mining of the sulphur. Understandably, the sulphur remained untouched until another method could be devised (Hawkins and Jirik, 1966; Seni et al., 1984; Kyle 2002).

4.2 Frasch Mining

In 1891 Herman Frasch patented a revolutionary sulphur mining technology that has been used for decades. This process involves pumping large quantities of hot water into the earth for the liquefaction of the sulphur. A hole is drilled through the limestone caprock to the top of the underlying anhydrite and is cased with concentric pipes (Figure 2). "Frasch sulphur wells along the Gulf Coast are installed with uncemented casings. In these coastal areas, the space between the borehole and casing is occluded soon after casing is placed by clay strata which tightly squeeze against the casing", (Knape, 1984). Superheated water at a temperature of 330° Fahrenheit and at pressures of 125 to 250 pounds per square-inch (psi) is forced down the annular space between an 8-inch and 4-inch pipe and penetrates the sulphur-bearing formation through perforations in the 8-inch pipe. Sulphur melts at 283° F and at 284° F becomes almost as fluid as water (Baker

1935). After about two or three days the melted sulphur runs to the bottom of the well and is then forced several hundred feet up the 4-inch pipe by the pressure of the water pumps and the head of water. When sufficient melted sulphur has accumulated, a part of the water flow is discontinued and air is forced down a 1-1/4-inch pipe at a pressure of about 500 psi. The melted sulphur is forced to the surface by the air pressure and is carried by centrifugal pumps through steam-heated lines to storage bins. (Vail, 1912; Baker, 1935; Bartlett, 1946; Ellison, 1971; Seni et al., 1985)

To obtain one long ton of sulphur 500 to 900 cubic feet of compressed air and 1,500 to 7,000 gallons of hot water are required (Ellison 1971). This is a continuous process - the water and air must flow 24 hours a day for the life of the well. One well is able to remove the sulphur from an area of about one-half acre (Baker 1935). Normally two to four wells are required to deplete sulphur bearing limestone underlying one surface acre (Hawkins and Jirik, 1966). Wells are typically placed 50 to 100 feet apart. Separate wells must be drilled in a location, away from the sulphur wells, to remove the excess cooled water from the sulphur-bearing zone. These “bleed-off” wells reduce the injection pressure required to circulate the superheated water. Bleed-off water can be reused in the system (Ellison, 1971; Knape, 1984). These wells add to the hydrology of the upper segments of the overlying lithology.

The productive life of a sulphur well may range from a few days to several months, depending upon subsurface conditions related to the circulation of hot water, molten sulphur and subsidence. Subsidence can cause shifts in formations overlying the mining area that result in crushed or sheared well pipes and the collapse of well bores, thereby ending the useful life of wells (Hawkins and Jirik, 1966). The early wells were also affected by the corrosive action from the sulphur itself. A change to zinc and aluminum tubing and compressed air added to the system alleviated the tubing failures (Vail, 1912). Other operating problems encountered were tubing separation and a loss of the well due to subsidence.

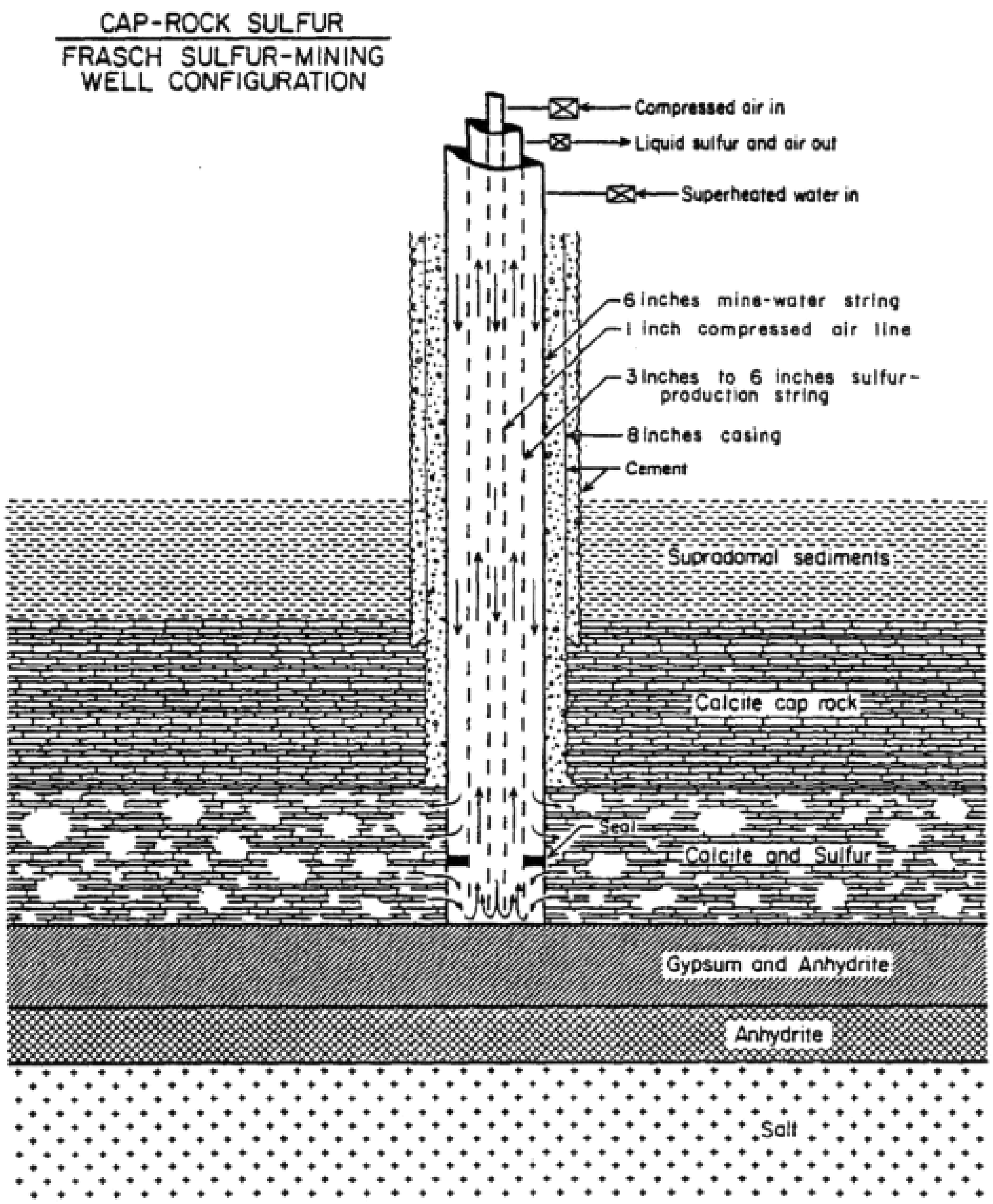

Figure 2. Casing string detail for caprock sulphur production well (after Myers, 1968, as taken from Seni et al 1985 with permission from UT-BEG).

As sulphur is withdrawn, the limestone naturally becomes more porous and cavernous. The rock is unable to support the weight of the overlying formations and begins to break down and subside (Marx 1935). The collapse of the mined rock fills the voids once the sulphur has been melted and removed, this results in sealing off the mined areas and ideally confines the hot water to the mineable portions of the caprock. In some areas, subsidence has not been entirely effective in preventing the escape of hot water, resulting in increased mining cost. As cavities develop, collapse and subsidence of the strata may cause breakage of pipe and damage to surface installations. When a well was lost, the Freeport Sulphur company would pump sawdust with the superheated water and be able to extend the life of the well and extract additional tonnage from that well. Mining practices evolved to injecting mud to fill and plug possible channels of escape. This reduced the need for increased hot water and lessened some of the dangers of collapse and subsidence. “The injection of the mud has resulted in increased tonnage per well and higher thermal efficiency” (Marx 1935). When a well was lost, the operator would dynamite the well and allow the overburden to fill in the hole. At this time in history there were no regulated processes to abandon a well. All wells are eventually lost to subsidence.

5. BRYAN MOUND SULPHUR MINING HISTORY

Bryan Mound was the second dome along the Gulf Coast to be mined for sulphur using the Frasch process. Bryan Mound was initially explored for oil, but the small quantities of oil discovered did not make the site attractive for oil recovery.

However, logs of those 16 drilled oil exploration holes showed the presence of large sections of sulphur (See Table 1 for an example). Eleven sulphur test wells were drilled in 1910. Sulphur in commercial quantity was found in 10 of the test wells between a depth 700 and 900 feet. Freeport Sulphur became the dome operator from 1912 to 1935 and initially reported that “about 760 ft. of gravel, ‘gumbo’ and caprock were encountered; then about 150 ft. of sulphur-bearing limestone, dolomite and gypsum; there were some beds of pure sulphur varying in thickness from a few inches to 7 ft.; the sulphur ceased at from 900 to 1100 ft., being succeeded by pure gypsum and rock salt, to which no commercial importance is at present attached” (Vail, 1912). A 1935 ore reserve map (Figure 3) shows the location of the approximately 300 acres of economical sulphur available for mining.

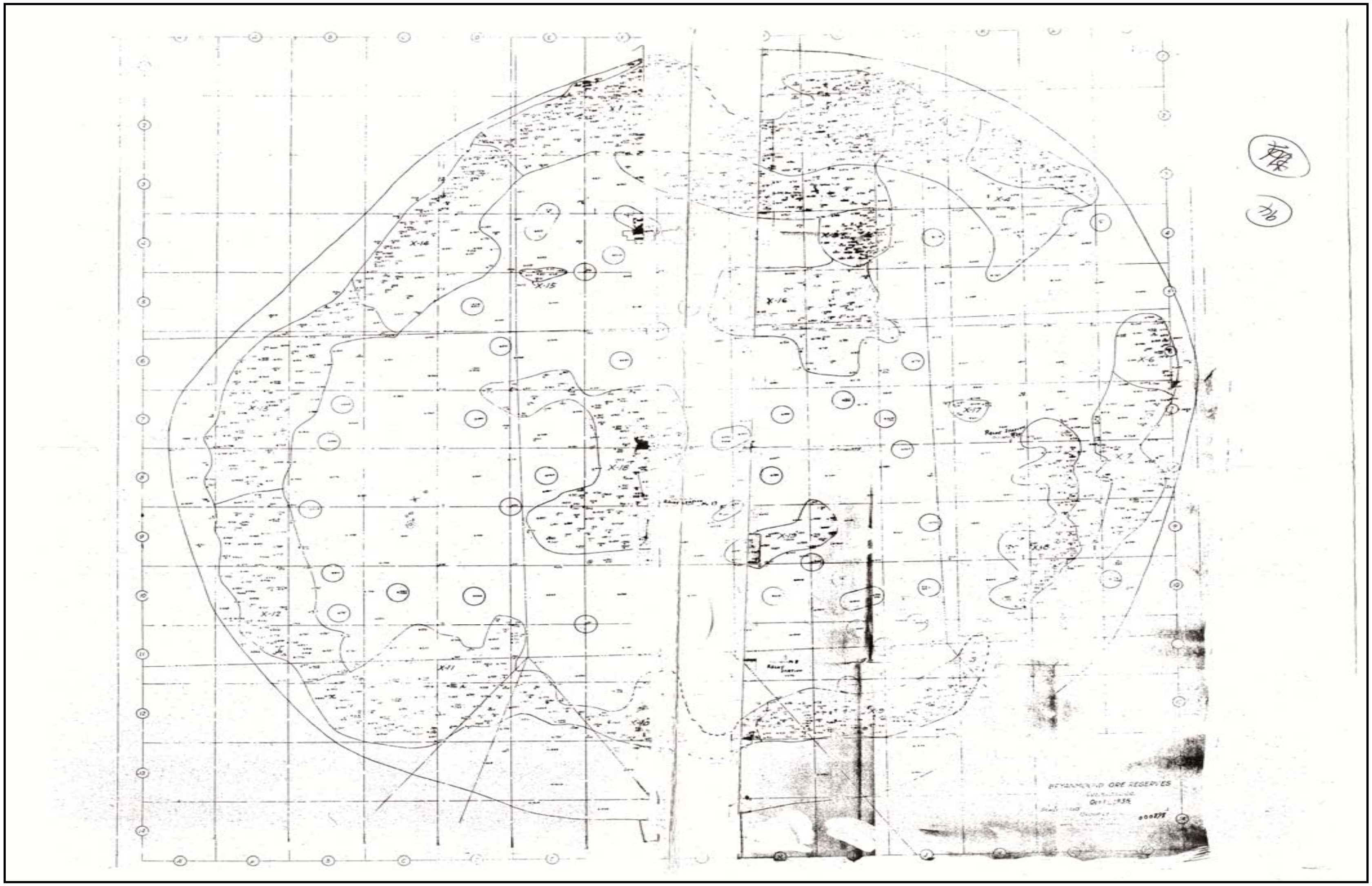

Figure 3 Freeport Sulphur 1935 Ore Reserves map.

During the life of Bryan Mound, 1897 wells were drilled, resulting in a total production of about 5,000,000 long tons, or slightly over 2,600 long tons per well (this statistic is simple math) (Bartlett, 1946). Halbouty (1979) gives a total production of sulphur mining for Bryan Mound of 5,006,248 long tons. With the additional 19 wells drilled by Monsanto and 42 Hooker wells we have a total of 1958 wells drilled or re-worked for a total production of 2556 long tons per well. Hooker extracted sulphur at slightly deeper depths, near 1,000 feet, within previously worked zones. Actual records of individual sulphur well production at Bryan Mound are simply not available. Some reports indicate there were over 2000 sulphur wells that were "steamed".

The porous nature of the sulphur-bearing rock requires an enormous volume of superheated water for melting the sulphur. According to Kennedy (1926), the average daily consumption of water at Bryan Mound in the early production years was 7,000,000 gallons. In actuality, Bryan Mound is said to have used 9,000,000 gallons per day (Bartlett 1946).

Table 1. Driller's log from Gulf Development Company Well no. 4 (from Vail, 1912)

Depth (feet)	**Lithology**
818-884	Limerock, sulphur and gypsum
844-900	Gypsum and sulphur
900-920	Gypsum and small amount of sulphur
920-925	Limerock and sulphur
925-960	Gypsum and small amount of sulphur
960-988	Limerock and sulphur
988-997	Gypsum
997-1034	Limerock and pyrites
1034-1039	Sand rock

1039-1067	Salt rock
1067-1086	Salt rock

* Note - Hole lost all water at about 915 ft. And while working the hole, a small amount of black sulphur water would flow. The rock in this hole was badly broken and considerable core was ground up, amounting in all to 62 ft.

6. SUBSIDENCE

Subsidence from sulphur mining is dependent on the distribution of sulphur deposits both laterally and vertically as well as the zones actually mined. The dip of the sulphur beds mined has the greatest impact to surface subsidence distribution. If production zones are flat lying then subsidence typically is caused by large horizontal movement and displays at the surface as broad subsidence bowls. Roughly circular collapse features occur from mining of thick sulphur beds at steep dips (Mullican, 1988). Sulphur deposits at Bryan Mound are generally flat lying and therefore display larger horizontal than vertical displacement. An additional contributor to subsidence related to sulphur mining was the dynamiting of sulphur wells once they were lost (see section 4.2).

Subsidence at Bryan Mound has been noted in early literature. Kennedy (1926) states the mound rose to an elevation of about 23 feet and covered an area of approximately 400 acres. “Since operations have been in progress, the surface has sunk about 2 feet”. In Sawtelle’s ‘Salt Dome Statistics’ (1936) he records the elevation of Bryan Mound at 20 feet. In 1980, Hogan reported the dome was at an elevation of 19 feet. Current elevation has dropped nearly a foot since 1985. There are no published subsidence records from Freeport Sulphur or Dow Chemical (operator of the first brine caverns mined on the dome). Notable surface features were the occurrence of Blue Lake to the north and northwest where a considerable amount of mining occurred and Mud Lake to the southeast. Both Lakes were not present when mining initiated.

7. DISCUSSION

It is thought that having a better understanding of the sulphur mining process, the extent of extraction, along with sulphur ore location would aid in caprock integrity modeling and cavern well integrity predictions. The sulphur information that was able to be collected and assembled certainly helps towards beginning to understand the extent of the mining damage done to the Bryan Mound caprock.

Sulphur crystalizes within voids and fractures and once the sulphur is removed open space is left behind. With the weight of the overburden the voids collapse and fill with surrounded crumbled rock which may be expressed as subsidence at the surface. It can be presumed that the vast amount of the broken up caprock is within the mapped sulphur ore regions.

Each well had the capacity to remove sulphur from a one-half acre area. It typically took 2 to 4 wells to deplete one acre of sulphur reserves. Over 2000 wells were drilled. However, it is presumed that not every well drilled was a successful producer based on the lack of continuity across the sulphur deposit. In addition, some wells collapsed before production could begin. It can be assumed that the majority of the mining activity occurred within these mapped ore regions. Out of the 2000 plus wells drilled Sandia only has approximately 600 of those wells in their database; therefore making it difficult to compare the actual sulphur well location to the mapped reserves.

Figure 4 displays the Bryan Mound salt dome, overlying caprock colored by depth, the SPR caverns, and the 1935 mapped sulphur ore reserves. The map allows for the comparison of the sulphur ore regions to the locations of the existing SPR caverns.

Caprock regions affected by sulphur mining can impact drilling. It is almost certain that the sulphur extraction impacted the natural fracture system of the caprock and that the crumbled rock within the mined regions caused issues while drilling the cavern wells. Circulation was lost in the upper caprock, the caprock/salt interface, and in some cases, down to 50 to 100 feet within the salt. It should be noted that it is probable that lost circulation zones encountered in the upper salt actually occurred within the caprock. A change in mud once reaching the salt zone could cause a breakdown in the mudcake accumulated within the caprock zone, giving the impression of loss of circulation within the salt (Hogan, 1980).

Well completion records (Louis Records and Assoc., 1979; Williams-Fenix & Scisson, 1979-1980; Jacobs/D'Apolonia Engineers, 1982-1983) for the wells drilled for DOE (drilling information for the original Dow Chemical cavern wells 1-5 was not found) indicate that many of the cavern wells had problems during drilling and the loss circulation zones encountered within the caprock affected 11 of the cavern wells while being drilled. However, in total, 21 wells out of 38 experienced loss of circulation within either the caprock, salt/cap interface, or salt. Figure 5 displays a plot of the cavern well loss circulation zones relative to the ore reserve map. Table 2 lists the cavern wells and notes if loss circulation zones were encountered and if so at what depths. In general, across a variety of salt domes, it is common to see loss circulation zones at caprock/salt interfaces. Also caprocks by nature are fractured and faulted and loss circulation zones can occur without the influence of sulphur mining. The cavern wells that were not plagued with drilling issues are all wells from caverns 101, 105, 112, and 113.

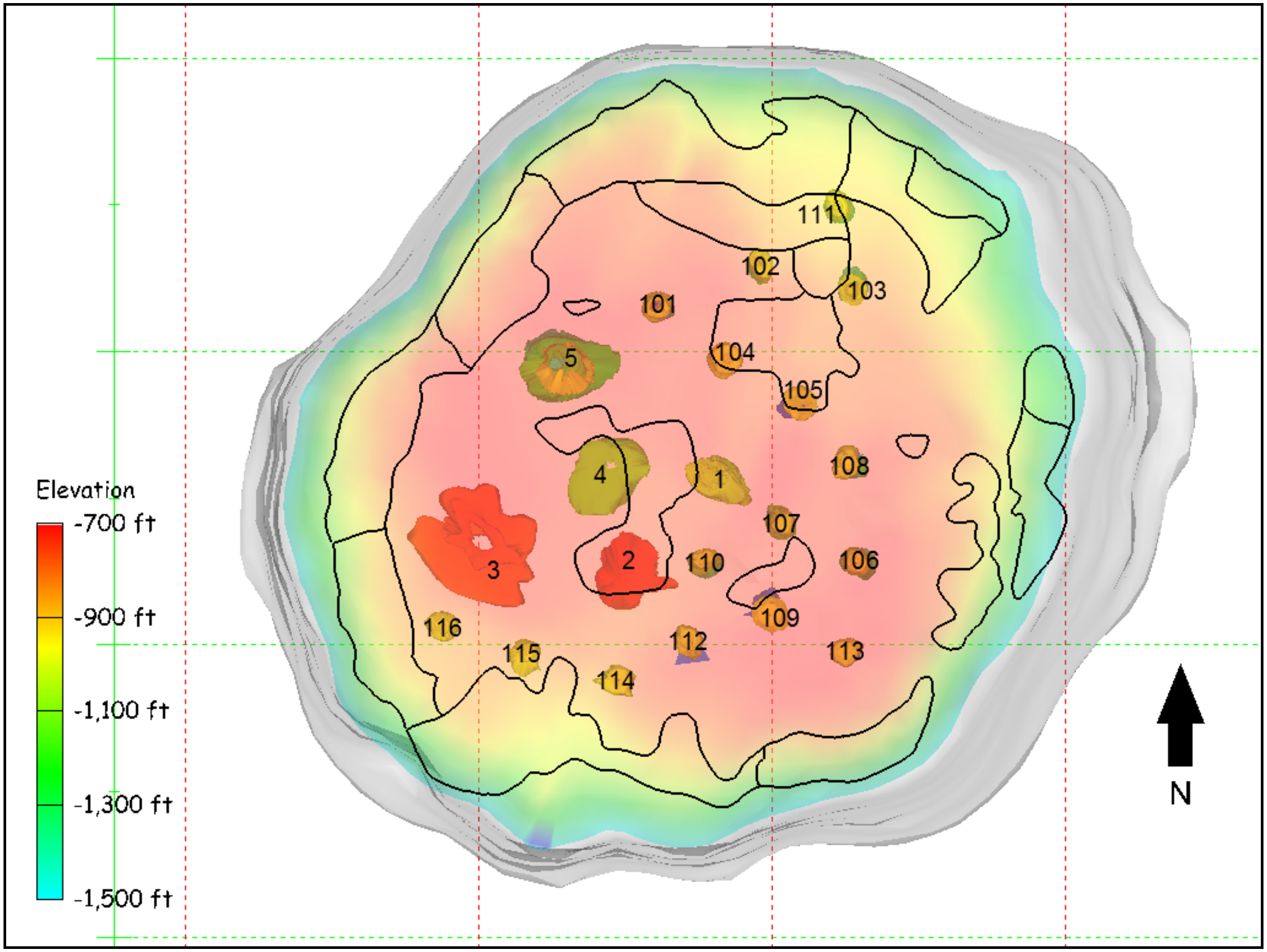

Figure 4. Map of the Bryan Mound salt dome, overlying caprock (elevation in color), SPR caverns, and the 1935 sulphur ore map (black lines).

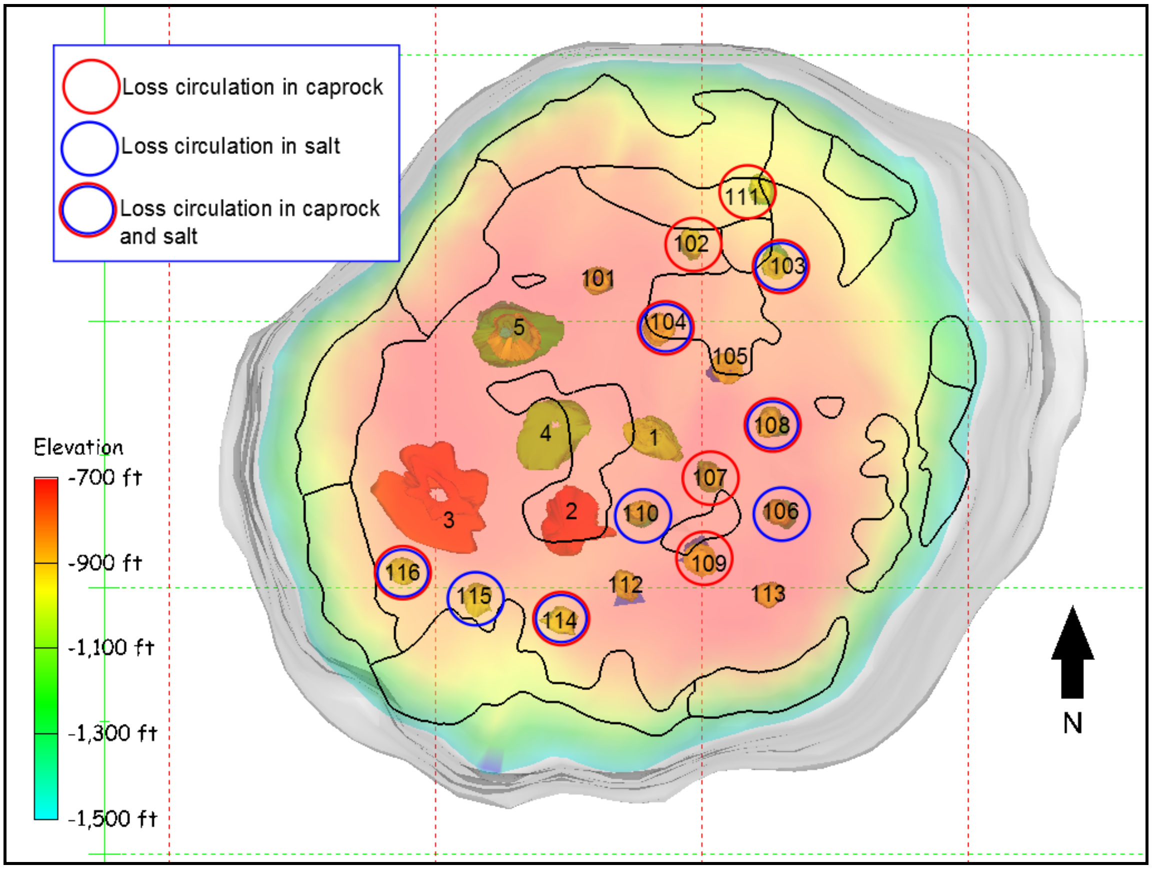

Figure 5. Plot of recorded cavern well loss circulation zones encountered during drilling. (No information for the original Dow Chemical cavern wells 1-5)

Table 2. List of cavern wells, top of salt, top of caprock, lost circulation zones, gas encountered, and pertinent notes. All measurements are depth.

Bryan Mound Caverns	TOP OF CAPROCK	TOP OF SALT	LOST CIRCULATION ZONE(S)	GAS ENCOUNTERED	ADDITIONAL NOTES
BM101A	UNK	UNK	none recorded		
BM101C	UNK	UNK	none recorded	3360	Took 90 hrs to drill thru CR (bit record)
BM102A	UNK	UNK	874', 944' - 1046', 1023' - 1067'		Casing stuck at 809'
BM102C	824'	1080'	none recorded		
BM103B	852'	1080'	691', 735', 887', 981' - 1280'		Bulk Density Log showed S at 1050'-1070'
BM103C	UNK	UNK	1010' - 1036', 1075' - 1081'		DP, Well gained mud from 103B at 939'
BM104A	UNK	UNK	829' - 984', 988' - 1061', 1122'		
BM104B	750'	1074'	976', 1055'		
BM104C	760'	1077'	1062', 1118' - 1154'		
BM105B	784'	1083'	none recorded		Sulphur zone: 784-1020
BM105C	722'	1091'	none recorded		"Junk" in hole at 820'
BM106A	729'	1083'	1040' - 1110'		
BM106B	730'	1084'	none recorded		
BM106C	728'	1082'	none recorded		
BM107A	UNK	UNK	none recorded		
BM107B	760'	1089'	954' - 1089'		Gas in Salt
BM107C	720'	1084'	964', 1091'	1685', 1707', 2052'	Washout at 1086'-1092'
BM108A	752'	1086'	1132', 1153'		
BM108B	UNK	1090'	none recorded	707', 3958'	S zone indicated at 940' - 1070'
BM108C	745'	1086'	824' - 885'		
BM109A	720'	1085'	none recorded		
BM109B	725'	1085'			26" bit stuck at 740'
BM109C	730'	1085'	900'		This is an extremely gassy cavern 7 separate "kicks"

KEY
UNK - Unknown - Drilling program had changed
DP - Drilling program changed, geophysical logging not done

Table 2 (continued). List of cavern wells, top of salt, top of caprock, lost circulation zones, gas encountered, and pertinent notes. All measurements are depth.

Bryan Mound Caverns	TOP OF CAPROCK	TOP OF SALT	LOST CIRCULATION ZONE(S)	GAS ENCOUNTERED	ADDITIONAL NOTES
BM110A	762'	1090'	none recorded		Drilling was changed on A while B was experiencing losses
BM110B	766'	1093'	1080' - 1235'		
BM110C	770'	1100'	1096', 1103'		
BM111A	938'	1093'		In Salt at 4510'	
BM111B	918'	1099'	951'		
BM112A	UNK	UNK			
BM112C	747'	1079'	none recorded		
BM113A	845'	1081'	none recorded		
BM113B	846'	1079'	none recorded		
BM114A	858'	1084'	1022' - 1026', 1026' - 1034'		
BM114B	863	1085'	1023' - 1080'		
BM115A	866'	1092'	965' - 987', 1056' - 1064', 1078' - 1080', 1130' - 1220		
BM115B	863'	1080'	1056' - 1064', 1078' - 1080'		
BM116A	918'	1100'	992' - 1016', 1026' - 1035'		Soft zone between 1055' and 1085'
BM116B	868'	1100'	1054' - 1087', 1122' - 1303'	1303' 1441'	

KEY

UNK - Unknown - Drilling program had changed

DP - Drilling program changed, geophysical logging not done

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The process of sulphur mining used superheated water, which resulted in residual high temperatures measured within the caprock zone (Hogan, 1980). Sattler and others (2004) presented concerns of corrosion to the well casing and cement due to the superheated water. The effect of high temperature in the presence of hydrogen sulfide and sulfate is extremely corrosive waters. The waters themselves do not necessarily affect caprock stability, but do impact casing and cement integrity. Examples of the impact of corrosion are, (1) in 1978 an abandoned brine well that was plugged spewed hot steamy water caused by corrosion of the pipe and cement plug and (2) in 1982 Cavern 4 lost oil from a failed cemented casing and abundant heated caprock fluid was found in the cavern (Schmit/Louis Records, 1978; Hogan, 1980).

Sattler and others (2004) created a map of the temperature distribution within the caprock (Figure 6) to help predict which wells may be at a higher risk to corrosion due to greater exposure to superheated waters. The distribution of maximum temperature across the dome correlates to a fault mapped by Neal in 1994. What the temperature distribution indicates, and was recognized by Sattler and others (2004), is that fluid flow and convection is occurring across the caprock and for that reason, the distribution of temperature does not correlate to the heavy mined regions along the periphery of the dome. Table 3 provides a listing of the most recent temperature measurements for the Bryan Mound cavern wells. The temperature distribution is similar to what Sattler plotted with the coolest temperatures measured at caverns 114, 115, 116, and 111, whereas the hottest temperature is measured at cavern 106.

Table 3. Most recent temperature measurements as of June, 2015.

Cavern	Date	Temperature (degF)	Depth (feet)
BM005	1/13/2015	151	820’
BM101	7/18/2013	151	840'
BM102	4/9/2013	148	880'
BM103	12/7/2007	153	910'
BM104	6/15/2015	143	850'
BM105	5/23/2012	148	840'
BM106	2/28/2012	161	730'
BM107	8/22/2011	153	780'
BM108	3/1/2011	157	760'
BM109	2/28/2011	160	730'
BM110	4/30/2013	157	780'
BM111	9/6/2011	140	990'
BM112	6/15/2015	153	780'
BM113	3/12/2012	154	730'
BM114	10/30/2012	131	900'
BM115	7/26/2012	131	1000'
BM116	9/15/2011	131	930'

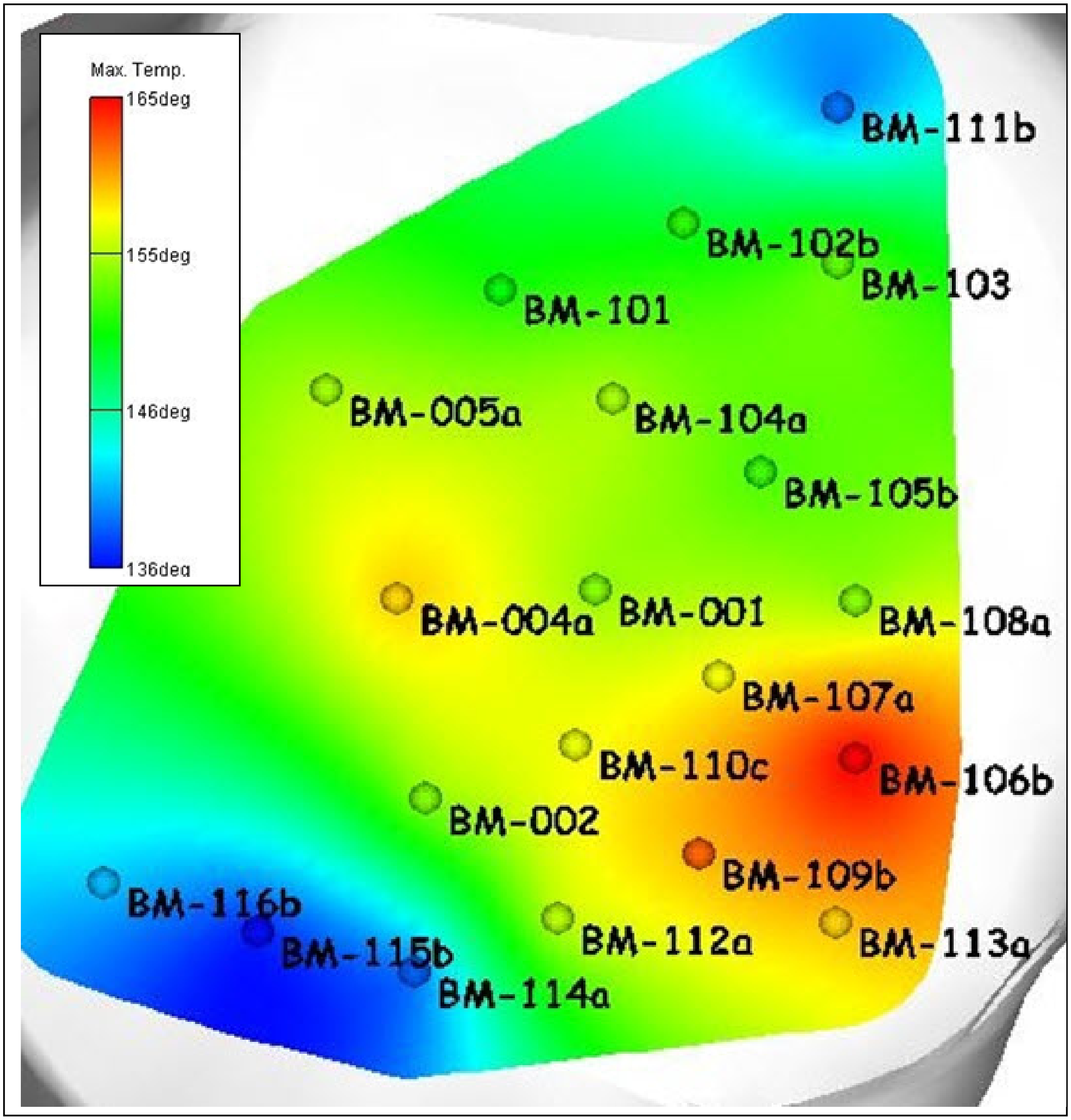

Figure 6. Caprock temperatures logged within the Bryan Mound caprock. Temperature in F. (from Sattler, 2004)

8. SUMMARY

In summary, a definitive conclusion on the caprock integrity cannot be formed from the paucity of data available. What can be inferred from the information Sandia was able to collect is the location of the mapped sulphur ore reserve and that the mapped sulphur ore regions most likely represent the most heavily mined regions of the caprock. Within those regions the caprock is likely to be more crumbled, fractured, and cavernous than other regions of the caprock, which were exposed to less mining activity. However, caprock by nature is fractured and vuggy and drilling issues are common from one dome to the next. The lost circulation zones noted at Bryan Mound, specifically within the caprock, in general do correlate to the mapped ore zones. Three out of the four caverns that had no issues with drilling are within regions outside the mapped ore zones. Water temperature within the caprock is still elevated and the temperature distribution does not correlate to the mined regions, but were not expected to, because of fluid flow through fractures. However, the hottest waters do correlate to a fault mapped by Neal (1994). Knowing the temperature distribution helps predict which wells are more prone to failure by corrosion, with the Cavern 106 wells located in the most corrosive region.

The cavern wells at Bryan Mound have had a high number of integrity concerns, compared to the other SPR sites. The insight gained from understanding the sulphur mining process and the resultant artifacts from the mining, especially at Bryan Mound, does help towards creating a better caprock model and prediction of cavern well integrity.

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