Core Study of Rustler Formation Over the WIPP Site

DO NOT MICROFILM
COVER

Charles C. Ferrall, John F. Gibbons
Civil Systems, Inc.

Sandia National Laboratories

DO NOT MICROFILM
THIS PAGE

Issued by Sandia National Laboratories, operated for the United States Department of Energy by Sandia Corporation.

NOTICE: This report was prepared as an account of work sponsored by an agency of the United States Government. Neither the United States Government nor any agency thereof, nor any of their employees, nor any of their contractors, subcontractors, or their employees, makes any warranty, express or implied, or assumes any legal liability or responsibility for the accuracy, completeness, or usefulness of any information, apparatus, product, or process disclosed, or represents that its use would not infringe privately owned rights. Reference herein to any specific commercial product, process, or service by trade name, trademark, manufacturer, or otherwise, does not necessarily constitute or imply its endorsement, recommendation, or favoring by the United States Government, any agency thereof or any of their contractors or subcontractors. The views and opinions expressed herein do not necessarily state or reflect those of the United States Government, any agency thereof or any of their contractors or subcontractors.

Printed in the United States of America

Available from
National Technical Information Service
U. S. Department of Commerce
5285 Port Royal Road
Springfield, VA 22161

NTIS price codes

Printed copy: \$8.00
Microfiche copy: A01

DISCLAIMER

This report was prepared as an account of work sponsored by an agency of the United States Government. Neither the United States Government nor any agency Thereof, nor any of their employees, makes any warranty, express or implied, or assumes any legal liability or responsibility for the accuracy, completeness, or usefulness of any information, apparatus, product, or process disclosed, or represents that its use would not infringe privately owned rights. Reference herein to any specific commercial product, process, or service by trade name, trademark, manufacturer, or otherwise does not necessarily constitute or imply its endorsement, recommendation, or favoring by the United States Government or any agency thereof. The views and opinions of authors expressed herein do not necessarily state or reflect those of the United States Government or any agency thereof.

DISCLAIMER

Portions of this document may be illegible in electronic image products. Images are produced from the best available original document.

SAND--79-7110

DE87 012754

CORE STUDY
OF RUSTLER FORMATION
OVER THE WIPP SITE

DISCLAIMER

This report was prepared as an account of work sponsored by an agency of the United States Government. Neither the United States Government nor any agency thereof, nor any of their employees, makes any warranty, express or implied, or assumes any legal liability or responsibility for the accuracy, completeness, or usefulness of any information, apparatus, product, or process disclosed, or represents that its use would not infringe privately owned rights. Reference herein to any specific commercial product, process, or service by trade name, trademark, manufacturer, or otherwise does not necessarily constitute or imply its endorsement, recommendation, or favoring by the United States Government or any agency thereof. The views and opinions of authors expressed herein do not necessarily state or reflect those of the United States Government or any agency thereof.

CSI 2055-03

Charles C. Ferrall
John F. Gibbons

November 6, 1979

Prepared for
Sandia Laboratories
P.O. Box 5800
Albuquerque, New Mexico 87185

Sandia Contract No. 13-4464

Prepared by
Civil Systems, Inc.
2201 San Pedro N.E.
Bldg. 3, Suite 214
Albuquerque, N.M. 87110
(505) 884-4471

MASTER

DISTRIBUTION OF THIS REPORT

TABLE OF CONTENTS

	<u>Page No.</u>
1 <u>INTRODUCTION</u>	1
1.1 REPORT ORGANIZATION	4
2 <u>CHARACTERIZATION OF RUSTLER ROCKS</u>	5
2.1 SUBSURFACE CONDITIONS AT WIPP 19	10
2.1.1 Lower Member	10
2.1.2 Culebra Dolomite Member	13
2.1.3 Tamarisk Member	13
2.1.4 Magenta Dolomite Member	15
2.1.5 49'r Member	16
2.2 AREAL VARIATION IN RUSTLER FORMATION	17
2.2.1 Lower Member	18
2.2.1.1 Dark gray siltstone and Salado "leached zone"	18
2.2.1.2 First solution residue/ halite/second solution residue	21
2.2.1.3 Anhydrite	23
2.2.1.4 Third solution residue	23
2.2.2 Culebra Dolomite Member	24
2.2.3 Tamarisk Member	26
2.2.3.1 Lower anhydrite	26
2.2.3.2 Solution residue	28
2.2.3.3 Upper anhydrite	28
2.2.4 Magenta Dolomite Member	29

TABLE OF CONTENTS (concluded)

	<u>Page No.</u>
2.2.5 49'r Member	33
2.2.5.1 Lower anhydrite	33
2.2.5.2 Solution residue	34
2.2.5.3 Upper anhydrite	34
2.3 IMPORTANT CONSIDERATIONS	37
2.3.1 Anhydrite-to-Gypsum Mineralogic Change	37
2.3.2 Interpretation	41
2.3.3 Impacts	47
2.3.4 Solution Residue Zones	48
2.3.5 Dolomites	49
3 <u>PARAMETERS FOR MODELLING</u>	49
3.1 GENERAL	49
3.1.1 Stratigraphy	50
3.1.2 Fracture	52
3.1.3 Cementation	54
3.1.4 Permeability	55
3.2 PHYSICAL PROPERTIES	55
3.2.1 Summary Discussion	58
3.3 CONCLUSIONS	58

LIST OF FIGURES, TABLES AND PLATES

	<u>Page No.</u>
Figure 1 Lithologic Log, WIPP 19	6
Figure 2 Location of WIPP Boreholes used, and Strike and Dip for Culebra Dolomite in the Rustler Formation (from Powers et al 1978)	7
Figure 3 Cored Intervals in Rustler Formation	8
Figure 4 Gypsum-Anhydrite Cycle	38
Figure 5 Outcrop of Tamarisk Anhydrite with Fractures which have been Gypsified	45
Table 1 Units, Thickness, and Elevations of Rustler Formation Members	9
Table 2 Rustler Stratigraphy of ERDA 9	51
Table 3 Physical Properties of the Rustler Units	56
Table 4 Summary of Recommended Model Para- meters	57
Plate 1 Lower Member Dark Gray Siltstone	61
Plate 2 Lower Member Anhydrite and 2nd Solution Residue	62
Plate 3 Culebra Dolomite	63
Plate 4A- I Tamarisk Member Lower Anhydrite	64-72
Plate 5 Tamarisk Member Solution Residue	73
Plate 6 Tamarisk Member Solution Residue	74
Plate 7 Magenta Dolomite	75
Plate 8 49'r Member Lower Anhydrite	76

1. INTRODUCTION

This core study deals with the nature of the Rustler Formation at the Waste Isolation Pilot Project (WIPP) site in support of evaluating the influence that the Rustler will have on the effective isolation of wastes potentially disposed in the underlying formation.

The Rustler Formation is the uppermost evaporite formation of the Ochoan age rocks of the Permian Basin in southeastern New Mexico and western Texas. In the region of the WIPP site, the Rustler rocks make up a laterally continuous formation that occurs between the Salado Formation and the existing topographic surface. It is the Salado Formation into which the proposed waste repository is to be placed.

The core study described in this report was conducted in order to provide parameters for the thermomechanical modeling of the behavior of the Rustler Formation in response to heating. The aim of the core study has been to characterize the various members and units of the Rustler Formation in terms of physical properties, distribution, internal discontinuities, and boundary effects. The principal features treated here are results of the original deposition, diagenetic changes which the rocks have undergone, and the strain history of the rocks since deposition. Special attention has been paid to the extent to which the formation is fractured and the nature of fractures so that some estimate

can be made of the potential for these discontinuities to be the locus of further strain.

The emphasis of this core study has been on megascopic observation of the rocks. For this purpose the photos of existing core which were taken by Sandia Laboratories were used extensively. In addition to brief field visits to the site, the rock cores were examined at the project facility in Carlsbad to provide further information regarding the nature of the rock and clarification of observations made from the photographs.

Comparison of core observations with geophysical data taken from available downhole logs (refer to SAND 79-0276: Basic Data Report for Drillhole WIPP 19) was also of value. Digitized data (Hern, pers. comm., 1979) derived from the BHC sonic log, the compensated neutron formation density log, the dual laterolog (micro-SFL) and the four-arm high-resolution continuous dipmeter log were processed using a computer code (Miller, 1979) developed to calculate physical and mechanical properties of the units surveyed and to approximate their mineral compositions. Several comparisons of core observations with these approximate compositions are reported here as checks on the data, and computed physical properties are also tabulated for reference.

There are some holes within the Rustler Formation for which there are geophysical logs but no core. However, these logs were not extensively used since the main thrust of our research was in holes where core photographs were available for correlation.

The results of this study indicate that the five members of the Rustler Formation are characterized by one to six subunits per member. The number of subunits in a given member is more or less laterally continuous within the holes examined. The rock types which are present include anhydrite, gypsum (the result of alteration of the anhydrite rock), halite, solution residue (characterized by siltstone/claystone, exhibiting a wide range of cementation), dolomite and siltstone.

The general scenario for formation of these rocks involves their deposition during the final stages of Permian Basin evaporite formation. These deposits were characterized by silty evaporites (calcium sulfate and sodium chloride) interlayered with deposits of siltstone and layers of lime mud (now dolomite). The calcium sulfate, probably primary gypsum, was dehydrated to anhydrite shortly after burial. Similarly the layers of lime mud were dolomitized by dense fluids activated by reflux through the sulfates. The halite (and to some extent the anhydrite) was subject to solution activity, leaving behind solution residues of clay and silt which are variously cemented. Finally, as erosion became dominant and depth of burial diminished, the anhydrite rocks are locally rehydrated to gypsum.

The distribution and orientation of fractures observed in these rocks are extremely variable. Breakage parallel to the bedding planes is the most common mode of fracture. Fractures tend to be more frequent in dolomite units which are the most

brittle members within the formation. There is little evidence within the cores of the fracture pattern observed in outcrop in and adjacent to Nash Draw. The vertical orientation of the holes and the vertical or steeply dipping orientations of some fractures make their identification as members of a larger regional fracture pattern difficult.

Observed high-angle fractures are variable in spacing and quality. It is probable that minimum fracture pattern spacing is on the order of one high-angle fracture per 10 feet (horizontal) in the thicker anhydrite beds. Irregular, vertical fractures indicative of extension are present in various members.

Fracture, in some cases brecciation, occurs in the units adjacent to solution residue units. This is due to localized deformation associated with the collapse of overlying beds into the voids created by solution. These residue zones represent former paths of migrating groundwater. Calcium sulfate in residue zones is sometimes hydrated which results in deformation due to the volume increase from anhydrite to gypsum.

1.1 REPORT ORGANIZATION

This report is presented in three sections. The first section discusses the characterization of the Rustler rocks, first by describing the core from borehole WIPP 19, and then by discussing the areal variations observed in Rustler Formation cores from various sites at greater distances from the repository location. The second section discusses various considerations which are particularly important to the evaluation of the thermomechanical response

of the Rustler Formation rocks; it identifies the areas of particular concern and some of the mechanisms involved. The third section of the report discusses the various parameters which are needed for numerical modelling.

2. CHARACTERIZATION OF RUSTLER ROCKS

For the purposes of this report, WIPP 19 is used as the basis of comparison. WIPP 19 is the closest borehole to the repository for which there is complete core of the Rustler rocks. The use of core photographs and actual observation of the core, augmented by information from geophysical logs, was chosen as an effective way of evaluating the character of the rocks. Photographs of the cores discussed are presented at the back of this report - arranged according to member (Plates 1 through 8).

A lithologic log has been prepared for WIPP 19 (Figure 1) and the analyses of geophysical logs have been used to provide a suite of parameters characterizing the rocks. Figure 2 shows the location of WIPP 19, north of the center of the repository (ERDA 9) by about 0.6 miles. Other holes discussed in this report are indicated in Figure 2. Detailed stratigraphic logs were prepared for available intervals of Rustler core from these holes. Cored intervals for various holes are indicated on Figure 3.

LITHOLOGIC LOG

WIPP 19

SURFACE EL. 3432 FT

GYPSUM

SANDY SILTSTONE

ANHYDRITE

HALITE

SILTSTONE

DOLOMITE

FIGURE 1. Lithologic Log of WIPP 19

FIGURE 3. Cored Intervals in Rustler Fm. (heavy lines)

Rustler Formation	Thickness Range (ft)	Elevation Range (Top) (Ft)
"49 -V Member"	48 ¹³ - 85 ²⁸	2842 ¹⁹ - 3141 ²⁶
Upper Anhydrite	22 ²⁶ - 42 ²⁸	2842 ¹⁹ - 3141 ²⁶
Solution Residue	6 ¹³ - 16 ^{25, 26}	2813 ¹⁹ - 3119 ²⁶
Lower Anhydrite	17 ⁹ - 24 ²⁵	2802 ¹⁹ - 3103 ²⁶
Magenta Dolomite	18 ¹³ - 32 ²⁶	2784 ¹⁹ - 3085 ²⁶
Tamarisk Member	83 ¹⁹ - 119 ¹³	2759 ¹⁹ - 3053 ²⁶
Upper Anhydrite	64 ⁹ - 91 ¹³	2759 ¹⁹ - 3053 ²⁶
Solution Residue	6 ^{12, 25} - 18 ²⁸	2684 ¹² - 2986 ²⁶
Lower Anhydrite	0 ¹⁹ - 22 ²⁵	2678 ¹² - 2977 ²⁶
Culebra Dolomite	22 ¹³ - 31 ¹²	2665 ¹² - 2968 ²⁶
Lower Member	80 ²⁸ - 126 ²⁵	2634 ¹² - 2945 ²⁶
3rd Solution Residue	7 ¹² - 10 ^{25, 26, 28}	2634 ¹² - 2945 ²⁶
Anhydrite	7 ³⁰ - 12 ¹³	2627 ¹² - 2935 ²⁶
2nd Solution Residue	59 ²⁸ - 108 ²⁵	2617 ¹² - 2925 ²⁶
Halite (with Anhydrite Locally) Only in 19,12,13,9		
1st Solution Residue		
Dark Gray Siltstone		
Bottom Rustler (Top Salado)		2519 ¹² - 2845 ²⁶
Rustler Total	279 ^{ERDA 6} 295 ²⁶ - 366 ²⁵	
Superscripts Indicate Borings of Occurrence		

Table 1. Units, Thickness and Elevations of Rustler Formation Members

After evaluation of the available core in the area of the repository, a series of laterally consistent units within each member of the Rustler has been identified as shown on Table 1. Range of thickness and elevation of occurrence of these units are also shown. By comparison of Figure 1 and Table 1, it can be seen that all of these units are represented in WIPP 19 with the exception of the lower anhydrite unit of the Tamarisk member.

2.1 SUBSURFACE CONDITIONS AT WIPP 19

The following discussion of the Rustler rocks in WIPP 19 serves as a basis from which to compare the conditions in the surrounding holes. (The reader may refer to Sections 2.3 and 3.1 for discussion of the general significance of the conditions described.)

2.1.1 Lower Member

The contact between the Rustler and Salado Formations occurs at about 894 ft. in WIPP 19. At the contact there is a solution residue which overlies the Salado salt and which represents the leached top of the Salado. This unit is overlain in turn by a dark gray siltstone which appears to have been deposited in relatively shallow water with some evidence of sedimentary structures and bioturbation. This siltstone is well cemented and includes numerous irregular, near-vertical

fractures that are normally filled with halite (Plate 1). These fractures indicate some extension in the lower siltstones, probably the result of undermining by solution of the underlying salt. There were few planar high-angle fractures observed in this member.

At a depth of 851 ft. the dark gray siltstone grades into a reddish brown siltstone with a significant fraction of fine-grained sand. The siltstone includes some zones of grayish coloration on the order of 3 to 6 inches thick. These are interpreted to represent local reducing conditions. In the lower part of this reddish brown siltstone, horizontal layering suggests sedimentary deposition either within voids produced by solution or as a primary sedimentary deposit. At around 833 ft. a solution residue occurs. This residue is characterized by a lack of bedding and an unstructured appearance, and frequently includes breccia clasts of the other units within it. In this case, some percentage of halite crystals and halite cement are preserved within the residue. This unit is well cemented and includes some high-angle fractures. High-angle fractures occur about 1 per vertical ft. and there are horizontal (bedding plane) fractures approximately 1 to 2 per vertical ft.

At 816 ft. the residue grades into a layer of halite with small zones of anhydrite within the halite. The halite here includes some reddish brown silt, which imparts a

reddish coloration. This halite is not significantly fractured.

At 809 ft. the halite grades into a reddish brown siltstone cemented with halite, with some visible halite crystals. This material is interpreted to be a solution residue from which the salt has not been completely removed (Plate 2). It is well cemented and does not show high-angle fracturing. Horizontal fractures occur at 1 to 3 per vertical ft.

An anhydrite unit occurs at 798 ft. The lower foot is actually a gray silt/claystone which may be a residue from dissolution of anhydrite or rock salt. Above this, the lower few feet of the anhydrite are partially gypsified. An extensively leached zone occurs from 795 ft. to 793 ft. which shows numerous bedding plane breaks as a result of the solution activity of ground water traveling along the bedding planes (Plate 2). Above 793 ft. the anhydrite is relatively unfractured; however, the upper 2 ft. of the unit are extensively gypsified.

A solution residue of red-brown siltstone occurs from 788 ft. to 781 ft. This material is cemented and includes some gypsum fragments and stringers as well as some gray zones which may represent residue from anhydrite solution. There is no significant high-angle fracture; horizontal fractures occur on the order of 1 to 3 per vertical ft.

From 781 ft. to 779 ft. there is a black shale layer which appears to represent an organic-rich sediment that preceeded the deposition of the overlying dolomite. This shale is well cemented and bedding plane fractures occur at a frequency similar to the underlying siltstone.

2.1.2 Culebra Dolomite Member

The Culebra dolomite extends from 779 ft. to 756 ft. This unit is a fine grained dolomite with numerous small vugs ranging from one to ten millimeters in diameter. These vugs are generally filled with gypsum. In the interval from 779 to 764 ft. this unit appears to be leached so that some of the carbonate has been removed and the remaining rock appears relatively clayey and only partially cemented. Bedding plane fractures are frequent, on the order of 3 to 8 per vertical ft. below 764 ft. and 1 to 3 per vertical ft. above 764 ft. Numerous irregular, near-vertical fractures occur - possibly associated with shrinkage during the transformation from limestone to dolomite (Plate 3). These fractures are generally filled with gypsum. In addition, high-angle planar fractures are present with spacing on the order of 1 per 5 vertical ft. This dolomite appears to be an aquifer with fracture permeability providing the dominant flow mechanism.

2.1.3 Tamarisk Member

Overlying the dolomite is another solution residue unit from 756 to 741 ft. This unit includes roughly one foot of layered sedimentary material at the bottom. Above 755 ft.

the bedding disappears and the solution residue contains some breccia clasts. These clasts are gray in color with maximum dimension on the order of 1 inch. They may represent different coloration of residue resulting from anhydrite solutioning. This residue unit is cemented and includes numerous gypsum stringers and zones of gray coloration. Bedding plane fracture occurs with spacing of 1 to 4 per vertical ft. No high-angle fracture was observed.

The Tamarisk anhydrite member occurs in the interval from 741 ft. to 673 ft. This is a dominantly anhydrite unit which is locally gypsified. The lower portion is laminated anhydrite in which the laminae dip 10° to 15° . In the interval from 737 ft. to 723 ft. this rock has a whiter color suggesting gypsification; however, analysis (Miller, 1979) of the geophysical logs does not support this conclusion. At the bottom of the unit the rocks are a gray clayey residue with a mottled texture. From 723 ft. to about 714 ft. the anhydrite is interlayered with gray sediment, possibly a dolomitized lime mud. Above 715 ft. the anhydrite is laminated. At 709 ft. it grades into a zone of anhydrite which is pseudomorphic after gypsum rosettes. At 701 ft. the anhydrite is laminated and "chicken-wire" structure (nodular anhydrite) is progressively more dominant with decreasing depth. This nodular form of anhydrite continues to the contact with the Magenta dolomite in the vicinity of 673 ft. Throughout

this interval the anhydrite shows horizontal breaks on the order of 1 to 2 per vertical ft. and only 2 high angle fractures in the entire member. The upper surface of this bed is gypsified from 673 ft. to 675 ft. Of interest is a 1 inch layer of bituminous material at 710-1/2 ft. which shows some slickensides implying relative movement parallel to the bedding.

2.1.4 Magenta Dolomite Member

The Magenta dolomite overlies the Tamarisk and extends from 673 ft. up to 648 ft. This unit consists of a dolomitized lime mud which, in the lower part from 673 ft. to 668 ft., shows algal laminae with spacing on the order of one per inch. These laminae are lined with gypsum crystals. Above 668 ft. the algal laminae grade out and the rock displays small ripple marks with amplitude about 1/4 to 1/2 inch. This unit is extremely fine grained and well cemented with some gypsum-filled voids. The lower part of the unit, up to 661 ft., is massive with horizontal breaks at about 1 per vertical ft. Above 661 ft. the rock is somewhat more fractured with horizontal breaks spaced at 1 to 4 per vertical ft. From 656 ft. to 648 ft. there are open high-angle fractures intersecting the core with 6 ft. vertical spacing. The area from 660 ft. to 665 ft. shows some signs of leaching of the carbonate, imparting a more clayey texture to the rocks. Most of the voids in this rock are presently filled with gypsum. These voids may be related to shrinkage during dolomitization. The upper contact of this

unit at about 648 ft. is gradational into the overlying anhydrite of the 49'r Member (Plate 7).

2.1.5 "49'r Member"

The lower anhydrite unit of the "49'r member" extends from 648 ft. to 630 ft. (Plate 8). In the lower part of this unit the anhydrite is interbedded with some 2 inch thick dolomite layers with gypsum infilling the voids. There is frequent gypsification so that the bulk of the lower rock is largely gypsum. Above 642 ft. the dolomite grades out and the rock becomes characterized by nodular anhydrite with occasional layers of pseudomorphic rosettes. Enterolithic structure occurs in some places and there appears to be local gypsification of rock in layers 1/2 to 1 inch thick. The upper 2 to 3 feet of this unit, at the contact with the overlying solution residue, is gypsified. This rock is massive, with horizontal fractures at 1 to 2 per vertical ft. and high-angle fractures on the order of 1 per 12 vertical ft. Between 630 ft. and 631 ft. there is a dark gray shale which grades upward into the red brown siltstone of the overlying solution residue.

Solution residue extends from 630 ft. to 619 ft. and is characterized by siltstone with some particles of gypsum and gypsum stringers. This residue is massive with horizontal breaks spaced at about 1 per vertical ft. There was no high-angle fracture observed.

From 619 ft. to the top of the Rustler Formation at 590 ft. lies the upper anhydrite unit of the "49'r Member." From 619 ft. to 615 ft. this unit is partially gypsified. Above 615 ft. it is laminated anhydrite, locally nodular, and contains numerous leached zones. Leaching occurs from 612 ft. to 608 ft., from 606.5 ft. to 605 ft., in a small zone at 601 ft., and between 596 ft. and 595 ft. Leaching creates voids parallel to the bedding and appears to be the result of groundwater traveling along the laminae. It is noteworthy that computer analysis (Miller, 1979) of logs and visual observation of these zones do not indicate a high degree of gypsification in the leached zones. (That is, the rock matrix of the solution cavities is still anhydrite.) This may be an instance of water dissolving anhydrite but removing it from the site before the calcium sulfate can be redeposited as gypsum. Outside the leached zones, the anhydrite is relatively massive with horizontal breaks spaced at 1 to 4 per vertical ft. Occasional high-angle fractures do not appear to be planar and are probably the result of gypsification. The contact with the overlying Dewey Lake Formation is abrupt with a thin layer of gray "residue" lining the contact; this may be an erosional unconformity.

2.2 AREAL VARIATION IN RUSTLER FORMATION

With the WIPP 19 as a stratigraphic basis, the following section presents a unit-by-unit discussion of the lateral variations of the members of the Rustler Formation. Special attention

is given to fracturing, variations in thickness, gypsification in anhydrite units and cementation variations in solution residue units.

2.2.1 Lower Member

This section is aimed at an overall characterization of the Rustler Formation in the site vicinity and, as such, is most pertinent to evaluation of the physical behavior of these rocks.

2.2.1.1 Dark gray siltstone and Salado "leached zone" - This siltstone appears to be a sedimentary unit. It overlies the "leached zone" of the Salado Formation which is an extremely variable zone on top of the Salado wherein the evaporites have been dissolved away leaving only solution residue. The actual contact between the Rustler and Salado is difficult to identify visually due to the variability of the solution residue. Determinations using the geophysical logs have been found to be more reliable. In WIPP 19 there is halite with red-brown silt at the contact and the dark gray siltstone starts within a foot or two of the contact defined on the logs. This relationship holds for the borings in the vicinity of WIPP 19 including WIPP 30. The effect of the increasing extent of dissolution nearer Nash Draw is evident in WIPP 25, 26, and 28 (Figure 2). In WIPP 25 there is 34 ft. of solution residue above the contact before the dark gray siltstone appears; there is halite at the contact. In WIPP 26, the first halite is 15 ft. below the contact and 18 ft. below

the siltstone. The difference in these two holes may be a question of stratigraphic definition, but the fact that there is significant solution residue between the uppermost Salado halite and the dark gray siltstone supports the presence of "leaching" of halite having taken place. In WIPP 28 the case is more extreme. The dark gray siltstone starts at the contact, but there is no obvious halite in the Salado "leached" zone down to the first Salado anhydrite unit. Furthermore, in all of these holes, where more leaching is demonstrated, the solution residue includes blocks and breccia clasts of anhydrite - implying that some collapse accompanied leaching.

Above the Salado contact similar patterns of leaching and solution residue development occur. WIPP 19 and WIPP 12 are characterized by irregular vertical fracture, filled with halite (Plate 1). In WIPP 12 the frequency of such fractures increases near the Salado contact. WIPP 13 appears to be a transitional case where the irregular vertical fractures are locally halite filled, but in some cases unfilled. This hole also demonstrates high-angle (70° to 80°) planar fractures. Some small vertical movement (1/8 inch) is evident along these fractures. In the holes closer to Nash Draw (WIPP 30, 25, 26, and 28) there is no halite filling of fractures. In most of these holes, both high-angle planar and irregular vertical fractures occur with increasing fracture frequency near the Salado contact. The exception to this is WIPP 28 where no significant fracture is observed.

The absence of halite coincides with a loss of cement in the siltstone. In WIPP 25, 26, and 28 the dark gray siltstone is approaching the strength of a very-stiff to hard soil as contrasted to the compact siltstone seen elsewhere. When computer analysis of geophysical logging is available for holes other than WIPP 19 it will be useful to compare strength parameters between these areas and to incorporate the variations in strength into the modelling effort.

The variations in thickness of the dark gray siltstone unit are clearly definable in only WIPP 19, 12, 13 and ERDA 9. The upper surface of the unit is less clearly identifiable in WIPP 30, 26 and 28 and unclear in WIPP 25. Within the repository vicinity (ERDA 9, WIPP 19, 12, 13) thickness is consistent (43 to 47 ft.). In WIPP 30 the thickness may be as little as 20 feet. However, changes in the rock character are subtle and not well defined either in the geophysical logs or in the core. In WIPP 25 there is a 2 ft. layer of solution residue with anhydrite breccia enclosed within the dark gray siltstone. This indicates that there was some evaporite deposition taking place locally, penecontemporaneous with deposition of the dark gray siltstone. Due to the difficulty of defining this unit in some boreholes, it is more useful to discuss the cumulative thickness of the units which occur between the anhydrite unit of the Lower Member and the Salado contact. These

units include solution residue, halite (WIPP 19, 12, 13) and the dark gray siltstone. In the boreholes where the halite unit occurs (7-8 ft. thick) the cumulative thickness is consistent - between 96-102 ft. However, in the boreholes where the halite has presumably been removed by solution, the range is from 59 ft. to 108 ft. The minimum thickness (59 ft. in WIPP 23) coincides with relatively thin occurrences of both the dark gray siltstone and the solution residue. The anomalously thin occurrence here may be the result of the original depositional thickness having been less or the percentage of soluble evaporite-versus-sediment having been greater than that at the other sites. Thus, if the distance from sediment source was greater than that at other boreholes, less sediment would be expected to accumulate. Similarly, if there was a higher percentage of soluble evaporite, after this evaporite had been removed by solution, the resulting thickness would be anomalously thin. It is likely that both of these factors (i.e., less sedimentation and more evaporite) account for this anomalously thin occurrence.

2.2.1.2 Lower Member First Solution Residue/ Halite/Second Solution Residue - WIPP 19 is the only borehole studied for which core is available for the halite unit in this sequence. The presence of this halite is also indicated in the geophysical logs for WIPP 12 and 13. This halite (in WIPP 19) is silty and contains a one-foot layer of anhydrite.

The "solution residue" above and below the halite are similar, red-brown siltstones with some halite crystals visible. These units in WIPP 19 do not appear to have been extensively leached and therefore are not "residues". However, in all other boreholes studied, they have been leached and are residues. In boreholes where the halite unit is not present the first and second residues are considered as a continuous unit. The bottom 20 to 30 ft. of residue typically shows some layering, indicating a complex sedimentary origin. In WIPP 30 this lower (layered) section includes some gray zones and a significant sand fraction within the siltstone. This layered zone is well cemented whereas the overlying residue appears less structured and has the strength of a very stiff to hard soil, presumably due to the removal of halite cement. In WIPP 25 and 26 the cementation is variable but generally comparable to a very stiff to hard soil.

The upper surface of the residue is variable and is characterized by large anhydrite "blocks" (typically 1 ft. thick) interlayered with red silt. These clasts grade upward into anhydrite with red brown silt laminae along the bedding planes.

Fracture in this unit is characterized by horizontal breaks spaced 1 to 4 per vertical ft. In the more consistently cemented lower zone some high-angle fracture (some planar) occurs

locally - ranging in frequency from 1 per vertical ft. in WIPP 30 to 1 per 30 vertical ft. in WIPP 25 (versus 1 per ft. in WIPP 19). In the upper poorly cemented residue some high-angle fracture also occurs in WIPP 30 and 25 with spacing ranging from 1 per 3 vertical ft. to 1 per 10 vertical ft.

2.2.1.3 Lower Member Anhydrite - The anhydrite in WIPP 19 is laminated, with the exception of a 2 ft. leached zone in the lower half of the unit (Plate 2). Geophysical log analysis indicates complete gypsification of the upper 2 ft. and partial gypsification throughout. With the exception of horizontal breaks in the leached zone, no fracture was observed. This condition is generally consistent in the other boreholes. In some boreholes, red-brown uncemented silt is found lining laminae in the anhydrite. This fact and the presence of anhydrite blocks elsewhere in the underlying residue are evidence that part of the anhydrite unit collapsed as the underlying halite was removed by solution near Nash Draw. Presumably not enough halite has been removed in WIPP 19, nearer the site, to induce collapse. In terms of thickness, this unit only varies between 7 and 12 ft. in the boreholes studied. One high-angle fracture occurs in WIPP 26 and it is filled with gypsum.

2.2.1.4 Lower Member Third Solution Residue - In WIPP 19 the third residue is well cemented with some gray stringers and some platy gypsum. The unit grades to black shale

within 2 ft. of the contact with the Culebra. In WIPP 30 and more distant holes, the residue is partially cemented. Clasts in the residue are completely gypsified. In WIPP 25 there is a 1 ft. block of dolomite 5 ft. down in the residue indicating collapse of dolomite as well. Horizontal breaks are the dominant fractures with spacing of 1 to 3 per vertical ft. This unit is consistent in thickness for the boreholes studied.

2.2.2 Culebra Dolomite Member

The Culebra is a fine grained dolomite with beds on the order of 6 in. to 12 in. in thickness. Laminations are generally indistinct. It includes vugs ranging from less than 1/16 in. to about 1/2 in. These vugs generally occur in zones parallel to bedding. The vugs and openings along bedding planes are frequently filled with gypsum in WIPP 19, with a decreasing degree of void filling in the boreholes nearer Nash Draw. Interestingly, from computer analysis of geophysical logs the interval from 772 ft. to 768 ft. in WIPP 19 is classified as gypsum/anhydrite although there is no visual difference in the appearance of the rocks within and outside of this interval (it all appears to be dolomite) (Plate 3).

The thickness of the Culebra, ranging from 22 ft. to 31 ft., is consistent within the boreholes studied. However, presence of fracturing, leaching and the absence of void filling are more pronounced nearer Nash Draw.

The contact between the underlying solution residue and the Culebra is characterized by about 3 ft. of black shale which grades upward into the dolomite. In the lower half of the Culebra, the dolomite appears somewhat leached. This is probably the result of leaching by groundwater. The Culebra dolomite, although it is a low-permeability rock, is the primary water-bearing unit of the Rustler Formation. Its permeability is largely of the fracture type, although some porosity may have been produced by dolomitization.

The Culebra is extensively fractured although some massive intervals also occur. Irregularly-curved vertical fractures occur with a frequency of 1 to 4 per vertical ft. (Plate 4). These fractures are for the most part interpreted to be the result of subsidence and/or shrinkage due to the change in volume from calcite to dolomite, and in some outcrops display a polyhedral geometry similar to mudcracking. High-angle fractures (60° to 70°) in WIPP 19 are spaced at about 1 per 5 vertical ft. The frequency of the high-angle breaks increases at Nash Draw (1 to 2 per vertical ft. for WIPP 25 and 26). High-angle fractures, in places, appear to be occurring in sets whose strikes are oriented at 60° to one another. Dip slip (probably normal in sense) is implied by striations and orientation of gypsum crystals which fill the fractures. Their association with Nash Draw and their geometry implies that this fracture set is in response to solution related collapse.

Bedding plane breaks occur roughly 1 to 4 per vertical ft. Zones where fractures coincide are highly brecciated and such zones are more susceptible to leaching. In WIPP 25 and 26 very little recovery was obtained in the lower half of the Culebra - presumably due to the combination of fracturing and leaching.

2.2.3 Tamarisk Member

2.2.3.1 Lower Anhydrite - In all of the boreholes studied - with the exception of WIPP 19 - there is an anhydrite unit immediately overlying the Culebra. This unit ranges from 9 to 22 ft. thick. It is noteworthy that although it is not present at all in WIPP 19, this anhydrite is 13 ft. thick in the adjacent ERDA 9 (based on geophysical logs). Similarly it is 22 ft. thick in WIPP 25 and only 9 ft. thick in the nearby WIPP 26 - an extremely variable thickness.

Where it occurs this unit is completely gypsified (partially in WIPP 25) and provides an excellent example of possible deformation due to the anhydrite-to-gypsum transformation. It is characteristically brecciated at one or both contacts and the breccia is cemented with gypsum. The anhydrite varies in character from laminated to nodular with a considerable laminated fraction occurring in WIPP 26. In the zone of WIPP 19 where this unit should be, there are areas of gray coloration up to 1 ft. thick in the solution residue which probably represent the residue from anhydrite dissolution.

Fractures in this unit have largely been recemented with gypsum. Open fracture is primarily along bedding planes and spaced at 1 to 2 per ft. In WIPP 30 there is a 1 ft. zone of open fractures indicating two sets of fractures with moderate angles of dip. The localized nature of this zone suggests it may be a response to volume change.

The core photographs of this unit in WIPP 13 from 704 ft. to 687 ft. (Plates 4a through 4i provide some evidence of deformation due to the volume change which accompanies the mineralogical change from anhydrite to gypsum. Within this sequence the contacts of the unit (particularly at the Culebra) show distorted laminae suggestive of plastic deformation. Closer to the middle of the unit, high-angle fracture is dominant with the rock between the fractures still demonstrating the presence of some anhydrite. At the center of the unit the rock is highly brecciated, gypsified, and recemented with gypsum. Assuming that the adjacent units (dolomite below and solution residue above) were/are water ways, it appears that gypsification proceeded more or less simultaneously from both contacts and that the volume change was cumulative toward the center of the unit. This situation would produce strong local variation in the stress field in the layer and the progressively more extreme mode of deformation consisting of plastic flow at the contacts, shear fracture and ultimately brecciation at the highest stress levels in the middle of the unit.

2.2.3.2 Tamarisk Solution Residue - This unit is present in all the boreholes studied and is characterized by partially to poorly cemented red-brown silt with gypsum filled stringers (Plate 5). Although moderately cemented in WIPP 19, the residue has the strength properties of very stiff to hard soil in the other holes. Breccia clasts of anhydrite occur in some holes and in WIPP 13 there are anhydrite blocks up to 1 ft. thick (Plate 6) which are infilled with the residue, implying collapse.

The thickness of this unit varies from 6 to 18 ft. In WIPP 19 the thickness is 15 ft. as compared to 6 and 9 ft., respectively, in WIPP 12 and ERDA 9. The extra thickness of residue in WIPP 19 is possibly attributable to the solution residue from the lower anhydrite which has been completely removed in WIPP 19. Fracture may be characterized as bedding planes breaks spaced 1 to 4 per ft.

2.2.3.3 Tamarisk Upper Anhydrite - This anhydrite is dominantly nodular with some zones of rosettes or laminar structure. It is partially gypsified throughout, and the geophysical logs in WIPP 19 indicate essentially complete gypsification within 5 ft. of the upper and lower contact (Miller, 1979). The anhydrite includes a sediment fraction in the central portion of the unit and in WIPP 19 a thin, 1 in. layer of bitumen is present. The geophysical log analysis identifies dolomite in the interval from 729 to 741 ft., however, this unit visually appears to be a gypsified laminar anhydrite.

The lower contact between the anhydrite and the solution residue is brecciated and recemented whereas the contact at the overlying Magenta dolomite is clear cut and undisturbed. Gypsified zones appear either white or dark/translucent in comparison to the light blue-white of the anhydrite intervals. This unit is remarkably similar from hole to hole and no salient differences were observed. Thickness varies from 64 ft. to 91 ft. This variation does not follow a clear pattern and may reflect some local differences in the degree of volume change due to the anhydrite-to-gypsum reaction.

These rocks are not extensively fractured and horizontal breaks are the most common fracture, in general spaced 1 to 2 per vertical ft. High-angle fracture is not common and generally occurs as isolated single fractures spaced tens of feet apart. Fractures are frequently filled with gypsum.

2.2.4 Magenta Dolomite Member

The Magenta is characterized as a fine-grained dolomite with few leached or vuggy zones. It appears to be a dolomitized lime mud (silt and very fine sand) apparently formed in relatively shallow water in intratidal and subtidal environments.

The upper contact with the anhydrite varies from relatively abrupt in WIPP 12 and 19 (Plate 7) to more gradational in WIPP 25 and 26. In general, there is some interlayering of dolomitic sediments with anhydrite at the top of the Magenta.

For most of its thickness, the Magenta is characterized by laminated beds which are the result of rippled-drift cross bedding (amplitude up to 1 in.). The cross beds remain generally consistent; however, in some cases, the mid-portion of the unit displays some thicker cross beds (to 8 in.). In all boreholes the bottom few feet of the member contain other - possibly algal - laminae between the cross beds. These laminae are highly distorted in some cases and platy gypsum crystals are commonly aligned parallel to them, indicating that these laminae have been conduits for ground water.

The thickness of the Magenta ranges from 18 to 32 ft. (although if gradational zones are included, the thickness is more consistent). Thickness in the site vicinity ranges from 18 to 28 ft. In the Nash Draw boreholes there is smaller variation with a thickness of 25 ft. in WIPP 25 versus a thickness of 32 ft. in WIPP 26.

High-angle fracture within the Magenta is variable and seems to be more a function of overburden than any other factor. In WIPP 12 and 19 there is infrequent high-angle fracture ($> 70^\circ$ dip) and no gypsum filling of fractures. The frequency of high-angle fractures here suggests minimum vertical spacing of 10 ft. for such fractures. (Depth of overburden 696 ft. and 648 ft. for WIPP 12 and 19 respectively). At WIPP 13, about 1 mile from the site, the high-angle fracture frequency is about the same but the fracture picture is complicated by frequent,

moderate-angle (30° to 60° dip) fractures which extensively break up the Magenta. This is the most fractured interval of Magenta found in any of the boreholes studied and there is no gypsum filling of these fractures. The fractures in WIPP 13 have a different character than that in any other borehole. The rock is more highly broken, brecciated - whereas the other boreholes show throughgoing single fracture planes in this interval which do not pulverize the rock. In the vicinity of Nash Draw, the high-angle fracturing is more or less consistent in WIPP 12 and 19, however, additional near-vertical, irregular, discontinuous extension-type fracture is present. These near-vertical breaks are particularly well developed in WIPP 26 (overburden 69 ft.) and are filled with gypsum (1/2 in. wide). Vertical extension fracture is not clearly developed in WIPP 25 (overburden 310 ft.). Such cracks are present in WIPP 30 (near Nash Draw - overburden 512 ft.) but these fractures show little or no gypsum filling. Horizontal breaks occur throughout the member with frequency typically in the 1- to 2- per vertical ft. range.

Development of high-angle planar fractures appears to be uniform across the site with a minimum spacing of about 10 ft. implied. Moderate angle (45° to 60°) fractures occur primarily in WIPP 13. The drastically different nature of the fracturing (shattering) here may suggest a local origin (i.e., due to collapse or local anhydrite-gypsum reaction). Vertical and near-vertical irregular tension fractures occur near Nash Draw

and appear to be best developed under low overburden pressure. Similarly, gypsum filling of fractures becomes more extensive near Nash Draw and also increases in frequency with decreasing overburden pressure. This suggests that some contemporary strain is taking place (possibly due to gypsification and/or solution) and that its effect becomes well defined at depths of less than 300 ft.

One interesting feature of the Magenta is spherical voids filled with translucent gypsum which occur in various sizes and appear to occur in the troughs of ripple marks. The origin of these spheres is not clear, but the relation to the ripple marks suggests they may have been primary - perhaps particles of gypsum rounded by mechanical action or originally carbonate oololiths which were subsequently dissolved out and replaced by gypsum. The sphere size is somewhat larger in the boreholes closer to Nash Draw.

The Magenta is a clayey dolomite and the carbonate reaction to testing with HCl is of relatively low intensity. Due to the extensive filling of the voids in the Magenta and the fine grain-clayey nature of the original limestone, this unit exhibits very low permeability. It is less permeable than the Culebra, and it produces low water yeilds to some local wells for live stock.

2.2.5 "49'r Member"

2.2.5.1 Lower Anhydrite - The lower anhydrite unit of the "49'r Member" is a largely gypsified anhydrite which ranges from nodular (enterolithic) to laminated with some thin (1 in.) gypsum rosette layers. In WIPP 19 and nearby holes, the contact of this unit with the Magenta is a gradational zone 2 to 3 ft. thick, however, in WIPP 25 and 26 there is visible, presumably dolomitic sediment within the anhydrite over a gradational contact of ten ft. or more. The contact between the anhydrite and the overlying solution residue is abrupt and accompanied by some brecciation.

Analysis of the geophysical logs indicates that the anhydrite is at least three-fifths gypsified (in WIPP 19) and the upper 4 ft. is completely gypsified. However, in this case the manner of gypsification is clearly different from the brecciation and cumulative deformation which is characteristic of the lower anhydrite of the Tamarisk as shown in Plates 4a through 4j. It is possible that water has traveled parallel to laminae (horizontal) dissolving the anhydrite and depositing gypsum in seams on the order of 1 in. thick (Plate 8). These seams mimic the sedimentary structure. However, there is no evidence of deformation due to the volume change. This suggests that not all of the dissolved calcium sulfate was reprecipitated as gypsum. It is possible that some of the calcium sulfate was transported out of the rock so that there was not any significant stress-producing volume change.

The thickness of this unit ranges from 17 to 24 ft. and is generally consistent from borehole to borehole.

Little high-angle or vertical fracture was observed within this unit with the exception of the minor brecciation which occurs at the contacts. Bedding plane fracture occurs on the order of 1 to 2 per vertical ft. There are also a few zones which appear to have been leached and then filled with gypsum. Bedding is essentially horizontal and the unit is well cemented throughout. There is some gypsum lining of laminae suggesting water movement along these structures.

2.2.5.2 "49'r Member" Solution Residue - This unit is the uppermost solution residue in the Rustler. At its contact with the lower anhydrite, it has a dark gray color grading to the typical red-brown color about 2 ft. above the contact. In WIPP 19 it appears to be well cemented throughout but in the other holes studied, a very stiff to hard soil strength is more typical with only the lower 4 ft. of the unit being well cemented.

This residue includes some gypsum stringers and occasional breccia clasts and gypsum-filled voids. Fracture is typically bedding plane breaks spaced 1 to 2 per vertical ft. In WIPP 25 and 26 there are a few high-angle planar fractures, locally filled with gypsum.

2.2.5.3 "49'r Member" Upper Anhydrite - The uppermost unit of the Rustler Formation is a laminated anhydrite with laminations sub-horizontal to horizontal. Within laminations

the anhydrite is generally nodular. Laminae occur throughout the unit ranging from 1 to 2 per ft. to continuous zones a foot or more in thickness. In boreholes where there is a noticeable pattern (WIPP 12 and 30) the occurrence of laminae is more common in the lower portion of the unit. In two boreholes, the middle 3 to 4 ft. of the unit appears to have clastic sediment disseminated within the anhydrite. In some zones in WIPP 26 and 30 the laminations have been distorted and folded to 45°, possibly as a result of the anhydrite to gypsum transformation. These zones are generally limited to within a few feet of the top or bottom of the anhydrite unit.

In WIPP 19, the analysis of the geophysical logs indicates gypsification in the upper 3 ft. and the lower 1 ft. of this unit. This gypsification appears to be more extensive in the boreholes closer to Nash Draw. At the lower contact (with the solution residue) there is some brecciation - related to either the gypsification or to collapse caused by undermining of the unit by solution.

There are significant leached zones in this unit. In WIPP 19 these zones are open. In the other boreholes, similar zones occur which appear to have been subsequently filled with gypsum. This suggests that while there is active solution going on in the site vicinity, to the north and west solution may be essentially complete and reprecipitation has largely filled in voids opened by solution activity.

The thickness of this "49'r Member" upper anhydrite unit ranges from 22 to 42 ft. Both maximum and minimum thicknesses occur in the Nash Draw boreholes (WIPP 28 and 26, respectively). In the site vicinity thickness is consistent in the 26 ft. to 31 ft. range.

Fracture in this unit is not extensive. Bedding plane breaks occur at a frequency of 1 to 2 per vertical ft., normally with a frequency of 3 to 12 per vertical ft. in the opened leach zones. In WIPP 12 and 30 there are some high-angle and irregular, vertical fractures with highly variable frequency ranging from zones of 1 per vertical ft. to 1 per 20 vertical ft. Occasional widely spaced moderately dipping (30° to 60°) fractures are also found. Generally, these fractures are filled with gypsum.

The upper contact of the Rustler Formation with the Dewey Lake Redbeds is extremely abrupt, possibly because erosion took place after the last evaporite deposition. In two cores (19 and 25) there is a thin (1/2 in.) layer of gray clayey material which marks the contact. This may be a solution residue of the anhydrite or some sort of alteration resulting from interaction between the redbeds and anhydrite. This gray material is similar to that in clasts in the red-brown solution residue further down in the Rustler.

2.3 IMPORTANT CONSIDERATIONS

A number of major considerations have been encountered in the context of this core study which are of particular concern in the evaluation of the thermomechanical response of the Rustler rocks. These considerations include:

- 1) the anhydrite-to-gypsum mineralogic change and the potential strains induced by the accompanying volume increase;
- 2) the variability in the degree of cementation of the solution residue and the resulting difficulty in defining a stress/strain response for these units;
- 3) the role of the dolomite units both as brittle, fractured members and as the major aquifers in the formation.

2.3.1 Anhydrite-to-Gypsum Mineralogic Change

In terms of general stability fields, the gypsum-anhydrite cycle is shown on Figure 4. This is derived from a paper (Ref. 4) by Raymond Murray (Univ. of Montana) who acted as a consultant during this study. It is based on the premise that in most cases, calcium sulfate is deposited initially as gypsum. Under certain circumstances it can be altered to anhydrite soon after burial, as in a sabkha environment. In any case, with burial the gypsum will be dehydrated to anhydrite as a result of

Figure 4. Gypsum-Anhydrite Cycle

increasing temperature, among other parameters. Increasing temperature favors the formation of anhydrite although an increase in pressure favors gypsum. Since the reaction is much more sensitive to the effect of temperature, the increase in temperature which accompanies burial will lead to the formation of anhydrite (Murray, pers. comm., 1979).

In discussing these concepts, it is important to realize that the actual stability field and the temperature of conversion of anhydrite and gypsum are not well known and are subject to such things as salt content. Thus, there is a reasonable expectation of variation in these factors from the theoretical numbers quoted in the literature. Therefore, these ideas should be regarded conceptually and actual percentage values may vary from those quoted herein.

From our core study, as discussed in the preceding sections, it appears that the calcium sulfate of the Rustler Formation was probably initially deposited as gypsum (evidence - pseudomorphic rosettes) part of which was, at least partially, diagenetically altered to anhydrite with burial. Subsequent uplift has returned the formation to the gypsum stability field. However, there is still significant anhydrite present in the Rustler Formation either due to the fact that it has not come in contact with water or because contacting waters were too saline to permit rehydration to gypsum.

It appears that gypsification of anhydrite can be the result of two mechanisms; one, whereby the system remains open and the volume increase accompanying gypsification is offset by transport of dissolved anhydrite away from the site; in this case, there is no significant volume change. Two, the system becomes closed after the introduction of active waters, producing some volume increase which in turn imposes deformation and ultimately brecciation.

Within the Rustler cores there is evidence that both of these mechanisms operate. There are gypsified layers on the order of one-inch thick interlayered with one-inch layers of anhydrite. Such layers are shown on Plate 8. They do not show fracture, plastic flow or other indications that volume change has produced stresses. This scenario is also supported by the observation of apparent leached zones in WIPP 19 in the upper anhydrite, these zones show no significant gypsification. Apparently, the anhydrite was dissolved but the resulting calcium sulfate solution was carried away from the site of dissolution and no gypsum was precipitated. The presence of gypsum filling in the voids and fractures of the dolomite and solution residue units adjacent to the anhydrites may represent the final resting place of the calcium sulfate which was carried away from the sites of anhydrite dissolution.

In contrast, the photo sequence on Plates 4a through 4i from WIPP 13 indicates a case of deformation which appears to be the result of the increase in volume accompanying gypsification. In this case, the adjacent dolomite and solution residue units probably acted as the source for the groundwater. From the literature, the most convincing case for volume change accompanying gypsification is presented in a paper by Anderson and Kirkland (1966) wherein laminae within calcium sulfate beds of the Castile Formation were correlated across the Permian Basin. In some cases individual lamina were traceable from areas in the anhydrite rock to areas where the same lamina occurred in rock that had been gypsified. In these cases, the lamina was smaller in thickness where it was anhydrite and of greater thickness where it was gypsum (although the theoretical increase of 38 percent was not realized). Charles Jones of the United States Geological Survey has also discussed with us the concept that some stratigraphic relationships in the vicinity of the WIPP site indicate no reduction in Rustler thickness in areas where halite and other soluble units have been removed by solution. This leads to the conclusion that the loss of halite is being compensated by the increase of volume due to the gypsification of the anhydrite units (C. Jones, pers. comm. 1979).

2.3.2 Interpretation

Several paradoxes are suggested by the foregoing discussion of secondary gypsum solution and precipitation in the

Rustler. Of special interest is the simultaneous existence of evidence for extensive solution and deposition of gypsum over short distances. Similarly, the evidence for extensive solution and collapse in some layers is at least partially offset by expansion in other layers of the same lithology. Some layers which also share the same history and composition have delicate sedimentary structures preserved, implying almost no change since diagenesis.

These observations, combined with the observation of small-scale leaching and solution features throughout the Rustler Formation strongly imply that the dominant factor in the petrology of the Rustler Formation is water supply.

The Pleistocene Epoch in New Mexico has been punctuated by cycles of humid climate (pluvials), alternating with dry interglacial periods. Perhaps these are related to the climatic influence of the continental glaciers of the Pleistocene. The last Pluvial Cycle ended about 10,000 years ago. The extensive solution residues and much of the widely distributed evidence of collapse are possibly relicts of that climate or of one of the preceeding pluvials. Conversely, smaller open solution channels, enlarged fractures and bedding plane solution zones possibly result from modern processes.

The hydration potential of anhydrite in the Rustler Formation is probably too great to allow the existence

of inactive open spaces over long times. Filled, small openings comparable to modern openings are abundant, and imply the effectiveness of the system in closing inactive openings. The most probable explanation is that the fracture permeability which facilitated solution during humid times has probably survived to some degree. That fracture system has been modified by the closing of the smallest solution passageways (including interstitial passageways) by deposition of gypsum and by the maintenance or widening of the effective channelways by solution.

The scenario which most satisfactorially explains all the features of the Rustler Formation is a system in which water is present most of the time in quantities far below that required for substantial gypsification. Flow in an inherited fracture system seems to be the most appropriate means of delivery of water to the anhydrite units. Peak flow dissolved away accumulated gypsum and exposed fresh anhydrite along opening walls and maintain channel openings.

Water left in the rocks when flow slows or effectively ceases gradually becomes more and more gypsum saturated. On free surfaces this results in the deposition of coarse crystalline gypsum and a zone of hydration of the adjacent anhydrite, if present. Isolated pockets of water may be forced out into the country rock by the force of hydration, but in general, this form of gypsum deposition is only locally expansive. If the permeability

of the original evaporite sediment was controlled by sedimentary structure, then this mode of deposition may produce pseudomorphous structures.

The deposition of fibrous aggregates of gypsum in fractures, (Plates 6, 4g) and the preservation of some very deformed rocks (Plate 4h) imply the existence of strongly expansive gypsum formation. The fibrous habit of gypsum growth is present only in fractures in the core and in outcrop. The prismatic gypsum fibers are oriented perpendicular to the fracture walls. Gypsum exhibits strongly anisotropic, directional growth and solution properties in this habit. Prismatic crystals as a class tend to grow most rapidly in the direction parallel to the crystal faces. Solution tends to proceed most rapidly in the direction perpendicular to the crystal faces.

The nucleation and growth of closely spaced fibers of gypsum across a fracture causes the maximum growth pressure (crystalloblastic pressure) exerted by these fibers to be effectively transferred to the walls of the fracture. Near the tip of the fracture Griffith effects may cause propagation of extension fractures in the brittle anhydrite rocks. The geometry of the interconnected, dendritic, fiber filled fractures in the Rustler Formation strongly suggests that this mechanism of fracture propagation is very effective (Figure 5). Pre-existing fractures of all classes, in all rock types, can propagate in this way. New fractures can initiate by branching from older fractures.

Outcrop of anhydrite of Tamarisk Member of Rustler Formation on west side of Nash Draw. Shown are linear fractures along which the anhydrite has been hydrated to gypsum. (Scale: yellow pen is 6 inches long)

FIGURE 5

Outcrop of Tamarisk Anhydrite with fractures which have been gypsified. Note extensive fracturing.

The continual supply of water to deliver the chemical constituents necessary for crystal growth at the fracture tip is a product of the differential solubility of gypsum. Water saturated with gypsum with respect to the fast growing fiber ends, but undersaturated with respect to the prism faces can move through the fibrous fracture fillings. The recession of prism faces due to solution provides the necessary permeability for water to move toward the new volume at the tip of the crack. At the same time the fiber ends protect the fracture walls from solution and apply continued crystalloblastic force (simultaneous growth in one direction and solution in another is a well known phenomenon in some prismatic crystals). These considerations also explain the relatively uniform size of gypsum fibres and the lack of zoning in fibrous fracture fillings, since each new injection episode induces a new solution-growth equilibrium.

A continuous supply of ground water of the chemical nature necessary to drive this process is unlikely. If the Rustler Formation were saturated with ground water at that composition, all available fracture spaces would be filled, or all anhydrite would be converted to gypsum. The existence of evidence for fresh solution of fracture and bedding surfaces implies that water exists in the system which is low enough in dissolved calcium sulfate concentration to dissolve anhydrite directly.

A variability in water chemistry as a direct result of a variance in flow volume is the most probable mechanism. At the peak of flow the water dissolves gypsum and anhydrite and maintains or enhances the primary open fracture permeability. As flow wanes, the calcium sulfate content of the remnant water grows greater as residence time increases. When the concentrations reach the critical value for fibrous aggregate growth and fracture propagation, the remnant waters may be entirely or partially used up by being drawn into growing secondary fractures. Supersaturation of the last remnant water by calcium sulfate may shut off circulation in growing fractures by thickening fibers, and thus sealing off the bases of the fractures. Pressure due to confined volume increase would be added to gypsum growth pressure in this case. (Fractures of this type several feet long and two or three inches across at the base are not uncommon in Rustler anhydrite rocks in outcrop. In boreholes in the site vicinity, such gyp-filled fractures are on the order of one-inch thick.) This process may account for most of the recent strain in the Rustler Formation.

2.3.3 Impacts

With respect to the stability of the Rustler Formation three important impacts are implied:

- 1) the permeability of all fibrous gypsum fillings in fractures may be unexpectedly high with respect to water saturated with calcium sulfate. We suggest that laboratory study of permeability under the stated conditions would be prudent;

- 2) the permeability which exists as a result of fracture fillings may be increasing at a presently unknown rate;
- 3) groundwater flow in the Rustler is cyclical, alternating from CaSO_4 saturated, or nearly CaSO_4 saturated fracture flow through CaSO_4 unsaturated fracture flow, to a condition which implies that all water in the system may be used. This variance in flow is envisioned to be the result of relatively short term climatic variance.

2.3.4 Solution Residue Zones

The solution residues provide a number of functions in the system:

- 1) they represent previous zones of water migration which dissolved away evaporites, primarily the halites, and which contributed to the gypsification of the adjacent anhydrite units;
- 2) they are intervals where significant material has been removed and some brecciation of the surrounding rock has taken place as a result of the subsequent collapse;
- 3) they are presently at various stages of cementation, generally less than completely cemented rock, and thus provide a zone of more plastic, less brittle material, probably capable of accommodating much of the anticipated strain imposed by the potential thermal gradient developed by a repository. Photographs of solution residue in various stages of cementation are shown on Plates 2, 5, and 6.

An important implication of the fact that the solution residues represent previous waterways is that in general the anhydrite units are not significantly gypsified beyond the relatively thin rind adjacent to the residue. This supports the contention that the solution residues formed during times of plentiful groundwater flow when calcium sulfate and newly formed gypsum could be removed in solution.

2.3.5 Dolomites

The dolomites represent the most permeable units presently in the Rustler Formation. However, these are of low permeability relative to most dolomites because many of the voids have been infilled with gypsum. On the other hand, the units are highly fractured due to subsidence as a result of dissolution, the characteristic shrinkage cracks that take place as a result of volume loss in transforming from calcite to dolomite, and the strains due to regional stresses and those imposed through the anhydrite-gypsum volume increase. These rocks are also the most brittle rocks in this section, and therefore will respond with brittle failure before the other units.

3. PARAMETERS FOR MODELLING

3.1 GENERAL

For the purpose of modelling the thermomechanical response of the Rustler Formation, the following section presents a summary of parameters which are based on the results of this core study. In many cases, it will be necessary to model extreme

cases in order to bracket the range of parameters which exist. Such a delimiting approach will help in defining areas which need to be studied more extensively.

3.1.1 Stratigraphy

The stratigraphy which should be used for the model should be based upon the stratigraphy defined by the geophysical logs of ERDA 9. Although no cores were taken in the Rustler in this borehole, it is the closest hole to the proposed repository location. The information gained from the study of the cores and photographs of WIPP 19, and the correlation of this information with the available geophysical logs of both WIPP 19 (Miller, 1979) and ERDA 9 provide a good basis of comparison between these two holes. The stratigraphy of ERDA 9, based on this analysis is presented on Table 2. Anhydrite units within ERDA 9 should be input as gypsum in the zones within 5 ft. of the contacts with other units.

The dip of the Rustler, based on the structure contours on top of the Culebra Dolomite Member (Geological Characterization Report, Vol. I, Fig. 4.4-II) is variable in direction but within one degree of horizontal. Generalized dip values for the Rustler Formation are shown on Figure 2. For the purposes of modelling, it appears that an easterly dip on the order of 1/2 degree would be appropriate. The variability of dip angle as a result of collapse due to undermining by solution activity

ERDA 9

Member/Unit	Depth (ft.) (TOP)	Thickness (Ft.)	Elevation (ft.) (TOP)
"49'r Member"	550	58	2870
Upper Anhydrite	550	30	2870
Solution Residue	580	11	2840
Lower Anhydrite	591	17	2829
Magenta Dolomite	608	24	2812
Tamarisk Member	632	84	2788
Upper Anhydrite	632	64	2788
Solution Residue	696	9	2724
Lower Anhydrite	705	13	2715
Culebra Dolomite	716	24	2704
Lower Member	740	120	2680
3rd Solution Residue	740	8	2680
Anhydrite	748	10	2672
2nd Solution Residue	758	12	2662
Halite	770	10	2650
1st Solution Residue	780	36	2640
Dark Gray Siltstone	816	44	2604
Bottom of Rustler	894		2560

Table 2. Rustler Stratigraphy of ERDA 9

and volume change due to gypsification has produced considerable variation in the local dip of the beds so as to make this parameter difficult to estimate with precision.

The various units of the Rustler appear to be laterally continuous, within the cores studied with the exception of the Tamarisk Lower Anhydrite and the general loss of soluble evaporites with proximity to Nash Draw.

At some point to the west of ERDA 9 and WIPP 19 there is a "solution front" to the west of which much, if not all, of the halite and to some extent the other evaporites have been removed from the section by solution (Griswold, 1977). Based on the cores, there is no significant halite in the boreholes to the west or north of WIPP 13. Thus, the model should reflect this by deleting the halite layer in the Lower Member from the stratigraphy to the west of WIPP 13.

3.1.2 Fracture

The fracture distribution and frequency indicated on the Lithologic Log of WIPP 19 represents the best available information for the repository location. High-angle fracture may be characterized as oriented at 70° to the horizontal; moderate-angle fracture at 30°; bedding plane breaks as horizontal; and near-vertical fracture as vertical. Bedding-plane-breaks frequencies presented on the Log represent fractures actually observed in the core. In obvious cases, breaks were classified

as drilling breaks and eliminated from consideration; however, in most cases, such determinations were difficult to make. Therefore, in order to account for breaks which are solely the result of the mechanics of the drilling operation, bedding plane fracture frequencies (on the Log) should be reduced by a factor of 2 to 4 in order to be more representative of the conditions in situ. A number of trials using different reduction factors would be useful in determining the sensitivity of the model to this parameter. The frequencies given for the higher-angle fractures should be reasonably accurate due to the fact that drilling breaks do not generally occur as high-angle fractures and where they do occur they are relatively easy to identify.

Fracture filling and degree of opening on fractures is of course variable. Fracture filling ranges from no filling to fractures lined with halite, gypsum or clay and some minor calcite filling.

In the anhydrite units gypsum typically lines fractures and the thickness of filling may range from 1/16 inch to over 1/2 inch. Typically, bedding plane breaks are filled with thicknesses of gypsum that fall in the lower part of the range while the high-angle fractures in some cases demonstrate filling up to 0.4 inch. In the dolomite units, fracture filling is highly variable. These units, although typically characterized

by open high-angle and near-vertical fracture do show gypsum filling of pores and gypsum lining of bedding planes, particularly along algal laminae. The dark gray siltstone of the lower member is characterized by halite-filled fractures, up to 1-inch thick, within the holes in the vicinity of the repository site and decreasing tendency for fractures to be filled in the boreholes near Nash Draw. The solution residues display a wide range of fracture filling. In some residue units the contact adjacent to an overlying anhydrite unit is characterized by anhydrite blocks in a matrix of residue (clay) wherein the matrix behaves as fracture filling.

3.1.3 Cementation

Degree of cementation is a factor primarily pertaining to the solution residue. In the vicinity of the repository site, the residue is generally cemented and possesses the properties of weak sedimentary rock. However, with proximity to Nash Draw (in general terms) the solution residue units typically approach the strength properties of a very stiff soil. In order to delimit the effect of this factor, uplift calculations should be run with the residue strength at the maximum and minimum values. The plastic nature of the poorly cemented portions of the residue units may provide to reduce fracturing where deformation in adjacent units is "absolute" thus enhancing the overall competency of the formation as a barrier.

3.1.4 Permeability

This study was primarily aimed at a study of the properties of the Rustler that could be estimated on the basis of observation. Thus, quantitative evaluation of permeability is well beyond the scope. However, observation of the nature of the openings in the rock do lead to the conclusion that there is relatively little porous permeability in the Rustler rocks and that in all likelihood, the little permeability that does exist is the result of flow along fractures. Such fractures include leached zones (eg., in the anhydrite) as well as the extensively fractured zones in the dolomite units. Similarly, the water which produces the gypsification of the anhydrite and solution of the evaporites appears to be primarily supplied by the fracture permeability. Secondary, low velocity flow along "chicken-wire" structure in the anhydrite and along laminae is estimated at many orders of magnitude lower than the fracture flow.

3.2 PHYSICAL PROPERTIES

The physical properties of the units of the Rustler are presented on Table 3. A summary of recommended model parameters and trials is presented on Table 4. Strength parameters including Young's Modulus, Bulk Modulus, and Shear Modulus were derived from computer analysis of geophysical logs of WIPP 19 (Miller, 1979). Due to the fact that the residue units in WIPP 19 were all cemented, the strength parameters for uncemented residues

UNIT	DENSITY (g/cc)	Poisson's Ratio	Young's Modulus (E6 psi)	Bulk Modulus (E6 psi)	Shear Modulus (E6 psi)	Angle of Internal Friction (degrees)
Anhydrite	2.9-3.0	0.30	9.0-10.3	6.0-8.6	3.0-4.0	
Gypsum	2.35-2.45	0.25	3.0-8.7	2.6-5.9	1.5-3.6	
Dolomite						
Magenta	2.5-2.6	0.22	2.7-6.0	2.5-4.3	1.0-2.4	35°-50°
Culebra			5.5-7.0	4.0-4.5	2.2-2.8	
Halite	2.1-2.3	0.26	5.1	3.6	2.0	
Dark Gray		0.29-				
Siltstone	2.3-2.45	0.40	2.1-2.5	2.3-2.7	0.8-0.9	20°-40°
Solution Residue		0.28-				
Cemented	2.12-2.5	0.38	1.4-3.7	1.4-4.4	0.5-1.4	15°-30°
Very Stiff		0.3-	0.001-			
to Hard	2.1-2.4	0.4	0.0025	-	-	10°-15°
Stiff	2.1-2.3	0.35-0.4	0.0006- 0.0012	-	-	5°-10°

Table 3. General Physical Properties of the Rustler Units

2

	FRACTURE SPACING (Fractures per ft. Unless Noted)					*** Fracture Filling	** ‡ Fracture Opening (or Filling Thickness)	‡ (E6 psi) Young's Modulus	‡ (E6 psi) Bulk Modulus	‡ (E6 psi) Shear Modulus	
	* Depth	‡ Low Δ 0-30°	Moderate Δ 30-60°	High Δ 60-90°	Vertical Irregular (Extensional)						
"49'r MEMBER"											
Gypsum	550	1-4				Gypsum	(A)	14.2	2.8	1.7	
Upper Anhydrite	553	2-4				Gypsum	(A)	10.2	8.5	3.9	
Gypsum	578	1-4				Gypsum	(A)	8.1	5.2	3.2	
+ Solution Residue	580	1-2				None	(A)	1.9	1.8	0.7	
Gypsum	591	1		1 per ft.		Gypsum	(A)	3.8	2.6	1.5	
Lower Anhydrite	599	1				Gypsum	(A)	9.1	6.3	3.6	
Gypsified	602	1		1 per 4 ft.		Gypsum	(A)	8.6	5.5	3.5	
MAGENTA DOLOMITE						Hi Δ open Lo Δ gypsum	(A)				
	608	1-4		1 per 6 ft.				3.0	2.7	1.2	
TAMARISK MEMBER						Hi Δ open Lo Δ gypsum	(A)				
Gypsum	632	1		1 per 5 ft.				7.0	4.6	2.8	
Upper Anhydrite	637	1-2				Gypsum	(A)	10.0	8.4	3.9	
Gypsum	688	1-2			1 per 3 ft.	Gypsum	(A)	6.5	4.4	2.6	
+ Solution Residue	696	1-4				Gypsum	(A)	1.4	1.3	0.5	
Gypsum	705	1-2		1 per 5 ft.		Gypsum	(A)	6.5	4.4	2.6	Assumed
Lower Anhydrite	709	1-2				Gypsum	(A)	10.0	8.4	3.9	Assumed
Gypsum	712	1-2				Gypsum	(A)	7.0	4.6	2.8	Assumed
CULEBRA DOLOMITE	716	1-3		1 per 10 ft.	1-3 per ft.	Open	(A)	7.0	4.5	2.8	
Culebra Leached Zone	720	3-8		1 per 10 ft.	1-3 per ft.	Open	(A)	6.3	4.2	2.5	
LOWER MEMBER											
3rd Solution Residue	740	1-4				Gypsum	(A)	1.5	1.4	0.6	
Gypsum	748	1				Gypsum	(A)	4.7	2.6	2.0	
Anhydrite	751	3				Gypsum	(A)	9.3	7.4	3.6	
+ 2nd Solution Residue	758	1-3				Halite	(A)	3.3	2.7	1.3	
Halite	770	1-3				Halite	(B)	5.1	3.6	2.0	
1st Solution Residue	780	1-3		1 per 5 ft.		Halite	(A)	3.6	4.4	1.3	
Dark Gray Siltstone	816	1-2	1-2		1-3 per ft.	Halite	(C)	2.3	2.3	0.8	
BOTTOM OF RUSTLER	894										

- NOTES: Stratigraphic Dip: 1/2° East Stratigraphic interval based on geophysical logs and observation, see text.
- + Due to variability of cementation of solution residue, three trials should be performed for varying degrees of cementation to test sensitivity. See Table 2.
- ‡ Due to presence of drilling breaks parallel to bedding planes. Do three trials using reduction factors 2, 3, 4.
- * From ERDA 9. For Trial 2 delete Tamarisk Lower Anhydrite.
- ** Approximation based on little hard data. A number of trials are necessary to test the sensitivity of this parameter.
- (A) < 1/8 inch
- (B) 1/8 to 1/4 inch
- (C) > 1/4 inch
- *** For friction factors for fracture fillings, see Table 2.
- ‡ Best estimate value. For ranges, see Table 2.

Table 4. Summary of Recommended Model Parameters

are estimated from the literature. Similarly, friction angles for all units are estimates. Important values which need to be further defined for all units include Poisson's Ratio, coefficients of friction and ultimate strength.

3.2.1 Summary Discussion

This core study has provided a basic "hands-on" understanding of the Rustler Formation and the kinds of geologic processes which have or are operating. From this point considerable effort is necessary to better define the physical properties of the units - particularly with respect to lateral variations within a given unit, for example, strength properties of the solution residue at various levels of cementation. In addition, further drilling - addressed to the Rustler Formation - would be helpful to provide additional views of the rock.

In general, this core study should be considered a start at a detailed evaluation of the formation. While the parameters identified do provide the basis for initial modelling and sensitivity testing with more "real" input than has been used to date, the scope of questions which have been identified may be used as an indicator of directions in which study can proceed.

3.3 CONCLUSIONS

- 1) The extensive presence of open fractures, open solution channelways, and solution residues strongly imply that historic or recent flow through the Rustler Formation is not confined to the Culebra and Magenta dolomites.

- 2) Except where solution has extensively altered the rock there is no interstitial permeability in the Rustler Formation. Most flow through that formation is through fractures or along bedding surfaces. The resulting channelways are roughly planar, but are extremely complex.
- 3) Small fractures and small interstitial spaces are generally filled with gypsum. Fractures, solution residues, and large solution channelways exist which imply active intraformational solution. The evidence of penecontemporaneous solution and deposition suggests a non-equilibrium condition. The variations in water availability may result in radical local differences in the solution of gypsum.
- 4) The layering and geometry of zones of diagenetic alteration and deposition are sufficiently predictable that the Rustler Formation is divisible into physically modelable layers, separated by zones of decoupling. Individual layers are segmented by steeply dipping or vertical fractures.
- 5) The most important new source of permeability in the Rustler may be the growth of fractures due to gypsum crystal growth. Gypsum with fibrous growth habit in fractures exerts the crystal's growth pressure on the walls of the fracture. Griffith considerations imply that small stresses thus applied are very effective. Such fractures filled

with fibrous gypsum are widely distributed in the Rustler anhydrite rocks. Fibrous gypsum exhibits differential solubility, allowing circulation of fluids between stable or dissolving crystal faces while crystal forces grow against the fracture walls. For this reason, fluids near the critical saturation concentration probably can move through fibrous masses of gypsum freely.

Plate 1. Lower Member, Dark Gray Siltstone: with irregular near-vertical salt-filled fractures (WIPP 19,864-870 ft)

Plate 2. Lower Member Anhydrite: (with leached zone) and second solution residue with halite cement (WIPP 19, 794-800 ft)

Plate 3. Culebra Dolomite: with dolomitization (shrinkage) cracks, bedding plane breaks and high-angle fractures (WIPP 19, 764-770 ft)

Plate 4a. Tamarisk Member Lower Anhydrite: contact with overlying solution residue (Series: 1 of 9, WIPP 13, 686-688 ft)

Plate 4b. Tamarisk Member Lower Anhydrite: (Series 2 of 9, WIPP 13, 689 ft)

Plate 4c. Tamarisk Member Lower Anhydrite: Anhydrite rock with high-angle planar fracture filled with gypsum (Series: 3 of 9, WIPP 13, 689-691 ft)

Plate 4d. Tamarisk Member Lower Anhydrite: (Series 4 of 9, WIPP 13, 692-693 ft)

Plate 4e. Tamarisk Member Lower Anhydrite: brecciated and extensively gypsified (Series 5 of 9, WIPP 13, 694-696 ft)

Plate 4f. Tamarisk Member Lower Anhydrite: (Series: 6 of 9, WIPP 13, 697-698 ft)

Plate 4g. Tamarisk Member Lower Anhydrite: anhydrite rock with high-angle fracture filled with gypsum (Series 7 of 9, WIPP 13, 699-700 ft)

Plate 4h. Tamarisk Member Lower Anhydrite with distorted laminae (Series 8 of 9, WIPP 13, 701-703 ft.)

Plate 4i. Tamarisk Member Lower Anhydrite, at contact with Culebra Dolomite (Series 9 of 9, WIPP 13, 704-705 ft.)

Plate 5. Tamarisk Member Solution Residue, poorly cemented, very-stiff-soil strength (WIPP 30, 684-685.5 ft.)

Plate 6. Tamarisk Member Solution Residue, with blocks of anhydrite and gypsum stringers (WIPP 13, 682-683 ft.,)

Plate 7. Magenta Dolomite (with ripple marks) at contact with 49'r Lower Anhydrite (648) (WIPP 19, 648-654 ft.)

Plate 8. 49'r Member Lower Anhydrite laminated with nodular, partially gypsified (lighter zones) (WIPP 19, 633-639 ft.)

CITED REFERENCES

1. Anderson, R. Y. and Kirkland, Intra basin Varve Correlation, Geological Society of Am. Bull., V. 77, p. 241-256, 1966.
2. Gibbons, J. F., Ferrall, C. C., Faith, S. F., "Progress in Modelling the Mechanical, Hydrologic, and Geochemical Response of the Rustler Formation for the WIPP Project", April 26, 1979, prepared by Civil Systems, Inc.
3. Hern, J. L., data digitized by G. Hardy Long and Associates, Houston, TX, 1979.
4. Miller, W. B., unpublished, Sandia National Laboratories, Albuquerque, NM, 1979.
5. Murray, R. C., "Origin and Diagenesis of Gypsum and Anhydrite", Jour. Sed. Petrol., V. 34, No. 2, p. 512-523, 1964.
6. Murray, R. C., "Origin of Porosity in Carbonate Rocks", Jour. Sed. Petrol., Vol. 30, No. 1, pp. 59-84, 1960.
7. Powers, D. W., Lambert, S. J., Shaffer, S., Hill, L. R., Seart, W. D. (editors) "Geological Characterization Report, The Waste Isolation Pilot Plant (WIPP) Site, Southeastern New Mexico, August 1978, SAND 78-1596, Volume I, Volume II.

BIBLIOGRAPHY

1. Adams, J. E., 1944, "Upper Permian Ochoa Series of Delaware Basin, West Texas and Southeast New Mexico", Am. Assoc. Petrol. Geol. Bull.
2. Blanchard, W. G. Jr.; and Davis, J., "Permian Stratigraphy and Structure of Parts of Southeastern New Mexico and Southwestern Texas", Am. Assoc. Petrol. Geol. Bull., Vol. 13, p. 957-1929.
3. Bradshaw, et al, 1968, "Properties of Salt Important in Radioactive Waste Disposal", Geol. Soc. Am. Spec. Paper 88, p. 543-595.
4. Cooper, V. B. and Glanzman, V. M., 1971, "Geohydrology of Project Gnome Site", U.S. Geol. Survey, Professional Paper 712-A.
5. Crandall, K. H., 1940, "Permian Stratigraphy of Southeastern New Mexico and Adjacent Parts of West Texas", Am. Assoc. Petrol. Geol. Bull., Vol. 24, No. 1.
6. Dean, W. E., Davies, G. R., and Anderson, R. J., "Sedimentological Significance of Nodular and Laminated Anhydrite", Geology, Vol. 3, No. 1, p. 367-372, 1975.
7. Dean, W. E., Schreiber, B. C., (Ed.), Marine Evaporites, SEPM, Course No. 4, 1978.
8. Dickey, R. I., 1940, "Geologic Section from Fisher County thru Andrews Co. Texas to Eddy Co., New Mexico", Am. Assoc. Petrol. Geol. Bull., Vol. 24, No. 1, Jan.
9. Fairbridge-Rhodes, 1964, "Mechanical Properties of Evaporites", Chapter 21, and Bibliography, Salt Deposits: The Origin, Metamorphism and Deformation of Evaporites, D. Van Nostrand Comp. Ltd.
10. Gard, Jr., L. M., 1968, "Geologic Studies, Project Gnome, Eddy County, New Mexico", U. S. Geol. Surv. Professional Paper 589.
11. Garrels, R. M. and C. L. Christ, 1965, Solutions, Minerals and Equilibria, Harper and Row, 450 p.
12. Goldman, M. I., 1952, Deformation, Metamorphism, and Mineralization in Gypsum-Anhydrite Cap Rock, Sulphur Salt Dome, Louisiana, Geol. Soc. Am., Memoir 50, pp. 175.

13. Griswold, G. B., 1977, "Site Selection and Evaluation, Los Medanos, New Mexico", Sandia Laboratories Report.
14. Hafner, W., 1951, "Stress Distributions and Faulting", Bull. Geol. Soc. Am., Vol. 62, p. 373-398.
15. Hardie, L. A., 1967, "The Gypsum-Anhydrite Equilibrium at One Atmosphere Pressure", The American Mineralogist, Vol. 52, p. 171-200.
16. Hayes, 1958, "Salt in the Ochoa Series, New Mexico and Texas", U. S. Geol. Survey, TEI-709.
17. Heard, H. C., Rubey, W. W., "Tectonic Implications of Gypsum Dehydration", Geol. Soc. Am., Bull., Vol. 77, pp. 741-760, 1966.
18. Hill, A. E., "The Transition Temperature of Gypsum to Anhydrite", Jour. Amer. Chem. Soc., Vol. 59, p. 2242-2244.
19. Hills, J. M., 1968, "Permian Basin Field Area, West Texas and Southeastern New Mexico", Geol. Soc. of Am. Spec., Paper 88, p. 17-27.
20. Jones, C. L., 1960, "Thickness, Character and Structure of Upper Permian Evaporites in Eddy County New Mexico", U. S. Geol. Surv., TEM-1033.
21. Jones, C. L.; 1972, "Permian basin potash deposits, southwestern United States", Geology of Saline Deposits, Proc. Hanover Symp., 1968, UNESCO.
22. King, P.B., 1942, "Permian of West Texas and Southeastern New Mexico", Am. Assoc. Petrol. Geol. Bull., Vol. 26.
23. Lambert, Steven J. and Jerry W. Mercer, 1977, "Hydrologic Investigations of the Los Medanos Area Southeastern New Mexico", Sandia Laboratories Report.
24. Lang, W. B., "Upper Permian Formation of Delaware Basin of Texas and New Mexico", Am. Assoc. Petrol. Geol. Bull., Vol. 19, No. 2, p. 262-270.
25. Macdonald, G. F., 1953, "Anhydrite-Gypsum Equilibrium Relations", Amer. Jour. Sci., Vol. 251, p. 884-898.
26. Maxwell, Wahi, and Dial, 1978, "The Thermochemical Response of WIPP Repositories", Report to Sandia Corporation.

27. Mercer, J. W. and Orr, B. R., 1978, "Geohydrology of the Proposed Waste Isolation Pilot Plant, Southeastern New Mexico", U. S. Geologic Survey report submitted to DOE (preliminary).
28. Murray, R. C., 1964, "Origin and Diagenesis of Gypsum and Anhydrite", Jour. of Sed. Petrology, Vol. 34, No. 3, p. 130.
29. Murray, R. C., 1960, "Origin of Porosity in Carbonate Rocks", Jour. Sed. Petrology, Vol. 30, No. 1, p. 59-84.
30. O'Neill, K., 1978, "The transient Three Dimensional Transport of Liquid and Heat in Fractured Porous Media", Princeton University Water Resources Program, p. 130.
31. Posnjak, E., 1938, "The System $\text{CaSO}_4\text{-H}_2\text{O}$ ", Am. Jour. Sci., Vol. 235-A, p. 247-272.
32. Powers, Lambert, Shaffer, Hill, Weart, (Editors), 1978; "Draft Site Characterization Report for the Waste Isolation Pilot Plant (WIPP), Southeastern New Mexico", Sandia Laboratories Report SAND78-1596.
33. Prucha, J. J., "Salt Deformation and Decollement in the Fire-tree Point Anticline of Central New York", Tectonophysics, Vol. 6, No. 4, p. 273-299, 1968.
34. Robertson, E. C., 1962, "Physical Properties of Evaporite Minerals", U. S. Geol. Surv. Report, TEI-821.
35. Shearman, D. J., 1971, "Review Marine Evaporites: The Calcium Sulfate Facies", Am. Soc. Petrol. Geol. Seminar, University of Calgary, Canada, pp. 65. N/P
36. Snider, H. I., 1966, Stratigraphy and Associated Tectonics of the Upper Permian Castile - Salado - Rustler Evaporites Complex, Delaware Basin, West Texas and Southeastern New Mexico, Ph.D. dissertation, University of New Mexico.
37. Sterns, D. W., 1967, "Certain Aspects of Fracture in Naturally Deformed Rocks", N.S.F. Rock Mechanics Seminar, (Editor) Riecker, R. E., Vol. I, p. 97-118, 1967.
38. Vine, J. D., 1960, "Recent Domal Structures in Southeastern New Mexico", Am. Assoc. Petrol. Geol. Bull., Vol. 44, No. 12, p. 1903-1911.
39. Weber, R. H., 1965, "Gypsum and Anhydrite", in Mineral and Water Resources of New Mexico", New Mexico State Bur. Mines Mineral Resources Bull. 87, p. 324-332.

DISTRIBUTION

B. J. Thorne
Civil Systems, Inc.
2201 San Pedro, NE
Building 3, Suite 214
Albuquerque, NM 87110

Sandia Internal:

4510 W. D. Weart
4511 D. W. Powers
4511 L. J. Barrows
4511 D. D. Gonzalez
4512 T. O. Hunter (10)
4512 R. V. Matalucci
4537 D. R. Fortney
5521 R. D. Krieg
5531 S. W. Key
5532 B. M. Butcher
5532 L. S. Costin