Dr. 1635-1

SANDIA REPORT

SAND83—0166 • Unlimited Release • UC—70

Printed June 1983

I-10521

Petrographic Study of Evaporite Deformation Near the Waste Isolation Pilot Plant (WIPP)

SAND--83-0166

DE83 014796

David J. Borns

Prepared by
Sandia National Laboratories
Albuquerque, New Mexico 87185 and Livermore, California 94550
for the United States Department of Energy
under Contract DE-AC04-76DP00789

MASTER

DISTRIBUTION OF THIS DOCUMENT IS UNLIMITED

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: A04
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

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.

Petrographic Study of Evaporite Deformation Near the Waste Isolation Pilot Plant (WIPP)

David J. Borns
Earth Sciences Division 9731
Sandia National Laboratories
Albuquerque, NM 87185

Abstract

The Delaware Basin of southeastern New Mexico contains ~1000 m of layered evaporites. Areas in the northern Delaware Basin, bordering the Capitan reef, have anomalous seismic reflection characteristics, such as loss in reflector continuity. Core from holes within this zone exhibits complex mesoscopic folds and extension structures. On a larger scale, anticlines and synclines are indicated by structure contours based on boreholes. The deformation is probably gravity-driven. Such a process is initiated by basin tilting during either a Mesozoic or Cenozoic period of uplift. The age of deformation is equivocal, ranging from Permian to Recent.

Small-scale structures suggest that deformation was episodic with an early, syndepositional stage of isoclinal folding. Later, open-to-tight asymmetric folding is more penetrative and exhibits a sense of asymmetry opposite to that of the earlier isoclinal folding. The younger folds are associated with development of zonal crenulation cleavage and microboudinage of more competent carbonate layers. At the same time, halite beds developed dimensional fabrics and convolute folds in anhydrite stringers. Late-stage, near-vertical fractures formed in competent anhydrite layers. Microscopic textures exhibit rotated anhydrite porphyroblasts, stress shadow growth, and microboudinage. Except during late-stage deformation, anhydrite and halite recrystallized synkinematically. Drastic strength reduction in anhydrites through dynamic recrystallization occurs experimentally near 200°C. However, evaporites of the WIPP site never experienced temperatures >40°C. Microscopic fabrics and P, T history of the evaporites suggest that pressure solution was the active mechanism during deformation of evaporites at the WIPP site. This conclusion stresses the importance of fluid in facilitating deformation in low-temperature evaporite sequences. The formation of pressurized brine pockets is empirically associated with deformation. The development of high-angle fractures in the uppermost anhydrite unit of the Castile in response to folding provides the reservoir for the brines. Brine fluids may have emanated from deforming halite and anhydrite units through pressure-solution-induced reduction of porosity.

Contents

1. Introduction	7
1.1 Previous Work	12
1.2 Method of Study	12
2. Mesoscopic Structures	15
2.1 Syn- to Closely Postdepositional Structures	15
2.2 Shape Fabrics	17
2.3 Open-to-Tight Asymmetric Folding	17
2.4 Convolute Folds of Anhydrite Stringers in Halites	17
2.5 Relict Primary Halites	24
2.6 Contacts Between Halite and Anhydrite Units of the Castile	24
2.7 Shear Zones Within Halites	24
2.8 Boudinage	24
2.9 Veins and Fractures	24
2.10 Oriented-Core Studies	29
2.11 Discussion: Mesoscopic Structures	29
2.11.1 Areal and Depth Distribution of Deformation	29
2.11.2 Deformation Stages	36
2.11.3 Fluids Associated with Deformation	36
2.11.4 Effects of Deformation	36
2.11.5 Directions of Movement	36
3. Microscopic Structures	37
3.1 Deformation Mechanisms	37
3.2 Microscopic Textures: Description	38
3.2.1 Anhydrite	38
3.2.2 Halite	38
3.2.3 Carbonate	38
3.3 Discussion: Microstructure	43
4. Conclusions	45
4.1 Deformation Stages and Fold Styles	45
4.2 Strength Reduction by Intergranular Fluids	45
4.3 Interrelationship of Fluids and Deformation	46
4.4 The Bearing of Observed Meso- and Microscopic Textures on Hypothesis of Origin for Deformation	47
4.4.1 Dissolution	47
4.4.2 Gypsum Dehydration	48
4.4.3 Halokinesis	48
4.4.4 Gravity Sliding	49
4.5 Age of Deformation	50
4.6 Summary of Conclusions	50
References	50

Figures

1 Location of the Delaware Basin and WIPP Site	9
2 Basin Stratigraphy	11
3 Location of WIPP Site and Areal Distribution of Disturbed Zone	12
4 Drillhole Locations	13
5 Secondary and Primary Anhydrite Growth Structures	16

Figures (cont)

6	Second-Order Fold Symmetries and Asymmetries	17
7	Early-Stage (Syndepositional) Structures in Castile Anhydrite State Line Outcrop	18
8	Deformation Styles in Laminated Carbonate Anhydrite Units in the Castile (WIPP 13, 3727 ft)	19
9	Deformation Styles in Laminated Carbonate Anhydrite Units in the Castile (WIPP 13, 3227 ft)	19
10	Deformation Styles in Laminated Carbonate Anhydrite Units in the Castile (WIPP 13, 3729 ft)	20
11	Deformation Styles in Laminated Carbonate Anhydrite Units in the Castile (WIPP 13, 3733 ft)	20
12	Tectonic Deformation Structures in Castile Anhydrite State Line Outcrop	21
13	Deformation Structures From Castile Anhydrites and Halites	22
14	Convolute Folds of Anhydrite Stringers in Halite Units of the Castile	23
15	Vein Structures in the Castile and Infra Cowden Anhydrites	25
16	Vein Structures in Anhydrites From ERDA 6	26
17	Boudinage Structures	27
18	Boudinage Structures in Laminated Anhydrite-Carbonate Units in the Castile	28
19	Folded Anhydrite Stringer in Halite Units of Castile, Where Distinctive Markers Can Be Traced and Which Define Fold Closure	30
20	Linear and Planar Structures, WIPP 12	31
21	Linear and Planar Structures, DOE 1	31
22	Hole-to-Hole Deformation Features, ERDA 6 and AEC 7	32
23	Hole-to-Hole Deformation Features, AEC 8 and ERDA 10	33
24	Hole-to-Hole Deformation Features, WIPP 11 and WIPP 12	34
25	Hole-to-Hole Deformation Features, WIPP 13	35
26	Relict Anhydrites (AR)	40
27	Anhydrite Textures	41
28	Anhydrite Textures	42
29	Volume of Castile Rock and Fluid Involved in the WIPP 12 Anticline	47
30	Arrangement of Fold Hinges About a Growing Dome, After Balk (1949)	49
31	Folding of an S-Surface, After Wilson	49

Tables

1	Stages of Deformation	15
2	Hole-to-Hole Microscopic Structures	39

Petrographic Study of Evaporite Deformation Near the Waste Isolation Pilot Plant (WIPP)

1. Introduction

The Delaware Basin of southeastern New Mexico contains layered evaporites ~1000 m thick (see Figure 1). An area in the northern part of the basin has been selected as the site for the Waste Isolation Pilot Plant, herein called WIPP. Rock units of interest in this report are largely Ochoan. The oldest unit is the Castile Formation, which primarily consists of three anhydrite units separated by two halite units (see Figure 2). The second oldest is the Salado Formation, which consists of halite, anhydritic, and/or polyhalitic halite. The youngest unit is the Rustler Formation, which contains siltstones, anhydrites, dolomitic siltstones, dolomites and halite.

Evaporite beds are deformed within portions of the Delaware Basin along its margins and in some areas in the middle of the basin (see Figure 3). The term "Disturbed Zone" (DZ) has been used to identify areas with deformation features in the northern part of the WIPP site. This DZ is now delineated based on the evidence of structure exhibited in boreholes and by seismic reflection data (Borns et al, 1983).

The origin of deformation at the WIPP site remains controversial. Kirkland and Anderson (1970) described the occurrence of microfolded anhydrite-calcite laminae in the Castile Formation in Eddy County, New Mexico, and Culberson County, Texas. They related this folding to compressional deformation that accompanied regional tectonism rather than to syndepositional processes. Starting in the mid-1970s, an extensive drilling program was started in the northern Delaware Basin to assist site selection and characterization for a nuclear-waste test facility. The first of these drillholes, ERDA 6, encountered a large-scale anticline and mesoscopic folding, in part

complex (Anderson and Powers, 1978; Jones, 1981). Anderson and Powers correlated this deformation to the microfolding observed by Kirkland and Anderson (1970). Subsequent drillholes (WIPP 10, 11, 12, and 13) in the northern portions of the site revealed deformation styles similar to those of ERDA 6.

The origin of these deformation features has been the source of considerable debate. The envisaged possible mechanisms for deformation are as follows:

1. Dissolution (Anderson and Kirkland, 1980)
2. Gypsum dehydration (Kirkland and Anderson, 1970).
3. Halokinesis (Trusheim, 1960; Borns et al, 1983)
4. Gravity sliding (Kirkland and Anderson, 1970; Borns et al, 1983)

No real consensus has emerged from the various viewpoints. Currently, more detailed geochemical and petrological data are becoming available that may provide the answer.

Another crucial question is the timing of deformation. Several workers (Kirkland and Anderson, 1970; Anderson and Powers, 1978; Barrows, pers. comm., 1982) have inferred that the deformation has occurred during regional tilting over the last 30 my or that the deformation is ongoing because of deep dissolution or gravity inversion (halokinesis or gravity slide). On the other hand, C. L. Jones (1981) has suggested that deformation was limited to the Permian or Triassic, since Pliocene deposits such as the Ogallala are undeformed above DZ structures. Crucial to this argument is the question whether deformation in a layered evaporite sequence is always transmitted to overlying units.

Figure 2. Basin Stratigraphy

Figure 3. Location of WIPP Site and Areal Distribution of Disturbed Zone

The microscopic textures and petrofabrics of rocks from the DZ have heretofore received little attention. Callender and Ingwell (1978) reported on the structural petrology of experimentally deformed halite from the WIPP site. However, the experimental conditions extant probably cannot be extrapolated to the conditions during site deformation primarily because of the presence of natural fluids during deformation at the site. The study of petrofabrics generates insights into the mechanisms of deformation, relative movements, and possibly (but indirectly) the age.

1.1 Previous Work

Kirkland and Anderson (1970) reported the occurrence of microfolded evaporites from the Castile Formation. Their work was based on drill core, mine exposures, and limited outcrops in Eddy County, New Mexico, and Culberson and Winkler Counties, Texas. The microfolding was also apparently second-order to some larger scale warping (wavelength ~ 5 m). Kirkland and Anderson concluded that folding was tectonic in origin rather than syndepositional.

ERDA 6 was an early exploratory test hole in the Delaware Basin to evaluate a candidate site for a

nuclear-waste test facility (Jones, 1981). ERDA 6, however, revealed large-scale upward displacement in the Castile accompanied by thickening of Halite I (Anderson and Powers, 1978; Jones, 1981). Along with the large-scale deformation, complex meso- and microscopic folding similar to textures described earlier by Kirkland and Anderson (1970) was apparent in the drill core.

Seismic reflection data in the northern Delaware Basin are characterized by anomalous areas where reflector continuity is lost (Borns et al, 1983). Structure contours in this area indicate a terrain of anticlines and synclines (Snyder, 1982). Drill cores (WIPP 11, 12, and 13) from the anomalous areas also exhibit complex folding and extension structures similar to those encountered in ERDA 6. For the large part, the structures are restricted to the evaporite sequence without involvement of either the underlying Bell Canyon Formation or the overlying Dewey Lake Redbeds.

1.2 Method of Study

Core, which is housed in the WIPP Core Library, Carlsbad, New Mexico, was the source of samples used in this study. Oriented core was obtained from WIPP 12 and DOE 1. Samples were examined and described from drillholes ERDA 6, AEC 8, WIPP 11, 12, 13, and DOE 1 (see Figure 4). Core photographs, which are stored in the WIPP Central File from these holes and from ERDA 10, were also used in the reconnaissance of deformation structures. During mesoscopic study, intervals of interest were selected for microscopic study. These samples were slabbbed into half-core barrels and moved to Albuquerque. Portions were cut and trimmed down to thin section size. These chips were impregnated with epoxy and mounted. Halite thin sections were cut with a Buehler wafer saw to reduce deformation caused by the sectioning process. Machine-ground specimens were finished by hand grinding. Microscopic description employed standard procedures. Petrofabric orientations were determined with a Leitz 5-axes universal stage following the methods of Emmons (1943) and Turner and Weiss (1963).

Figure 4. Drillhole Locations

2. Mesoscopic Structures

Deformed evaporites display structures equivalent to metamorphic fabrics that have developed in silicate rocks (Balk, 1949 and 1953). Because of this similarity, evaporites have been used as field and experimental analogs for crustal deformation of silicate rocks. Hence, many techniques used in unraveling complex structural terrains apply to deformed evaporites, especially layered sequences such as in the Delaware Basin. The first step here is to characterize the styles of deformation. Such styles can be grouped together and used to fingerprint different stages of deformation.

These styles and related structures assist the structural geologist in four basic ways (Wilson, 1982): the visualization of larger scale structures; the indication of directions and sense of local movements; the indication of stress distribution; the placement within a time sequence of the different stages of deformation.

Table 1 shows the arrangement of deformation styles and stages in the northern Delaware Basin as inferred from the mesoscopic structures. In the following pages, each style and association is described in detail.

2.1 Syn- to Closely Postdepositional Structures

In Anhydrite I from both WIPP 13 and DOE 1, anhydrite laths grow upward from a flat surface and contort the overlying laminae (see Figure 5b and 5c). Elsewhere, isoclinal folds are exhibited in 1-cm layers. Such folds are isolated to the layer and commonly show an opposite sense of asymmetry relative to the more penetrative open-to-tight crenulation folds. Fold asymmetry and vergence are inferred senses of direction derived from this geometric relationship between a structure and the larger structure that contains it (Bell, 1981; Wilson, 1982, see Figure 6). In laminated anhydrite and carbonate units, some laminae have corrugated bottoms while their upper surface is flat. Dipping laminae (10° to 15°) are truncated along an unconformity at 1744 ft, ERDA 6. The restriction of these features to individual layers and relative incompetency of anhydrite-carbonate laminae at the time of deformation suggest that these structures formed locally during deposition or closely after deposition but before consolidation.

Table 1. Stages of Deformation (Decreasing Relative Age Downward)

Stage	Process (What Occurred)*		
Syn depositional to Closely Postdepositional	Isoclinal Folding 1. Isolated to single layers 2. Opposite sense of asymmetry relative to later stage folds More open Polyharmonic Crenulations (State Line Outcrop)		
Tectonic	Laminated* Anhydrites	Halites	Infra-Cowden Cowden Anhydrite
Younger ↓	a. Shape fabric b. Open-to-tight asymmetric folding Microboudinage Crenulation cleavage c. Near-vertical fractures	a. Shape fabric b. Convolute Fold of anhydrite stringers c. Shear zones	b. Crenulation and zonal crenulation cleavage (stylolites)
Youngest Stage			

*Syn depositional processes are independent of rock-type compared to tectonic processes, in which different processes occur in the individual rock-types during the same stage.

a. Deformed Coarse Laminated Anhydrite, ERDA 6, 2021 ft, Crenulation Microfolds, Incipient Crenulation Microfolds, Incipient Crenulation Cleavage

b. Relict Anhydrite (a) Needles (Syn- to Postdepositional) Growing Upward Into Anhydrite-Carbonate Laminae, WIPP 13, 3864 ft

c. Detail of b, Anhydrite Needles (a)

Figure 5. Secondary and Primary Anhydrite Growth Structures

Figure 6. Second-Order Fold Symmetries and Asymmetries (symmetric M fold, asymmetric S and Z folds that have opposite senses of asymmetry)

At the State Line outcrop (Kirkland and Anderson, 1970), chaotic or disrupted layers up to 10 cm thick, are found sandwiched between undeformed laminae (see Figure 7). Some folds are abruptly truncated adjacent to their hinges. Another observation is of juxtaposed antiforms and synforms that share the same axial plane (Kirkland and Anderson, 1970, Figure 3b). Each layer needs to act independently of the over- and underlying units to accommodate the deformation. Also, the interlayer boundary must be a sliding surface. This independent behavior and the non-parallelism of folds from laminae to laminae suggest that these structures developed before consolidation. Similar folding has formed in the Zechstein salt deposits during redeposition (Schlager and Bolz, 1977). The deformation at the State Line outcrop is not to be taken as entirely syndepositional, for there exists a sizable component of microfolding that is penetrative and tectonic in origin (see Figure 7).

2.2 Shape Fabrics

A shape or dimensional fabric is defined as the tendency towards parallelism of one or more of the morphological axes as defined by inequidimensional units such as elongate, flaky, or prismatic crystals (Spry, 1969, p 207). In recrystallized halites, especially Halite II in the DZ, a foliation is defined by the planar arrangement of halite elongation axes (aspect ratios: 1:2). The foliation is parallel to the axial plane of folds exhibited by anhydrite stringers in the halites. The elongation of halite grains is commonly parallel and defines a lineation. Such fabrics are not mesoscopically as obvious in anhydrite laminae. Microscopically

(see Sec 3), anhydrites exhibit shape fabrics similar to those of halites.

2.3 Open-to-Tight Asymmetric Folding

As high in the section as the Cowden and Infra Cowden, a crenulation of the bedding surface has developed (see Figure 5a). Inclined to the bedding surface and parallel to the axial plane of the crenulation, a crenulation cleavage (stylolitic) is observed. Within the Castile proper, microfolding has a greater amplitude than in the beds above it (see Figures 8-13). Such microfolds are commonly asymmetric with a consistent sense of vergence at the core barrel scale. These asymmetric folds are most highly developed in the finely laminated (varved) anhydrite-carbonate units. When the core is broken along a foliation surface in a microfolded unit, the hinge lines of the folds mark a distinct lineation. Microscopic textures suggest that this fold stage developed after the initial shape fabric (see Sec 3).

The folding of anhydrite-carbonate laminae is not homogeneous. Layers, adjacent to microfolded layers, may be relatively undeformed. In larger amplitude microfolds, the laminae are discontinuous in the hinge zone, which imparts a blocky appearance to the fold. Halite and/or anhydrite veins commonly occur in the hinge zone parallel to the axial plane of the fold.

2.4 Convolute Folds of Anhydrite Stringers in Halites

Throughout Halites II and I, anhydrite stringers 0.5 to 1.0 cm wide occur. Such stringers can exhibit an asymmetric color banding with a basal red zone that is caused by the presence of carbonate. Idioblastic halite porphyroblasts are also common to the stringers. Convolute or ptygmatic folds of these stringers have developed (see Figures 13d and 14). Folds are tight to isoclinal with the axial plane parallel to the foliation imparted by the halite shape fabric. The fold hinges are at high angles to the shape fabric lineation of the halite. The asymmetric band coloration permits layers to be connected and, hence, helps to delineate larger scale folds (see Figure 14). Axial planes are predominantly subhorizontal. Some 20° inclinations are recorded, e.g., ERDA 6. The ptygmatic folding occurs in halites from relatively undisturbed areas encountered in holes such as AEC 7, 8, and DOE 1. Commonly, in the highly deformed regions, one limb of the fold has been displaced, and stringers developed pull-apart structures. In contrast, fold stringers in less deformed regions are largely continuous.

1 m
a. Box Fold With Disrupted Marker Layer

10 cm
b. Chaotic Layer Confined in Horizontal Layers

1 m
c. Blocky Fold Hinge, Sharp Truncations, Disrupted Marker Layers

Figure 7. Early-Stage (Syndepositional) Structures in Castile Anhydrite State Line Outcrop

Figure 8. Deformation Styles in Laminated Carbonate Anhydrite Units in the Castile (WIPP 13, 3727 ft; width of slab 4 in.)

Figure 9. Deformation Styles in Laminated Carbonate Anhydrite Units in the Castile (WIPP 13, 3227 ft; width of slab 4 in.)

Figure 10. Deformation Styles in Laminated Carbonate Anhydrite Units in the Castile (WIPP 13, 3729 ft; width of slab 4 in.)

Figure 11. Deformation Styles in Laminated Carbonate Anhydrite Units in the Castile (WIPP 13, 3733 ft; width of slab 4 in.)

a. Open Fold With Compression (Microfolds) and Extension (Boudinage) Exhibited on Opposite Sides of Neutral Surface

b. Asymmetric Microfolds and Crenulation Cleavage

Figure 12. Tectonic Deformation Structures in Castile Anhydrite State Line Outcrop

a. Complex Folding, Disrupted Layers, Anhydrite Recrystallization Patches and Stress Shadow Growth, ERDA 6, 2573 ft

b. Tight Fold of Anhydrite-Carbonate Laminae, ERDA 6, 2574 ft

c. Boudinage of Carbonate Laminae With (a) Anhydrite Stress Shadow Growth, ERDA 6, 2699 ft

d. Convolute Isoclinal Folds of Anhydrite Stringers in Halite, 2775 ft; (a) shows anhydrite stringer

Figure 13. Deformation Structures From Castile Anhydrites and Halites (bars are 1 cm)

WIPP 11

2831

2774

AEC 8

3734

Figure 14. Convolute Folds of Anhydrite Stringers in Halite Units of the Castile

2.5 Relict Primary Halites

Some portions of the halite units in the Castile are relatively undeformed, e.g., Halite I in WIPP 12 and DOE 1. Such intervals are characterized by alternating layers of grey and clear halite, 5 to 10 cm in thickness. The alternation appears cyclic. Such layers are generally near-horizontal. Grain size is large (about 1 cm in diameter), and the core intercepts some single halite crystals greater in diameter than the core dimensions. Grain boundaries are relatively unstrained relative to boundaries in more deformed halites. Because of this looseness, the core is easily granulated. Anhydrite commonly forms an intergranular lacework in the cyclic halites.

2.6 Contacts Between Halite and Anhydrite Units of the Castile

Cores from holes bored in relatively undeformed and moderately deformed halites (AEC 7, 8, WIPP 12, and DOE 1), show that contacts between superimposed lithologic units are conformable. In contrast, other contacts observed in the Castile of ERDA 6 and WIPP 13 commonly crosscut the layered fabric of the anhydrites. Halite veins in the anhydrites occur adjacent to contacts, regardless of whether the contacts are conformable. These veins form either as infillings of vertical fractures (see Figure 15) or as irregular embayments into anhydrite (see Figure 16). In the embayments, halite replacement of anhydrite is commonly initiated along foliation planes. Larger halite patches contain clay residues that are planar and mark relict foliation surfaces inherited from the laminated anhydrite (see Figure 16c). Deformation of halite units is more distinct adjacent to contacts with anhydrite units. Near such contacts, ptigmatic folding of anhydrite stringers occurs, and the foliated shape fabric of halite grains has commonly developed.

2.7 Shear Zones Within Halites

Discrete subhorizontal zones, ~10 cm wide and subhorizontal, occur within both foliated halites and unrecrystallized primary halites, e.g., 3519 ft, 3645 ft (WIPP 12). These zones are characterized by a finer grain size than its host halite. When the host is a primary halite, the grain boundaries of the recrystallized shear zone are markedly tighter than those of the host. The shape fabric and boundaries of the shear

zones can crosscut the bedding of the primary halite or the shape fabric of foliated halites outside the shear zone.

2.8 Boudinage

A boudinage structure consists of a segmented rock layer or vein of one type surrounded by a rock of a different type (Stromgard, 1973). The shape of boudins may be either rectangular, rhomboidal, or barrel-like. Between adjacent boudins, there generally occurs a pressure (stress) shadow. Such pressure shadows are either a *secretionary* type (filling of opening fracture) or replacement type (replacement of matrix).

Boudin structures are observed commonly in laminated anhydrite-carbonate units and in anhydrite stringers within halite units (see Figures 10, 11, 17, 18). Such structures were called “snap apart” by Anderson and Powers (1978). Boudins in the laminated anhydrite-carbonate units exist at several scales; a sequence of boudinaged laminae (1 to 5 mm thick) are in turn boudinaged as a stack (5 cm thick; see Figure 8). Small-scale boudins are rectangular, with the carbonate bands the segmented competent rock type. Larger scaled boudins of multiple layers exhibit necking and are barrel-shaped. Secretionary-type pressure (stress) shadows have formed between segmented carbonate laminae. Anhydrite in-fills these shadows; halite may occur in larger scale shadow zones. Necking, if it occurs, is observed in the shadow zone or in the matrix (see Figure 16). Boudinage of anhydrite stringers in halite units is of the rectangular type.

2.9 Veins and Fractures

Veins and associated fractures developed in the anhydrites and carbonates through the main stage of deformation and into the waning stages. An irregular-to-planar vein network developed through the interconnection of stress shadows in pull-aparts (see Figures 8-11). Such veins are in-filled by anhydrite and, to a lesser degree, halite. Halite veins occur crosscutting or along the foliation of laminated anhydrite (see Figures 15 and 16). In such veins, the halite has replaced portions of the laminated anhydrite, but a clay-rich residue remains in the halite and records the foliation of the laminated anhydrite that was replaced. These halite veins are also found as en echelon structure.

ERDA 6

2076

a. Near-Vertical Vein of Halite Extending Into Massive (Cross-Hatched) and Layer Anhydrite From Massive Halite at Contact

2168

b. En Echelon Halite Veins (Cross-Hatched) in Laminated Anhydrite

WIPP 13

3523

c. Crosscutting and Layer-Parallel Halite Veins (Cross-Hatched) in Laminated Anhydrite

WIPP 12

3062

d. Halite-Filled Fractures at HII-AIII Contact

Figure 15. Vein Structures in the Castile and Infra Cowden Anhydrites

ERDA 6

2733

a. Halite Vein (Solid) Embaying and Replacing Laminated Anhydrite

2733

b. Halite (Solid) Replacing Anhydrite Along Foliation Plane

2732

c. Halite (Solid) Replacing Anhydrite, Clay Residues (Stippled) Records Foliation (Ruled) Inherited From Replaced Anhydrite

Figure 16. Vein Structures in Anhydrites From ERDA 6

WIPP 11

3505

a. Boudinage of Carbonate Layer in Laminated Anhydrite, Stress Shadow (Black) Growth is Anhydrite, Necking of Stress Shadow and Matrix

WIPP 12

3055

b. Boudinage of Anhydrite Stringer in Halite

3054

c. Boudinage of Anhydrite Stringer in Halite

WIPP 13

3728

d. Comminuted Carbonate Layer in Anhydrite Matrix, Late-Stage Fractures Emanate From Zone Into Bounding Anhydrite

Figure 17. Boudinage Structures

a. & b. Barrel-Shaped Boudins in Carbonate Layers, Anhydrite and Halite Stress shadows, ERDA 6, 2561 ft

c. Comminuted and Rectangular Boudins of Carbonate Layer, Late-Stage High-Angle Fractures, WIPP 13, 3593 ft

d. Comminuted Carbonate Layer ERDA 6, 2021 ft

Figure 18. Boudinage Structures in Laminated Anhydrite-Carbonate Units in the Castile (bars are 1 cm)

Near-vertical fractures are observed crossing laminated anhydrites. Such fractures are of interest since they are associated with the brine occurrence at WIPP 12. In the core, these fractures are seldom greater than 2 mm wide, although 1-cm-dia gypsum crystals were found in a wide vug associated with a fracture at 2944.3 ft from WIPP 12. Fractures may be open or in-filled by halite, anhydrite, and/or gypsum. Several fracture sets of different orientation have formed and are observed to intersect, e.g., WIPP 12, 3051 ft. Near the contact with Halite II at WIPP 12, the vertical fractures widen to 1 cm and are in-filled with halite (see Figure 19).

These high-angle fractures crosscut deformation structures such as anhydrite foliation and microfolds. Hence, such fractures are a late-stage manifestation in deformed anhydrites. These fractures are related to the brine reservoirs encountered in the DZ. The orientation of the fractures is an important consideration in characterizing the brine reservoirs.

In discussing the orientation of the fractures, Popielak et al (1982) have chosen to use teleseis viewer data. Their choice was based on the orientation of fractures, which the teleseis viewer shows as parallel and less random than the orientation pattern created with the oriented-core data. This conclusion was based on the assumption that the fractures should be parallel; however, in the domal structure such as at WIPP 12, radial and orthogonal fracture sets may develop. Some fractures observed in the WIPP 12 core, e.g., 3051.5, do intersect at a high angle. In this report, we have chosen to use the oriented-core data. As seen in Figure 20, a consistent orientation of lineations and poles-to-S-surfaces is displayed through the use of data from different oriented-core, which in turn implies a core-to-core consistency in orientation. The reader must be wary that the different interpretations of the orientation data cannot be reconciled at this time.

2.10 Oriented-Core Studies

Oriented core was obtained from WIPP 12 and DOE 1. For graphical analyses, limitations are imposed on the interpretation by the low number of readings (≤ 50) from each hole. Also, a discrepancy exists between teleseis viewer orientations and the oriented core. However, the consistency of fabric orientation in the three oriented barrels from WIPP 12 suggests the internal reliability of these data.

Graphical analyses of WIPP 12 orientation data indicates that fractures are near-vertical, but do not

have a preferred orientation (see Figure 20). S-poles delineate a partial girdle that trends NE-SW. This girdle would indicate the existence of a fold axis, running NW-SE. Such an axis corresponds to the cluster of lineations in the NE. This cluster is slightly NE of the expected axes; hence, there may be a rotation of this cluster to the NE into a movement direction.

The halites from DOE 1 are weakly deformed. S-poles produce a diffuse pattern with no suggestion of an oriented fabric (see Figure 21). Also, no apparent concentration of lineations exists.

2.11 Discussion: Mesoscopic Structures

2.11.1 Areal and Depth Distribution of Deformation

Figures 22, 23, 24, and 25 diagrammatically display the distribution of deformation in the holes studied. Inclined bedding and crenulation folds are observed as high as the lower Salado in ERDA 6 and WIPP 13. Such deformation becomes more distinct in the Infra Cowden. Even in relatively undisturbed areas encountered in holes (e.g., AEC 7, 8, ERDA 10, DOE 1), folded anhydrite stringers in Halite I or II suggest some salt movement. Within a single hole or from hole to hole, the intensity of deformation between Halite I and II varies. Generally, Halite II exhibits more recrystallization and folding than does Halite I. Exceptions are the relatively undisturbed areas encountered in AEC 8, where the folded anhydrite stringers are found in Halite I. In highly deformed regions, cyclic primary halite is preserved in Halite I. Still, shear and folded zones locally cross these primary halites.

The correlation of thickening or thinning of Halite I or II to the intensity of deformation is not defined. In part, this is due to incomplete sampling of the units in question, such as at ERDA 6. For example, in WIPP 11, Halite II is apparently thickened and exhibits some of the most penetrative deformation observed. However, at WIPP 12, Halite I is apparently thickened but preserves primary halite bedding, although there are discrete zones of deformation present. Thinned halite units in WIPP 13 show extensive recrystallization. Hence, deformation structures are related to salt movement, but the actual connection is as yet unclear.

WIPP 12

3198

3105

3107

AEC 8

3726

Figure 19. Folded Anhydrite Stringer in Halite Units of Castile, Where Distinctive Markers Can Be Traced and Which Define Fold Closure

Figure 20. Linear and Planar Structures, WIPP 12 (• Normal to S-Surface; o Normal to Fracture Surface; * Fold Hinge Lineation)

Figure 21. Linear and Planar Structures, DOE 1

Figure 22. Hole-to-Hole Deformation Features, ERDA 6 and AEC 7 (depths in ft below ground level; for location of holes, see Figure 4)

Figure 23. Hole-to-Hole Deformation Features, AEC 8 and ERDA 10 (depths in ft below ground level; for location of holes, see Figure 4)

Figure 24. Hole-to-Hole Deformation Features, WIPP 11 and WIPP 12 (depths in ft below ground level; for location of holes, see Figure 4)

WIPP 13

Figure 25. Hole-to-Hole Deformation Features, WIPP 13 (depths in ft below ground level; for location of hole, see Figure 4)

2.11.2 Deformation Stages

In the northern Delaware Basin, deformation has been episodic and progressive. Early-stage syndepositional folding is seen in layer-bound isoclinal folding and crenulations. Such features may have developed through soft-sediment deformation on inclined surfaces and redeposition (Parea and Ricci-Lucchi, 1972). Progressive tectonic deformation initiated with flattening of original grains, which formed foliated-shape fabrics in anhydrites and halites. This fabric was folded when asymmetric open folds developed along with boudinage of competent carbonate laminae. The last stages of deformation were marked by the formation of near-vertical fractures in competent anhydrite-carbonate laminae.

2.11.3 Fluids Associated With Deformation

Vein systems developed syn- to postkinematically. Stress shadows and halite replacement zones in anhydrites suggest a process of solution and redeposition. The presence of fluid during deformation is inferred from such observations. This fluid is active in the sense that it migrates and is involved in the mass transfer during deformation.

2.11.4 Effects of Deformation

The extent of deformation is not homogeneous with hole-to-hole correlation nor within a single hole.

Cyclic primary halites are preserved in Halite I of deformed regions, e.g., WIPP 11 and 12. Strain may be accommodated along discrete shear zones in halites. With deformation confined to these zones, delicate primary structures such as hopper crystals are preserved. Deformation features are more extensive in Anhydrite II and Halite II than in other units of the Castile. Weakly deformed Anhydrite III lamina are characterized by inclined bedding, veins, and near-vertical fractures.

Halites, which recrystallized during deformation, appear to have more sutured (tighter) grain boundaries and to have experienced a reduction in grain size. Also, the intergranular anhydrite lacework, present in undeformed halite, is absent. Such observations suggest reorganization of the grain boundaries and, in turn, some destruction of porosity during deformation.

2.11.5 Directions of Movement

The minimal amount of reliable orientation data from holes in the DZ does not permit a determination of directions of elongation and shortening (see Sec 2.9). The near-horizontal orientation of axial planes from convolute and isoclinal folds in halite suggests a strong horizontal component of flow in the halite units. But the axes of folds show minimal rotation into a possible elongation direction, as inferred from the shape fabric.

3. Microscopic Structures

As with mesoscopic fabrics, microfabrics of evaporites can be indistinguishable from metamorphic tectonites (Schwerdtner, 1970). Anhydrite and halite deformation mechanisms have been studied in detail (Carter and Heard, 1970; Guillopé and Poirier, 1979; Heard, 1972; Muller and Briegel, 1978; Muller et al, 1981; Wawersik and Hannum, 1980). In part because of the difficulty in thin-sectioning, naturally deformed halites seldom have their microscopic textures described. Callender and Ingwell (1978) have studied microtextures from experimentally deformed halite. Anhydrites, on the other hand, have received more attention (Schwerdtner, 1970; Muller et al, 1981).

Again, the similarity of evaporite tectonites and metamorphic tectonites in silicate rocks suggests that standard textural analysis as developed for silicates is applicable to evaporites.

3.1 Deformation Mechanisms

The following deformation mechanisms may be active on the microscopic scale in geologic materials.

- Cataclasis (fracturing, frictional sliding)
- Dislocation mechanisms (dislocation glide, dislocation creep, steady-state flow processes)
- Shape changes of individual grains by grain boundary or through-the-grain (volume) diffusion, with a component of grain boundary sliding (Coble creep, Nabarro-Herring creep, superplastic flow)
- Pressure solution that is geometrically equivalent to the diffusion process above

The effectiveness of an individual mechanism is a function of several parameters: temperature (T); stress (deviatoric or differential, σ); strain rate ($\dot{\epsilon}$); viscosity (η); grain size; the presence or absence of an intergranular fluid. In experiments on the deformation of natural anhydrites, Muller et al (1981) found that at geologically reasonable strain rates, 10^{-10} to 10^{-14} s^{-1} , drastic strength reduction occurred at a threshold of 180°C to 200°C . Microscopically, samples deformed at lower temperatures exhibited undulatory extinction and, therefore, the deformation was some combination of cataclasis and ductile behavior. At higher temperatures twinning became the dominant mechanism. As deformation increased, lattice

reorientation occurred by shear twinning and twin boundary migration. Again, as temperature increased, dynamic recrystallization proceeded. Sutured grain boundaries were observed and suggest that grain boundary migration occurred. Generally, Muller et al (1981) found that intracrystalline glide and twinning were the major deformation mechanisms active during the steady-state flow.

The mechanical behavior of halite has been investigated for nearly 100 yr. A review of previous work up until 1970 appears in Carter and Heard (1970). Experimental studies have been done both on polycrystalline aggregates (Heard, 1972; Wawersik and Hannum, 1980) and single crystals (Carter and Heard, 1970). A common form of mechanical behavior in halite is translation gliding on $\{110\}$, $\{111\}$, and $\{001\}$; which of these glide systems is dominant depends on the crystal orientation relative to the principal stress axis, as well as temperature and stress. In experimentally deformed samples from ERDA 7 and 9, Callender and Ingwell (1978) observed intercrystalline rotation, followed by translation gliding.

In halites, strain rate and viscosity are related and dependent on the differential stress in the following ways: the strain rate is proportional to the differential stress raised to a power; viscosity is a function of differential stress (σ) and strain rate ($\dot{\epsilon}$), $\eta = \alpha \cdot \sigma / \dot{\epsilon}$ where α is a constant (Heard, 1972). The effect of rising temperature on the mechanical behavior of halite can be pronounced. At low T and P , Wawersik and Hannum (1980) noted that polycrystalline halite exhibited dilatancy and loss of load-bearing capacity. The development of microfractures governs this dilatancy. At low to intermediate temperatures (up to 300°C) and high stresses, the deformation of halite is controlled by slip systems, such as $\{110\}$, $\{1\bar{1}0\}$, which are dependent on crystal orientation (Heard, 1972). Guillopé and Poirier (1979) experimented with single crystals of pure and impure halite through a temperature range of 250°C to 790°C . Dynamic recrystallization occurred at the lower experimental temperatures and stresses through subgrain rotation without grain boundary migration. At higher temperatures and stresses, recrystallization resulted from migration of high-angle grain boundaries. Strain hardening, which is related to the interaction and piling up of dislocations at a barrier, occurs in association with the lower

temperature translation gliding. However, as temperature increases ($>300^{\circ}\text{C}$) and the strain rate decreases, dislocation climb and polygonization become dominant (Carter and Heard, 1970; Heard, 1972).

Unfortunately, experimental studies in anhydrites and halites have generally neglected the effects of an intergranular fluid on deformation. Means and Williams (1972) studied synthetic rocks that were created from clay and halite mixtures and deformed in brine or kerosene or dry. Brine and kerosene significantly weakened the rock compared to dry rocks. Hence, a fluid can play an important role in facilitating deformation either through pressure solution (see Sec 4) or through lubrication of the intergranular surface.

Hence, the deformation mechanisms of halite and anhydrite are well known from experimental studies. However, the effects of a saturated intergranular brine on rock strength are not always accounted for in the extrapolation of experimental conclusions to naturally deformed evaporites.

3.2 Microscopic Textures: Description

Samples from ERDA 6, WIPP 11, 12, and 13 were thin-sectioned and studied petrographically (Table 2). Petrographic reconnaissance of these sections reveals several stages of mineral growth associated with deformation (Table 2).

3.2.1 Anhydrite

Anhydrites from the lower Salado and Castile Formations within the DZ exhibit at least four stages of fabric development (oldest to youngest):

Stage I: Relict megacrysts (or porphyroblasts) show undulatory extinction. These grains are embayed by the younger anhydrite mosaic (see Stage II). The relict grains are commonly bent and display the development of shear bands. Such observations suggest a cataclastic component in the deformation of these grains (see Figure 26).

Stage II: A finer grained anhydrite mosaic forms the groundmass in deformed rocks. This mosaic commonly exhibits a dimensional or shape fabric. Mosaic grains do not show undulatory extinction and are idioblastic to hypidioblastic laths. The shape fabric marks a foliation plane and is often schistose (see Figure 27).

Stage III: Mosaic from Stage II is crenulated. Both polygonization of anhydrite grains about the crenulation folds, and formation of a second alignment of anhydrite laths (that defines a crenulation cleavage) indicate some recrystallization of the mosaic. At this time, anhydrite formed granoblastic or foliated stress shadows in carbonate pull-apart. Synkinematic porphyroblasts developed. These are idioblastic laths that rotated and included carbonate grains during growth (see Figures 27, 28).

Stage IV: Idioblastic to hypidioblastic anhydrite laths formed in veins with or without halite.

3.2.2 Halite

Natural halite deformation microtextures are hard to separate from structures developed during thin section preparation. However, in deformed foliated halites, 120° or triple junction grain boundaries are preserved in some samples. This texture suggests that textural equilibrium has been approached and that recrystallization has occurred syn- to postkinematically. Such postkinematic recrystallization is also inferred from adjacent anhydrite grains in deformed stringers within the halite units. These anhydrites are granoblastic laths in which polygonization, bending, and fabric realignment are absent.

3.2.3 Carbonate

Carbonate bands in laminated anhydrites are composed of rounded or subrounded grains (calcite, dolomite, or magnesite) that are relict chemical precipitates of major rock-forming minerals in the deformed Castile, such relict carbonates have escaped dynamic recrystallization. These grains are ~ 0.1 mm or less in diameter. The grains are speckled by opaque (organic) inclusion. At the laminae scale, the bands exhibit pull-apart and microboudinage structures. However, at the individual grain scale, adjacent grains come apart at the grain boundaries and accommodate strain without effects internal to the grain. Carbonate grains rarely exhibit twin lamellae or undulatory extinction. One notable exception is from a comminuted carbonate band, 3593, WIPP 13, where carbonate has recrystallized to form idioblastic grains with twin lamellae.

Table 2. Hole-to-Hole Microscopic Structures

Stratigraphic Unit	Whole and Depth in Feet			
	ERDA-6	WIPP-11	WIPP-12	WIPP-13
COWDEN & INFRA-COWDEN	1744: polyhalite at unconformity 2019: deformed halite and polyhalite grains 2022: crenulated feathery anhydrite			2802: folded nodular anhydrite; cataclastic portions which now show recrystallization; microcrenulation
ANHYDRITE III			3051: granoblastic anhydrite mosaic; no distinct boudinage; crenulated carbonate laminae 3051B: weak shape fabric in anhydrite; bent grains; shear bands	3119: stylolitic laminae; zonal crenulation cleavage; veins; granoblastic matrix
HALITE II		2775; 2832: folded anhydrite stringer fabric recrystallized	3055: folded anhydrite stringer; mostly recrystallized 3106: sutured grain boundaries; 120° triple junctions in halite mosaic; undulatory anhydrite porphyroblasts; schistose anhydrite matrix; flaser-like	3593: anhydrite stringer; undulatory extinction; twinned carbonate; halite strain shadows; granoblastic anhydrite mosaic
ANHYDRITE II	2561: stress shadow growth of anhydrite; helicitic halites; microboudinage 2570: schistose anhydrite; undulatory porphyroblasts veins 2571: stress shadow growth	3405: disharmonic microfolding; crenulated; stress shadow growth; recrystallized anhydrite matrix	3384: veins; microboudinage; rotated porphyroblasts; stress shadow growth; granoblastic anhydrite mosaic	
HALITE I				
ANHYDRITE I				3828: schistose anhydrite matrix; undulatory anhydrite porphyroblasts; sutured halite grains 3840: undulatory porphyroblasts; recrystallized anhydrite mosaic 3864: schistose matrix; microcrenulation; undulatory porphyroblasts

a. Deformed Relict Anhydrite, Kinked, Undulatory Extinction, Being Replaced by Fine-Grained Anhydrite Mosaic, WIPP 13, 3864 ft, Crossed Polars

c. Kinked Anhydrite Porphyroblast, WIPP 12, 3051 ft, Crossed Polars

b. Twinned Relict Anhydrite, Embayed by Finer Grained Anhydrite, Crossed Polars

d. Undulatory Extinction in Relict Deformed Anhydrite, WIPP 13, 3828 ft, Crossed Polars

e. Bent and Polygonized Anhydrite Laths, WIPP 13, 3840 ft, Crossed Polars ((a) anhydrite lath; (c) carbonate grains)

Figure 26. Relict Anhydrites (AR)

a. Schistose Anhydrite Mosaic, Crossed Polars

c. Carbonate Pull-Apart With Aligned Anhydrite in Stress-Shadow, WIPP 13, 3728 ft, Plane Light ((a) stress shadow, anhydrite; (c) calcite of pull-apart)

b. Deformed Anhydrite Stringer in Halite Unit, Halite (Extinct), Anhydrite Recrystallized Partially Decussate; WIPP 11, 2833 ft, Crossed Polars

d. Unoriented Anhydrite (a) in Carbonate Pull-Apart (c), WIPP 13, 3728 ft, Plane Light

e. Aligned Anhydrite Growth (a) in Pull-Apart

Figure 27. Anhydrite Textures

a. Stylolitic Growth (s) and Anhydrite (a) Vein Growth, WIPP 13, 3119 ft, Plane Light

c. Rotated Anhydrite Porphyroblast (a), Carbonate Laminae, WIPP 13, 3667 ft, Plane Light

b. Stylolitic Growth (s), WIPP 13, 3119 ft, Plane Light

d. Rotated Anhydrite Porphyroblasts (a), WIPP 13, 3667 ft, Plane Light

e. Secondary Anhydrite Growth (a) Parallel to Axial Plane of Microfolds, WIPP 11, 3405 ft, Crossed Polars ((c) carbonate grains)

Figure 28. Anhydrite Textures

3.3 Discussion: Microstructure

The development of microstructures and their relationship to deformation mechanisms in evaporites has been a target of experimental studies over the last 20 yr. The applicability of these studies to naturally deformed evaporite sequences needs to be ascertained in light of the relative paucity of petrographic studies of natural deformed sequences and the role of intergranular fluid in strength reduction.

Microtextures in deformed units of the northern Delaware Basin suggest that anhydrites and halites have recrystallized synkinematically. Carbonates, however, have not recrystallized and exhibit pull-aparts at the grain boundaries. In response to progressive deformation, anhydrites have recrystallized during at least four stages of growth. Despite the difficulty in the preservation of halite textures during

sample preparation, the textures suggest that halites have recrystallized coevally with the anhydrites.

Veins and growth, therein, of halite and anhydrite are evidence of fluid participation during deformation. The secretionary-type stress shadows in pull-aparts also suggest that a fluid facilitated the mass transfer required during deformation. Such observations suggest that pressure solution is active during the development of these fabrics. Indirectly, this conclusion is supported by the general absence of deformation twinning and cataclasis in deformed anhydrites, although an early stage of cataclasis is indicated by the relict anhydrite megacrysts. The significance of pressure solution mechanisms in regard to site deformation in the Delaware Basin is discussed in the following sections.

4. Conclusions

4.1 Deformation Stages and Fold Styles

Deformation was multistaged in the northern Delaware Basin. An early syndepositional or closely post-depositional deformation is suggested by layer-confined isoclinal folding and by angular unconformities. Later, progressive and penetrative tectonic deformation occurred, probably in response to basin tilting (King, 1948). Halites and anhydrites were synkinematically recrystallized during this event. Deformation was more homogeneous in Halite II than in Halite I. Strain in Halite I is commonly accommodated along discrete zones.

4.2 Strength Reduction by Intergranular Fluids

Temperatures in the Delaware Basin evaporite sequence never exceeded 35°C (Powers et al, 1978). Tectonism is limited to basin tilting. A tilt of 1° to 2° results in a shear stress of 3×10^5 Pa (3 bars) at the base of Halite I, calculated by using glacial flow as a model (Paterson, 1969). Experimental studies in anhydrite (Muller et al, 1981) and halite (Carter and Heard, 1972; Guillopé and Poirier, 1979) indicate that higher temperatures and stresses may be required for steady-state flow. If this is true, then some phenomenon has weakened the evaporite sequence to facilitate deformation. In the Iranian salt glaciers, Wenkert (1979), Talbot (1980), and Talbot and Rogers (1980) had similar difficulties in reconciling the ongoing glacier flow, considering strain rates and temperatures in the field, with the experimentally required conditions. These three authors concluded that fluids weakened the salt units. Experimentally, Means and Williams (1972) have shown that fluids weaken synthetic halite rocks. Wenkert (1979) suggested that enhanced intergranular diffusion produced the effect; Talbot appealed to the Joffe effect. However, the Joffe effect may not apply in these geologic occurrences since this effect requires a high ratio of water to rock. Essentially, the fluid that affects the salt by the Joffe effect needs to be unsaturated and remain so. The unsaturated fluid weakens the salt by etching crystal surfaces and thereby exposing fresh dislocation surfaces (see

Ode, 1968, and references therein). Water-to-rock ratios are likely to be low both in the Iranian salt glaciers and the Delaware Basin, and the fluids are expected to be saturated. Hence, intergranular diffusion is a more probable mechanism than the Joffe effect. The occurrence of oriented fabrics without significant twinning and cataclastic structures, and stress-shadow growth suggest that a process of pressure solution has been active in the northern Delaware Basin. Pressure solution would be equivalent to the intergranular diffusion mechanism suggested by Wenkert (1979) for the Iranian salt glaciers.

Pressure solution is the tendency for crystals to dissolve in places where the stress component normal to the crystal face is high and to precipitate simultaneously in places where this stress component is low (DeBoer, 1977, a, b; DeBoer et al, 1977). Confusion can stem from the application of pressure solution to both sedimentary (diagenetic) and tectonic processes. Diagenetic pressure solution occurs in response to gravitational load, and tectonic pressure solution occurs in response to weak tectonic/compressive loads (Durney, 1978). There may be gradations between the two regimes, but the WIPP site deformation is an example of tectonic pressure solution since the mass redistribution occurs in complex nonhorizontal structures other than just grain flattening.

Stress and permanent strain can act independently in controlling pressure solution (Bosworth, 1981). Stress gradients cause the migration of chemical components (Robin, 1978). Strain effects are caused by the variation in dislocation density and in turn the solubility product of the host grain (Bosworth, 1981).

For a given microstructural state, one can construct a map or diagram of deformation mechanisms in stress-temperature space (Ashby, 1972; Stocker and Ashby, 1973). Such deformation maps have been produced for halites by Munson (1979). In the case of pressure solution, Rutter (1976) derived a constitutive flow law that is of the same form as that for Coble creep. Hence, rates of deformation that are associated with pressure solution can be calculated and placed on deformation mechanism maps. Such calculations have

not been made for anhydrite and halite. However, we can use calcite and quartz calculations (Rutter, 1976) as analogs for the evaporite minerals. Rutter's deformation mechanism maps suggest that pressure solution is the controlling mechanism for deformation at relatively low stresses and temperature, if the rock contains a saturated intergranular fluid. In addition, steady-state flow can occur at lower stresses and temperatures than in dry rock experiencing geologically reasonable strain rates. Wenkert (1979) has made similar calculations for halite and mapped deformation mechanisms in strain rate-stress space. His calculations followed the derivation for fluid diffusive transport by Stocker and Ashby (1973). Stress and strain rates were calculated from field measurement of Iranian salt glaciers. Of the possible mechanisms, fluid diffusive transport equivalent to pressure solution is the only one that is consistent with the field-determined stress and strain-rates. Unfortunately, for essentially the same process, Rutter's (1976) and Stocker and Ashby's (1973) derivations are not equivalent. Further work is needed to reconcile the two approaches, but the variance may be less than an order of magnitude.

In conclusion, pressure solution is the only probable mechanism that would result in deformation of anhydrite units under the stress and temperature conditions of the Delaware Basin. Halites could deform by other mechanisms, but the microtextures suggest that pressure solution was also an active mechanism during halite deformation.

4.3 Interrelationship of Fluids and Deformation

In the previous section, the strength reduction that resulted from the presence of an intergranular fluid was discussed. Therefore, the importance of a fluid in facilitating deformation is stressed. This connection may explain the spotty distribution of deformation in the northern Delaware Basin. Areas of deformed evaporites may reflect original heterogeneities in water content during deposition or "wetter" areas adjacent to the Capitan Reef.

Deformation in part controls the present-day distribution of fluids in the basin. The empirical correlation has been noted that pressurized brine occurrences are found by drilling into the DZ. Conceptually, these correlations can be explained if WIPP 12 is taken as an example. Flow tests on the brine reservoir, which was encountered at WIPP 12, suggest that the reservoir had a volume of ~ 20 million bbl. The brine encounter is associated with vertical fractures in the

upper anhydrite, AIII, of the Castile Formation. With these observations in mind, we can construct some theoretical models. The assumptions for these models are as follows:

1. Time structure seismic maps of the WIPP 12 structure suggest that the feature can be approximated by a domal disk that is 1 km in radius and by using a seismic velocity of 7.4×10^3 s/ft.
2. The fold structure is assumed to be cylindrical and symmetric. The SE limb is used as the model shape (Borns et al, 1983, Figure 3.7).
3. Strain is calculated by the change in radius of the circle which contains the fold (Price, 1966).

From these assumptions, a volumetric strain of 1% is calculated for AIII. Strain in this unit is accommodated by fracturing, predominantly vertical, as suggested by field observations and finite-element modeling. The 1% strain produces a reservoir in the form of fractures with a volume of 19 million bbl. This value closely agrees with the 20-million-bbl volume predicted by the flow tests. Hence, deformation-induced strain that is accommodated by fracturing is a mechanism by which the physical reservoir volume for the brine can be produced. One problem still arises in that brine has been encountered only in the lower portion of the first anhydrite intersected. In WIPP 12, fractures existed higher in the section but still did not produce brine. Only equivocal explanations exist as yet for this spotty distribution of fluid-filled fractures.

Another consideration is the source of the fluids present in the DZ. These fluids could be derived from original depositional fluids, from gypsum dehydration, or from groundwater external to the evaporite sequence. The rarity of pseudomorphs after gypsum suggests that the amount of fluid produced by gypsum dehydration is insignificant. To understand the rationale for the other sources mentioned above, let us reconsider the WIPP 12 structure and imagine it as a layer cake (see Figure 29). This layer cake will have 1% by weight or 2% by volume of fluid (Braitsch, 1971; Powers et al, 1978). This fluid is distributed as an intergranular film and as fluid inclusions. C. Stein (personal communication, 1982) measured that fluid inclusions comprise volumetrically 1% of the WIPP halites. Therefore, the intergranular fluid is inferred to account for the other 1% of fluid present in these units. The volume of fluid present in the deformed stack of units at WIPP 12 is 200 million bbl. The volume present is 10 times more than that required to fill the brine reservoir. The common observation of grain boundary tightening with deformation suggests a "squeezed-sponge" effect. This effect would be the destruction of porosity through deformation, and an

upward migration of the displaced fluid into the fractured AIII. Although the original porosity of the layer cake is small (1%), a reduction to only 0.8% porosity would displace a volume of fluid necessary to fill the reservoir. This reduction is small and may be unmeasurable; however, it is suggested by recrystallization effects, such as the tightening of grain boundaries. The preceding arguments indicate that fluids external to the evaporite sequence are not required to facilitate the deformation nor to produce the brine reservoir encountered in WIPP 12. However, this discussion does not exclude external origins. Substantiation of such exclusions would come from chemical and fluid flux arguments. Still, a mechanism of fluid production internal to the evaporite sequence is feasible and consistent with the interrelationship of fluids and deformation.

Figure 29. Volume of Castile Rock and Fluid Involved in the WIPP 12 Anticline (Generalized stratigraphy from WIPP 12 and time structure maps)

4.4 The Bearing of Observed Meso- and Microscopic Textures on Hypothesis of Origin for Deformation

Four basic mechanisms have been proposed for the deformation in the DZ (see Chap 1). These are as follows:

- Dissolution
- Gypsum dehydration
- Halokinesis
- Gravity sliding

The pros and cons of these various hypotheses have been discussed on a basin-wide scale by Borns et

al (1983). The purpose of this section is, however, to specifically state how the observed medium- and small-scale structures limit the role played by the different driving mechanisms. Two basic problems exist for any such discussion:

1. The areal distribution of deformation is limited to the reef margins and localized regions internal to the basin. Any hypothesis must account for such distribution.
2. Sampling of structures is limited to the drill-core taken. More oriented drilling would answer questions regarding the regional consistency of fabrics.

4.4.1 Dissolution

Dissolution has been suggested as a driving mechanism for deformation (Anderson et al, 1978; Anderson and Kirkland, 1980; Davies, 1982). The volumetric removal of halite would result in collapse of the overlying units and lateral flow within the dissolved halite unit towards the point of halite removal. The most spectacular effects of this process are dissolution and collapse breccias; however, they are only an endpoint in a continuum of structures developed in response to dissolution (Davies, 1982). The important consideration is the rate of dissolution. Rapid rates would produce the breccias, and slower rates lead to more gentle warping. Mesoscopic structures in the DZ indicate an absence of collapse and dissolution breccias. Hence, if dissolution is responsible for the deformation structures, it proceeds at a relatively slow rate.

Lateral flow of the halite unit is inferred from the fold asymmetries, and the subhorizontal orientation of fold axes and lineations in the halite units. This subhorizontal fabric is observed under anticlinal limbs and nodes. Such observations do not exclude the lateral flow related to Davies' (1982) slow diffusion. Flow directions in the affected units would radiate inward towards the point of dissolution removal. But there is a sense of fabric alignment related to the direction of basin tilting (Anderson and Powers, 1978; this report). Still, this argument requires more oriented core studies in the DZ.

Anderson et al (1978) and Davies (1982) state that dissolution and related deformation are initiated in the lower Salado and upper Castile. However, this study indicates that deformation is most intense in Halite II and Anhydrite II within the DZ. If dissolution drove the deformation of Halite II and Anhydrite II, then dissolution would need to occur within these units and/or Halite I. However, dissolution breccias are lacking in these units. In fact, Halite I may display one or more intact primary halite units, e.g., WIPP 12.

Although some structural observations address the question of whether dissolution produces deformation, mechanisms that are inferred from DZ structures limit the role played by dissolution. The action of pressure solution indicates that the solution involved in deformation was saturated. Solutions involved in dissolution need to be undersaturated for the process to occur. On the microscopic scale, mass transfer within a relatively closed system is also indicated by solution and redeposition from one grain boundary to another. In some growing vein networks, halite replaces anhydrite nearly volume for volume.

In conclusion, much of the observed structures and the lack of dissolution and collapse structures in the DZ imply that dissolution either is not the driving mechanism for the deformation, or that, if it is, it proceeds very slowly. Deformation appears to be more in response to volume redistribution, and not to volume removal.

4.4.2 Gypsum Dehydration

Heard and Rubey (1966) noted the tectonic implications of gypsum dehydration. Experimentally, they found that gypsum aggregates during conversion to anhydrite underwent a tenfold decrease in strength. Not only did dehydration facilitate deformation, but the associated volume changes could be a driving mechanism. Kirkland and Anderson (1970) mentioned gypsum dehydration as a possible source of microfolding in the Castile; however, they discarded it as a hypothesis in favor of basin tilting or similar tectonic event. Popielak et al (1982) have recorded in their report on brine reservoirs the possible occurrence of anhydrite pseudomorphs after gypsum in WIPP 12 core. Recently, C. Stein (pers. comm., 1982) has found fluid inclusions that have anomalously low freezing temperatures from halites adjacent to laminated anhydrites. The volume of inclusions is also greater adjacent to the anhydrites compared to halite units away from the contact. The freezing point data may indicate Ca^{+2} and SO^{-2} enriched fluids in these inclusions. Such compositions and the greater volume of inclusions adjacent to halite-anhydrite contacts suggest to Stein that the fluids emanated from the anhydrites, probably as a result of gypsum dehydration.

Hence, we see several lines of evidence which indicate that this process is active in the evaporite sequence. However, Stein's Ca-enriched inclusions occur associated with hopper crystals. This suggests that the fluids were produced syndepositionally and, therefore, temporally separated from the bulk of site deformation. The evidence of Popielak et al is also equivocal. Their anhydrite pseudomorphs after gypsum from

WIPP 12 may be what is described herein as the cataclastically deformed stage 1 anhydrite porphyroblasts. However, the crux of the argument lies in determining what textures indicate pseudomorphs after gypsum. Relict patches of embayed gypsum in anhydrite would be a clear evidence. Some textures (Sec 2 and 3) indicate that anhydrite laths formed syndepositionally. This does not exclude the presence of gypsum, but suggests that it need not to have formed.

Meso- and microstructures place limits on the role in deformation of volume changes caused by dehydration. The pronounced parallelism of lineations and sense of asymmetric vergence suggest lateral flow. A more planar strain would be expected from massive gypsum dehydration. Again, information of the basin-wide consistency of lineations and fold orientations would help define the role that dehydration played.

4.4.3 Halokinesis

Halokinesis is the autonomous and isostatic movement of salt. Barrows (Appendix in Borns et al, 1983) constructs a model for halokinetic development of the DZ based on Ramberg's (1981) gravitational theories and centrifuge models. In the case of the DZ, density inversion of anhydrite and halite units of the Castile would provide the driving mechanisms for deformation. To determine what role halokinesis played, we need to consider structures that would be expected in and would be possibly unique to halokinesis. At one end of the halokinetic spectrum lies salt dome formation. In such, a parallelism, approaching vertical, of hinge lines and lineations in the direction of dome propagation would develop (Balk, 1949, see Figure 30). The rotation of fabrics into parallelism would be gradational, relative to the scale to which the structure has developed or the location of the observed fabric relative to the larger structure. Hence, we would expect to observe the development of an organized fabric in response to salt movement. This movement will have horizontal and vertical components associated with halokinesis. Finally, Barrow's modeling (Borns et al, Appendix, Figure A20) indicates that fold development will be nonparallel and noncylindrical and that the folded upper and lower boundaries of the anhydrite units will have different wavelengths.

Review of the meso- and mesoscopic structures from the DZ shows a strong subhorizontal trend of axial planes and lineations (hinge or mineral). This observation suggests that lateral flow is dominant in the halite units even under anticlinal crests such as WIPP 12 and in relatively undeformed regions, such as adjacent to DOE 1 and AEC 7. The asymmetric

development of microfolds in laminated anhydrites has not been observed in two-side symmetry as drag folds about a growing domal structure (see Figure 31). In conclusion, rock fabrics suggest lateral halite flow without a dominant vertical component as would be expected in portions of halokinetic structures.

4.4.4 Gravity Sliding

Fold hinges, foliations, mineral lineations, and axial planes of convolute folds in halite are dominantly subhorizontal. High-angle axial planes occur in crenulation microfolds of anhydrite laminae and larger overturned structures in ERDA 6. These structures from ERDA 6 are the important exception to the dominant horizontal fabric imparted by the halite units. Possibly more high-angle structures exist, but the drilling program has not, by chance, encountered such structures. However, the dominant subhorizontal pattern suggests lateral movement in the halite units of the Castile. Such inferences are consistent with gravity sliding as a driving mechanism. More oriented fabric data from drill holes would assist in defining the role of this mechanism by checking the consistency of fold asymmetries, lineation directions, etc, with a gravity slide hypothesis.

Figure 30. Arrangement of Fold Hinges About a Growing Dome, After Balk (1949)

a. Through Frictional Drag Within a Folded Envelope

b. Through Forward Movement of the Fold Core (Reverse Drag) as May Be Expected in Salt Dome or Halokinetic Push From Below

Figure 31. Folding of an S-Surface, After Wilson (1982)

In conclusion, gravity sliding is the favored mechanism producing the deformation within the Delaware Basin. However, difficulties exist in the distribution of structures within the Delaware Basin. If gravity sliding occurs and strain is accommodated by lateral flow in Halite I and II, the question arises as to where folding of the anhydrite units will occur. Should folding be concentrated on the down-dip side of the basin, or should the deformation occur on the up-dip side along the margin of detachment? Another consideration would be that the basin slides as a sheet, but more complex folding would occur along the margin where the Castile units are buttressed against the reef.

4.5 Age of Deformation

As stated before, angular unconformities and layered-confined isoclinal folds suggest some component of syndepositional (Permian) deformation. Some microfolds in DOE 1 and as seen at the State Line Outcrop are similar to those developed in the German Zechstein salt deposits during redeposition (see Figures 8 and 11; Schlager and Bolz, 1977).

But the bulk of tectonic deformation occurred after deposition in the Permian. Jones (1981) placed the deformation at ERDA 6 as pre-Miocene based on the unconformable contact between the Ogallala Formation and the units underlying it. The favored mechanism suggested in this report, gravity sliding, requires basin uplift and tilting. The following stages of uplift are based on stratigraphic arguments (King, 1948; Hayes, 1964; Anderson, 1981):

- Minor uplift and exhumation in the early Cenozoic
- Earliest identifiable phase of uplift in Miocene to early Pliocene
- Main phase of uplift, in late Pliocene and early Pleistocene

The problem exists in correlating the stages of uplift, these or others, to the event initiating gravity gliding. Ogallala Formation relationships are critical in this regard. If Jones' upper limit to deformation at ERDA 6, which is inferred from the basal Ogallala unconformity, is extended to the rest of the DZ, then gravity sliding initiated and was largely completed in the early stage of Miocene-Pliocene uplift. However, it may be difficult to exclude related Mesozoic orogenies and uplifts. The basin was uplifted to some extent in the Jurassic to escape the bulk of Jurassic sedimentation seen in central and northern New Mexico. Units of the DZ reached their maximum depth of burial during the Cretaceous. Fracturing probably developed in response to subsequent uplift and erosion (Narr and Currie, 1982). Vein networks in the Dewey Lake

Formation are probably results of this burial-denudation cycle. Such fracturing in the overlying units of the DZ, such as the Dewey Lake, is related to deformation of the DZ only in the sense that both are initiated by uplift.

4.6. Summary of Conclusions

1. WIPP site deformation was episodic with syn-depositional and later tectonic stages.
2. Tectonic deformation stages produced meso- and microscopic textures similar to those of tectonites in silicate rocks.
3. Fluids facilitated deformation under the relatively low temperatures and stresses in the Delaware Basin. Areas of concentrated fluids may have localized intense deformation. Pressure solution was the dominant deformation mechanism.
4. Large portions of the fluid encountered in brine reservoirs within the DZ may have been derived from intergranular fluids that were mobilized during deformation.
5. Small-scale structures and their distribution are consistent with gravity-driven deformation and not with dissolution processes.
6. Deformation initiated with basin tilting, the major component of which began within the last 30 my. Deformation may also be ongoing.

References

- R. Y. Anderson and D. W. Powers, *Salt Anticlines in Castile-Salado Evaporite Sequence, Northern Delaware Basin, New Mexico*, Cir 159 (Santa Fe, NM: NM Bur of Mines and Mineral Resources, 1978), pp 79-83.
- R. Y. Anderson, K. K. Kietzke, and D. J. Rhodes, *Development of Dissolution Breccias, Northern Delaware Basin, New Mexico and Texas*, Cir 159, (Santa Fe, NM: NM Bur of Mines and Mineral Resources, 1978), pp 47-52.
- R. Y. Anderson and D. W. Kirkland, "Dissolution of Salt Deposits by Brine Density Flow," *Geol*, 8:66-69 (1980).
- R. Y. Anderson, *Deep-Seated Salt Dissolution in the Delaware Basin, Texas and New Mexico*, Special Publication 10, *NM Geol Soc* (1981), pp 133-134.
- M. F. Ashby, "A First Report on Deformation-Mechanism Maps," *Acta Met* 20:887 (1972).
- R. Balk, "Structure of Grand Saline Salt Dome, Van Zandt County, Texas," *AAPG Bull* 33:1791-1829 (1949).
- R. Balk, "Salt Structure of Jefferson Island Salt Dome, Iberia and Vermilion Parishes, Louisiana," *AAPG Bull* 37:2455-2474 (1953).
- L. J. Barrows, Sandia National Laboratories, pers. comm. (February 1982).

- A. M. Bell, "Vergence: An Evaluation," *J Structural Geol* 3:197-202 (1981).
- D. J. Borns, L. J. Barrows, and D. W. Powers, *Interim Report: Deformation of Evaporites Near the Waste Isolation Pilot Plant (WIPP) Site*. With a section by R. P. Snyder, USGS, SAND82-1069 (Albuquerque, NM: Sandia National Laboratories, February 1983).
- W. Bosworth, "Strain-Induced Preferential Dissolution of Halite," *Tectonophysics* 78:509-525 (1981).
- O. Braitsch, *Salt Deposits, Their Origin and Composition* (Berline: Springer-Verlag, 1971).
- J. Callender and T. Ingwell, *Structural Petrology of Undeformed and Experimentally Deformed Halite Samples from USERDA #7 and #9, SAND78-7076* (Albuquerque: NM Sandia Laboratories, 1978).
- N. L. Carter and H. C. Heard, "Temperature and Rate Dependent Deformation of Halite," *Amer J of Sci* 269:193-249 (1970).
- H. C. Claiborne and F. Gera, *Potential Containment Failure Mechanisms and Their Consequences at a Radioactive Waste Depository in Bedded Salt in New Mexico*, ORNL-TM-4639 (Oak Ridge, TN: Oak Ridge National Laboratory, 1974).
- G. V. Cohee (Chairman), *Tectonic Map of the United States*, USGS and American Assn Pet Geol (1962).
- P. B. Davies, "Deep Seated Collapse and Subsidence Structures in Bedded Salt - Mechanics and Rates of Deformation," *GSA Abstracts with Programs* 14:472 (1982).
- R. B. DeBoer, "Pressure Solution Theory and Experiments," *Tectonophysics* 39:287-301 (1977a).
- R. B. DeBoer, "On the Thermodynamics of Pressure Solution - Interaction Between Chemical and Mechanical Forces," *Geoch Cosmoch Acta* 41:249-256 (1977b).
- R. B. DeBoer, P. J. C. Nagtegaal, and E. M. Duyvis, "Pressure Solution Experiments on Quartz Sand," *Geoch Cosmoch Acta* 41:257-264 (1977).
- D. W. Durney, "Early Theories and Hypotheses on Pressure-Solution Redeposition," *Geol* 6:315-317 (1978).
- R. C. Emmons, "The Universal Stage (With Five Axes of Rotation)," *GSA Memoir* 8 (1943).
- M. Guillopé and J. P. Poirier, "Dynamic Recrystallization During Creep of Single-Crystalline Halite: An Experimental Study," *J Geophys Res* 84:5557-5567 (1979).
- P. T. Hayes, *Geology of the Guadalupe Mountains, New Mexico*, Prof Paper 446, USGS (1964).
- H. C. Heard, "Steady-State Flow in Polycrystalline Halite at Pressure of 2 Kilobars," in H. C. Heard, I. V. Borg, N. L. Carter, and C. B. Raleigh, ed, *Flow and Fracture of Rocks*, Geophy Monogr Ser, Am Geophys Union, 76 (1972), pp 191-210.
- H. C. Heard and W. W. Rubey, "Tectonic Implications of Gypsum Dehydration," *GSA Bull* 77:341-360 (1966).
- C. L. Jones, *Geologic Data for Borehole ERDA-6, Eddy County, New Mexico*, USGS Open-File Report 81-468 (1981).
- J. C. Kelley, *Geology of the Pecos County, Southeastern New Mexico*, New Mexico Bureau of Mines and Mineral Resources Memoir 24 (1971).
- P. B. King, *Geology of the Southern Guadalupe Mountains*, Prof Paper 215, USGS (1948).
- D. W. Kirkland and R. Y. Anderson, "Microfolding in the Castile and Todilto Evaporites, Texas and New Mexico," *GSA Bull* 81:3259-3282 (1970).
- W. D. Means and P. F. Williams, "Crenulation Cleavage and Faulting in an Artificial Salt-Mica Schist," *J Geol* 80:569-591 (1972).
- W. H. Muller and U. Briegel, "The Rheological Behavior of Polycrystalline Anhydrite," *Eclogie Geol Helv* 71:397-407 (1978).
- W. H. Muller, S. M. Schmid, and U. Briegel, "Deformation Experiments on Anhydrite Rocks of Different Grain Sizes: Rheology and Microfabric," *Tectonophysics* 78:527-543 (1981).
- D. E. Munson, *Preliminary Deformation-Mechanism Map for Salt (With Application to WIPP)*, SAND79-0076 (Albuquerque, NM: Sandia National Laboratories, 1979).
- W. Narr and J. B. Currie, "Origin of Fracture Porosity-Example From Altamont Field, Utah," *AAPG Bull* 66:1231-1247 (1982).
- H. Ode, "Review of Mechanical Properties of Salt Relating to Salt Dome Genesis," in *Saline Deposits*, GSA Special Paper 88 (1968), pp 543-595.
- S. S. Oriel, D. A. Myers, and E. J. Crosby, "West Texas Permian Basin Region," *Paleotectonic Investigations of the Permian System in the United States*, Prof Paper 515, USGS (1967).
- G. C. Parea and R. Ricci-Lucci, "Resedimented Evaporites in the Periadriatic Trough (Upper Miocene, Italy)," *Israel J of Earth-Sciences* 21:125-141 (1972).
- W. S. B. Paterson, *The Physics of Glaciers* (Oxford: Pergamon Press, 1969).
- R. S. Popielak, R. Beauhim, S. R. Black, W. E. Coons, C. T. Ellingson, and R. L. Olsen, *Brine Reservoirs in the Castile Formation, Southeastern New Mexico*, TME-3153 (1982), (in preparation).
- D. W. Powers, S. J. Lambert, S-E. Shaffer, L. R. Hill, and W. D. Weart, ed, *Geological Characterization Report, Waste Isolation Pilot Plant (WIPP) Site, Southeastern New Mexico*, SAND78-1596, Vol I and II (Albuquerque, NM: Sandia Laboratories, 1978).
- J. J. Price, *Fault and Joint Development in Brittle and Semibrittle Rock* (Oxford: Pergamon Press, 1966).
- H. Ramberg, *Gravity, Deformation and the Earth's Crust* (2nd ed; New York: Academic Press, 1981).
- P.-Y. F. Robin, "Pressure Solution of Grain-To-Grain Contacts," *Geoch Cosmoch Acta* 42:1383-1398 (1978).
- E. H. Rutter, "The Kinetics of Rock Deformation by Pressure Solution," *Phil Trans Royal Soc London Ser A* 283:203-209 (1976).
- W. Schlager and H. Bolz, "Clastic Accumulations of Sulphate Evaporites in Deep Water," *J of Sedimentary Petrology* 47:600-609 (1977).
- W. M. Schwerdtner, "The Relationship Between Anhydrite Mineral Lineations and Directions of Megascopic Strain," in J. L. Rau and L. F. Dellwig, ed, *Third Symp on Salt*, Northern Ohio Geol Survey, Vol I:317-326 (1970).

R. P. Snyder, Section in D. J. Borns et al, *Deformation of Evaporites Near the Waste Isolation Pilot Plant (WIPP) Site*, SAND82-1069 (Albuquerque, NM: Sandia National Laboratories, 1983).

A. Spry, *Metamorphic Textures* (Oxford: Pergamon Press, 1969).

C. Stein, Sandia National Laboratories, pers. comm. (October 1982).

K-E. Stromgard, "Stress Distribution During Formation of Boudinage and Pressure Shadows," *Tectonophysics* 16:215-248 (1973).

R. L. Stocker and M. F. Ashby, "On the Rheology of the Upper Mantle," *Rev of Geophy and Space Phys* 11:391-426 (1973).

C. J. Talbot, "The Effects of Water Softening and Thermal Gradients on Salt Deformation," *Geologica Ultraiectina*, Special Pub Univ of Utrecht 1:53-67 (1980).

C. J. Talbot and E. A. Rogers, "Seasonal Movements in a Salt Glacier in Iran," *Science* 208:395-396 (1980).

F. Trusheim, "Mechanism of Salt Migration in Northern Germany," *AAPG Bull* 44:1519-1540 (1960).

F. J. Turner and L. E. Weiss, *Structural Analysis of Metamorphic Tectonites* (New York: McGraw-Hill, 1963).

W. R. Wawersik and D. W. Hannum, "Mechanical Behavior of New Mexico Rock Salt in Triaxial Compression up to 200°C," *J Geophy Res* 85:891-900 (1980).

D. D. Wenkert, "The Flow of Salt Glaciers," *Geophys Res Ltrs* 6:523-526 (1979).

G. Wilson, *Introduction to Small-Scale Geological Structures* in collaboration with J. W. Cosgrove (London: George Allen and Unwin, 1982).

DISTRIBUTION:

US Department of Energy, Headquarters (3)
Office of Nuclear Waste Management
Washington, DC 20545
Attn: Larry Harmon, Program Manager (WIPP)
Wade Ballard, Director,
Division of Waste Isolation (2)

US Department of Energy, Headquarters
Office of Defense Waste & By-Products
Washington, DC 20545
Attn: Dr. Goetz Oertel, Director (NE-320)

US Department of Energy (3)
Albuquerque Operations
PO Box 5400
Albuquerque, NM 87115
Attn: J. M. McGough, Mgr, WIPP Project Office (2)
D. Jackson, Director, Public Affairs Division

US Department of Energy
Carlsbad WIPP Project Office
Room 113, Federal Building
Carlsbad, NM 88220

US Department of Energy
c/o Battelle Office of Nuclear Waste Isolation
505 King Ave
Columbus, OH 43201
Attn: Jeff O. Neff

Battelle Memorial Institute
Office of Nuclear Waste Isolation
505 King Ave
Columbus, OH 43201
Attn: S. Goldsmith, Mgr, ONWI Library

Battelle Memorial Institute
Project Management Division
505 King Ave
Columbus, OH 43201
Attn: Neal Carter, General Manager

Bechtel National, Inc. (2)
Fifty Beale St
PO Box 3965
San Francisco, CA 94119
Attn: D. L. Ledbetter
Dale Roberts

D'Appolonia Consulting Engineers (10)
2340 Alamo, SE
Albuquerque, NM 87106
Attn: Dev Shukla

Westinghouse Electric Corporation (3)
PO Box 40039
Albuquerque, NM 87196
Attn: R. K. Brown
R. Jones (TSC)
C&C File, c/o Ginger Wilkenson

Frank L. Parker, Chairman
Department of Environmental and
Water Resources Engineering
Vanderbilt University
Nashville, TN 37235

Konrad B. Krauskopf, Vice Chairman
Department of Geology
Stanford University
Stanford, CA 94305

Karl P. Cohen, Consultant
928 N California Ave
Palo Alto, CA 94303

Neville G. W. Cook
Dept of Material Sciences and Engineering
University of California at Berkeley
Hearst Mining Building, #320
Berkeley, CA 94720

Fred M. Ernsberger
250 Old Mill Road
Pittsburgh, PA 15238

Richard R. Parizek
Department of Hydrogeology
Pennsylvania State University
University Park, PA 16802

D'Arcy A. Shock
233 Virginia
Ponca City, OK 74601

John W. Winchester
Department of Oceanography
Florida State University
Tallahassee, FL 32306

DISTRIBUTION (cont):

John T. Holloway
Senior Staff Officer
2101 Constitution Ave, NW
Washington, DC 20418

WIPP Public Reading Room
Atomic Museum, KAFB East
Albuquerque, NM 87185
Attn: Ms. Gwynn Schreiner

WIPP Public Reading Room
Carlsbad Municipal Library
101 S. Hallagueno St
Carlsbad, NM 88220
Attn: Lee Hubbard, Head Librarian

Thomas Brannigan Library
106 W Hadley St
Las Cruces, NM 88001
Attn: Don Dresp, Head Librarian

Roswell Public Library
301 N Pennsylvania Ave
Roswell, NM 88201
Attn: Ms. Nancy Langston

Hobbs Public Library
509 N Ship St
Hobbs, NM 88248
Attn: Ms. Marcia Lewis, Librarian

State of New Mexico (2)
Environmental Evaluation Group
320 Marcy St
PO Box 968
Santa Fe, NM 87503
Attn: Robert H. Neill, Director

NM Department of Energy & Minerals (2)
PO Box 2770
Santa Fe, NM 87501
Attn: Larry Kehoe, Secretary
Kasey LaPlante, Librarian

New Mexico State Geologist
PO Box 2860
Santa Fe, NM 87501
Attn: Emery C. Arnold

New Mexico State Library
PO Box 1629
Santa Fe, NM 87503
Attn: Ms. Ingrid Vollenhofer

New Mexico Tech
Martin Speer Memorial Library
Campus St
Socorro, NM 87801

Zimmerman Library
University of New Mexico
Albuquerque, NM 87131
Attn: Ms. Zanier Vivian

USGS, Water Resources Division (2)
505 Marquette, NW
Western Bank Bldg, #720
Albuquerque, NM 87102
Attn: J. W. Mercer

USGS, Conservation Division
PO Box 1857
Roswell, NM 88201
Attn: W. Melton

USGS, Special Projects Branch (2)
Federal Center, Bldg 25
Denver, CO 80225
Attn: R. P. Snyder

NM Bureau of Mines and Mineral Resources (2)
Socorro, NM 87801
Attn: F. E. Kottlowski, Director

Klaus Kuhn
Gesellschaft fuer Strahlen-und
Umweltforschung MBH Muenchen
Institut fuer Tieflagerung
Berliner Strasse 2
3392 Clausthal-Zellerfeld
Federal Republic of Germany

Klaus Eckart Maass
Hahn-Meitner-Institut fuer Kernforschung
Glienicke Strasse 100
1000 Berlin 39
Federal Republic of Germany

DISTRIBUTION (cont):

Michael Langer
Bundesanstalt fuer Geowissenschaften
und Rohstoffe
Postfach 510 153
3000 Hannover 51
Federal Republic of Germany

Helmut Rothemeyer
Physikalisch-Technische
Bundesanstalt
Bundesalle 100
3300 Braunschweig
Federal Republic of Germany

Rolf-Peter Randl
Bundesministerium fuer Forschung
und Technologie
Postfach 200 706
5300 Bonn 2
Federal Republic of Germany

Fenix & Scisson, Inc.
3170 W Sahara Avenue
Spanish Oaks D-12
Las Vegas, NV 89102
Attn: J. A. Cross

Gayle Pawloski, L-222
Geologist CSDP
Lawrence Livermore Laboratory
Livermore, CA 94550

US Nuclear Regulatory Commission (3)
Division of Waste Management
Mail Stop 69755
Washington, DC 20555
Attn: J. Martin
M. Bell
H. Miller

Dr. Gary L. Downey
Center of Waste Management Programs
Department of Social Sciences
Michigan Technological University
Houghton, MI 49931

Dennis W. Powers
Department of Geological Sciences
University of Texas at El Paso
El Paso, TX 79968

Prof. J. Rosenfeld
Dept. of Earth and Space Sciences
UCLA
Los Angeles, CA 90024

University of Texas
Department of Geological Sciences
PO Box 7909
Austin, TX 78712
Attn: J. K. Warren, Ph.D.
Assistant Professor

California State University, Long Beach
Department of Geological Sciences
1250 Bellflower Boulevard
Long Beach, CA 90840
Attn: J. G. Dennis, Ph.D.
Professor

Dr. Urs A. Pfirter
Universität Basel
Geologisch-paläontologisches Institut
Bernoullistrasse 32
CH-4056 Basel
SWITZERLAND

7111 L. J. Barrows
7133 R. D. Statler
7135 P. D. Seward
9700 E. H. Beckner
9730 W. D. Weart
9731 D. J. Borns (15)
9731 D. D. Gonzalez
9731 S. J. Lambert
9731 A. R. Lappin
9731 K. L. Robinson
9731 S. E. Shaffer
9731 C. L. Stein
9732 Sandia WIPP Central Files (12)
9753 J. C. Lorenz
8214 M. A. Pound
3141 L. J. Erickson (5)
3151 W. L. Garner (3)
3154-3 C. H. Dalin (25)
For DOE/TIC (Unlimited Release)