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GEOTECHNICAL ENGINEERS INC.

MASTER

# FINAL REPORT

# ON

# GEOLOGICAL STUDIES PERTINENT TO SITE SUITABILITY CRITERIA FOR HIGH-LEVEL WASTE REPOSITORIES

PURCHASE ORDER NO. 6562803

Submitted to

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# 1. INTRODUCTION

From the very early stages of the nuclear waste management program, salt has been advocated as the most suitable geologic medium in which to store high-level radioactive wastes (HLW). The primary reason for this is based on the fact that, relative to other rock types, salt has a low yield strength with the result that, at the confining pressures that exist at depths of a few thousand feet, salt will deform plastically. The consequence of this phenomenon is that fractures, along which escape of radioactive wastes might be possible, may not exist at the depths proposed for the HLW storage repositories.

However, a naturally-occurring geological process associated with salt deposits which may adversely affect the integrity of a HLW repository has become recognized in the relatively recent past. This process is the dissolution of salt when in contact with groundwater and the eventual formation of large solution cavities. Furthermore, as the solution cavities develop, the unsupported rock immediately overlying the cavity fractures and falls into the opening. This process often continues upward until a column of broken rock, which is called a breccia pipe, extends from the elevation of the dissolved salt stratum to the ground surface. Of major concern relative to the placement of repositories in salt is that pathways for the movement of the radioactive wastes to overlying aquifers or to the ground surface may develop as a consequence of the formation of solution cavities and the associated breccia pipes.

A considerable portion of GEI's efforts, to date, on the problem of storage of HLW has been directed toward gaining an understanding of the geological and geohydrological conditions that lead to the development of dissolution features in salt. This has been done primarily to provide The Analytic Sciences Corporation (TASC) with guidelines relative to the refinement of their computer model. However, a second compelling reason which is beginning to emerge is that such an understanding may lead to the possibility of selecting certain areas within a sedimentary basin which contains salt in which the geological and geohydrological conditions are such that the formation of solution cavities and breccia pipes will not occur.

This document consists, in part, of reports (previously submitted by GEI) which contain information on (1) the hydraulic conductivity of salt; (2) the various types of naturally-occurring salt solution collapse features, and (3) the rate of formation of solution cavities in salt. Some of the numerical values contained in these reports have already been submitted to the project for incorporation into the TASC computer model.

The data contained in these reports was, for the most part, obtained from the literature. Additional information on the geological and hydrological processes that exist within and adjacent to the extensive salt deposits of the Delaware Basin in southeastern New Mexico and west Texas was obtained by GEI from field investigations (surface and underground) of salt and salt dissolution features and participation in conferences which dealt with the geology of the Delaware Basin and salt dissolution phenomena. Reports which summarize these field investigations and conference presentations are presented in the Appendices.

The development of the TASC computer model of repositories for high-level radioactive waste has included consideration of the effect of various geological and geohydrological parameters on the long-term isolation of the stored materials. One class of parameters found to be important relative to the integrity of a repository consists of geologic features such as faults and shear zones which may have sufficient permeability so as to provide a pathway for the escape of the nuclear wastes.

In the refinement of the TASC model it was desired that probabilities be assigned to the possible existence of faults within the vicinity of the repository. Two classes of faults have been considered: (1) those that exist prior to construction of the repository but which escape detection and (2) those that do not exist at the time of construction but which develop subsequent to storage of the radioactive wastes. The consequence of the former type of fault appears to be the more important since such faults may provide pathways for escaping radioactive wastes from the outset whereas, for the latter, the development of the faults may not occur for a considerable length of time following the storage of the waste products, during which time the level of radioactivity would decrease.

As a result of this rationale and also because of the view held by several individuals on the project that the likelihood of pre-existing but undetected faults is probably greater than the development of new faults during the lifetime of the repository, GEI initiated a study to determine the probability of the existence of undetected faults.

The study consisted of an evaluation of the efficacy of exploration techniques, especially borings, in determining the presence of faults. The base data for this investigation was obtained from study of the geological reports of nuclear power plant sites because of the degree of detail of such studies and also because of the opportunity to compare what, geologically, is found during excavation with what was thought to occur prior to excavation. Although limited in scope, the study allowed tentative conclusions to be drawn as to the likelihood of a fault remaining undetected.

## 2. HYDRAULIC CONDUCTIVITY AND DISSOLUTION PROCESSES IN SALT

A major portion of GEI's effort has been directed toward providing The Analytic Sciences Corporation (TASC) with input relative to the characteristics of salt and the geological and hydrological processes associated with bedded salt. The purpose of this input was to assist TASC in the development of their computer model and to provide appropriate values for the in-situ properties of bedded salt.

The information for this portion of the study was obtained from the literature and from field investigations and participation in geological conferences.

### 2.1 Information Obtained From the Literature

#### 2.1.1 Porosity and Permeability of Bedded Salt

During the early stages in the development of the TASC model, data on the hydraulic conductivity of salt was required. GEI obtained data from various sources and provided TASC with preferred values and ranges of the porosity and permeability of salt. A copy of the GEI report submitted to the project which contains these values is included in Appendix A.

#### 2.1.2 Salt Dissolution and Collapse Structures

Study of the literature revealed that, in many localities, sedimentary deposits of and associated with bedded salt undergo certain geologic and hydrologic processes that may have adverse consequences on the integrity of nuclear waste repositories located in salt. In order to (1) provide guidance so that the development of the TASC model would include consideration of these dynamic processes and (2) determine appropriate topics for further study, GEI provided a detailed summary of the four major cases in which salt dissolution and collapse features exist. The GEI report submitted to the project which summarizes these events is included in Appendix B.

#### 2.1.3 Preliminary Input For Failure Events Related To Salt Dissolution

In recognition of the potential consequences of the salt dissolution phenomena relative to the integrity of a waste repository, TASC requested that data be provided on (1) the rates of development and frequency of occurrence of the salt dissolution cavities and associated collapse breccias, (2) the probability of existence of an undetected dissolution cavity of a size which in the lifetime of the repository could pose a threat to the integrity of the repository, and (3) the porosity and permeability of the breccia of the collapse features. A description of each of these topics and the rationale behind the development of the estimates is presented in the report which GEI submitted. A copy of this report is in Appendix C.

## 2.2 Information Obtained From Field Investigations and Geological Conferences

### 2.2.1 Information Summaries

GEI participated in field observations and attended two geological conferences in order to gain additional information on the geology and geological processes associated with bedded salt. The first conference was the Salt Dissolution Review Meeting which was held in Austin, Texas on March 29-30, 1977. Just prior to this conference, GEI participated in a field review of the WIPP Site Area with Dr. George Griswald of Sandia Laboratories. A summary of the field trip and the conference is presented in Appendix D.

The second conference dealt with the Ochoan and Guadalupian Rocks of southwestern New Mexico and west Texas. The Ochoan rocks comprise the salt strata that are under consideration for a repository and the Guadalupian rocks immediately underlie the Ochoan series. Field trips associated with this conference consisted of underground investigations of two potash mines in the Ochoan series. A summary of information obtained from this field trip and conference are presented in Appendix E.

### 2.2.2 New Information Pertinent To Development of the TASC Model

A review of the data obtained from the field observations and the geological conferences has yielded additional insight into the geological and hydrological processes associated with salt basins and, correspondingly, the appropriate considerations that should enter the further development of the TASC model.

There are some 7 categories into which the new information can be grouped. These 7 categories are presented in Table 1. Adjacent to each category in Table 1 is the specific portion of the information summaries presented in Appendices D and E. A brief description of the significance of the new information relative to the development of the TASC model is presented below, by category.

In-Situ Permeability - The hydraulic conductivity of the rock units within the vicinity of a nuclear waste repository has been recognized as an important parameter relative to the potential for escape of the radioactive materials. It has also been recognized that laboratory data is of limited use because of the substantial differences that may exist between laboratory and in-situ permeability values. One means for determining in-situ permeabilities which appears worthy of consideration is the utilization of data associated with oil seeps that occur in certain mines. For example, the observation of oil seeps in the Mississippi Mine appears to provide a means for determining the in-situ permeability of the Salado Fm. There are two possible sources for these hydrocarbons: one is that they originated from the Bell Canyon Fm. and migrated upward through the breccia pipe (this assumes that the breccia pipe bottoms in the Bell Canyon Fm.). The other is that the hydrocarbons originated from an oil well located approximately 500 ft from that portion of the mine in which the oil seep was noted. The latter is thought to be the more likely since the hydrocarbons are not found within or abutting the breccia pipe but are in the Salado Fm. within a few hundred feet of the breccia pipe. By assuming reasonable values of pressure differential, time, distance, and porosity (1000 ft, 10 yrs., 500 ft, 0.01, respectively) the in-situ permeability was calculated to be $10^{-7}$ cm/sec, a substantially higher value than the $10^{-9}$ cm/sec assumed, to date, in the TASC model. Similar occurrences of oil migration should be sought to provide additional data on in-situ permeability of the formations of interest.

The Rate of Formation of Breccia Pipes - The existence of breccia pipes is of concern relative to the integrity of repositories in salt because of the possibility of fluid flow and migration of the radioactive wastes within the breccia zone.

From our present understanding of the mechanism of the origin of collapse breccia, it appears that the rate of formation and the frequency of occurrence of the breccia pipes is directly proportional to the rate of formation of dissolution cavities in salt. Therefore, a better understanding of the factors which control the rate of formation of dissolution cavities would lead to an improved ability to estimate the rate of formation, and possibly the geological distribution, of collapse breccia.

In some cases collapse breccias have been noted to be associated with dissolution at the top of a salt unit and in other cases at the bottom. Some recent work on salt dissolution suggests that the rate of dissolution activity may be substantially different in these two cases.

The work by Dr. Richard Snow[1] on the mechanics of salt dissolution indicates that the geometry of growth of a solution cavity is controlled, in part, by the fact that the density of brine increases with increasing degrees of saturation. The consequence is that cavity growth is more rapid at higher elevations in the cavity because of the gravitational zonation of the brine that exists in the cavity, i.e., the less saturated brine is at the higher elevations.

Consideration of this in terms of solution cavities that begin at the bottom in contrast to those that begin at the top of a salt unit suggest that the geometry of growth will be markedly different. Specifically, those that begin at the bottom would tend to be smaller in width but greater in vertical extent that those that begin at the top. This is because in those cases where growth begins at the bottom of a salt unit the gravitational zoning that occurs would tend to remove the saturated brine from the salt surface at which dissolution occurs and the dissolution rate would be expedited by the continual exposure of the salt to the groundwater with the lowest salt content. For the case where dissolution begins at the top of a salt unit the most concentrated brine is in contact with the surface of the salt, and,

[1] IIT Research Institute, Chicago, Illinois

therefore, the rate of dissolution would be lessened because of the presence of the most saline water.

<u>"Time Windows" of High-Permeability Breccia</u> - The examination of the breccia pipe in the Mississippi Mine indicated that the breccia was completely healed with recrystallized salt and, therefore, would have a much lower permeability than must have existed prior to the salt recrystallization process. Consideration of this indicates that a finite period of time may exist for breccia pipes during which the permeability decreases from some initial, high value to a final, low value of the healed breccia.

It appears appropriate that further development of the TASC model include the change of permeability of the breccia with time. Data to establish the time-dependent hydraulic conductivity of breccia may be obtained from consideration of the conditions that control the rate of precipitation of chlorides and carbonates that occur in the groundwaters of salt basins and the conditions of groundwater flow that exist in collapse breccia.

<u>Fracturing of Overlying "Barrier" Layers</u> - The TASC model, to date, has included the existence of "barrier layers" immediately above and below the repository layer. These barrier layers are of low permeability and, as such, provide additional protection against the escape of the radioactive wastes. However, one of the common consequences of salt dissolution is the collapse and subsidence of the overlying strata. Consideration of the surface subsidence that follows the dissolution of salt over an area suggests that certain of the overlying stratigraphic formations may undergo strains adequate to cause fracturing. This would be particularly true for those formations which are brittle.

In terms of the development of the TASC model, it appears appropriate to increase the permeability and porosity of the overlying barrier layers simultaneously or shortly after the development of breccia blankets or sufficiently large solution cavities which could be thought to result in subsidence of the overlying areas. Furthermore, in terms of site suitability criteria it would be advisable to avoid areas of existing or potential mining or hydrocarbon production that could cause subsidence and fracturing of the overlying strata.

Influence of Aquifers Adjacent To Soluble Strata - The formation of dissolution cavities and associated collapse breccia are features which are controlled by certain geological and hydrological processes. The refinement of the TASC model and the development of guidelines relative to site suitability criteria requires that we obtain a good understanding of the effect of these natural processes on the generation of the dissolution collapse features. One factor that seems to have a strong effect on the location of dissolution cavities is the presence of permeable rock adjacent to the bedded salt. Furthermore, there appears to be a high correlation between the occurrence of areas of substantial surface subsidence and the existence of major underlying aquifers or features of relatively high permeability. An excellent example of this is the large area of surface subsidence known as the San Simone Swale which overlies the Capital Reef Limestone, a coral reef of high permeability. Another example is the association of the dissolution breccia blanket at the top of the Salado Fm. (the major salt stratum of the Delaware Basin) where it is in contact with the Rustler Fm. which contains clastic sedimentary rock zones of apparently substantial permeability.

Additional data on this association should be sought relative to the distribution of the channel sands of the Bell Canyon Fm. and the thinning, fracturing or absence of the overlying, thin, tight shale units (the Trap and Lamar) of the Bell Canyon Fm. and the distribution data would strengthen our understanding of the mechanics and distribution of the dissolution process as well as provide additional guidance in the development of site suitability criteria.

Depth and Zone of Salt Dissolution - The work by Dr. Roger Anderson[1] which documents the existence of dissolution activity at depths of approximately 3000 ft represents a substantial departure from earlier concepts that the dissolution phenomena are limited to depths of a few hundred, possibly a thousand, feet.

Of significance to the further development of the TASC model, this finding indicates that dissolution can occur at various depths with the actual location depending upon the particular geologic and hydrologic conditions.

[1] University of New Mexico, Albuquerque, New Mexico

Exploration Procedures - A better understanding of the development of dissolution cavities and collapse breccia requires knowledge of the location of these features relative to the geological and hydrological conditions of a basin as well as their actual frequency and stage of development. One of the problems, to date, has been the difficulty of remotely detecting the presence of dissolution activity. However, additional insight into appropriate exploration procedures to be considered for utilization in establishing site selection criteria were obtained from consideration of some of the new information obtained from the two conferences and the WIPP site review.

The first is the use of geophysical techniques for the detection of breccia features. It was pointed out that a combination of seismic and resistivity methods have been found to be useful in detecting the breccia blanket that forms at the base of the Rustler Formation. The usefulness of these techniques for the detection of breccia pipes is not as clear, however, for two reasons. The first is the obvious geometric problem that the grid of the geophysical survey must be small enough so that the breccia pipes, which are of limited areal extent, are detected. The second is that the procedures may only work for a breccia of substantial porosity and, therefore, would not detect those that are partially or completely healed with salt.

Another exploration technique which appears to have good applicability toward the development of site selection criteria is that employed by Dr. Roger Anderson[(1)] in which he interprets detailed well logs in terms of changes in the stratigraphy which, in turn, are interpreted in terms of dissolution activity. The utilization of this technique in other parts of the Delaware Basin and possibly in other salt basins would be likely to yield a more thorough understanding of the geological and hydrological processes that occur.

[(1)] University of New Mexico, Albuquerque, New Mexico

# 3. PROBABILITY OF EXISTENCE OF UNDETECTED FAULTS

The concern relative to the existence of faults in the vicinity of nuclear waste repositories in that they may provide a conduit for the flow of groundwater and the escape of the radioactive wastes. The rock associated with a fault plane or a fault zone may range in hydraulic conductivity from that of an open, brecciated, highly permeable material to a tight, cemented and/or gouge-filled zone with very low porosity and permeability. Although of low hydraulic conductivity, the healed faults may still have consequence relative to site integrity because of the potential for renewed movement along such pre-existing faults and the associated development of increased porosity and permeability. Therefore, in this study of determining the efficacy of exploration methods in detecting faults, we have included consideration of all faults regardless of their present hydraulic conductivity characteristics.

## 3.1 Data Sources and Method of Study

Best available sources of information on fault investigations are considered to be the geologic reports of power plants which represent thorough and well-documented compilations of geological data. On a typical nuclear site investigation, the initial site study includes geological mapping, geophysical surveys and test borings. The results are presented in a Preliminary Safety Analysis Report (PSAR). During construction of a nuclear power plant, detailed geological mapping is conducted in the excavations to further document the geological conditions at a site. The results of these studies are presented in a Final Safety Analysis Report (FSAR). The efficacy of exploration techniques relative to the detecting of faults can be evaluated by comparing the geological findings during excavation with the presumed geological conditions as determined from the initial site studies.

## 3.2 Results of Study of PSARs and FSARs

3.2.1 A summary of the geological studies of several nuclear stations in terms of fault detection is presented in Table 2. Brief descriptions of the fault exploration programs at the nuclear stations are given below.

### 3.2.2 North Anna Station, Mineral, Virginia

A fault was uncovered during the excavation for Units 3 and 4. Eleven exploratory borings intersected the fault during the original site study, but in none of the borings was the fault recognized as such. Evidence of faulting, including one or more of the following - extreme weathering of the rock; extreme fracturing of the rock, or the presence of clay gouge or chlorite - was found in all eleven borings.

### 3.2.3 Robert E. Ginna Station, Ontario, New York

During the examination of a nearby site, a fault was discovered that, when projected, passed near the already-operating Ginna Station. Additional borings were conducted to locate and date the fault. Three borings intersected the fault and in all three the fault was recognized as such. Three borings that did not intersect the main fault recovered microfractured rock, gouge, or "possibly brecciated" rock. Low-angle slickensides were distributed throughout many of the remaining cores. The fault was recognized in the three borings because its existence and location were known.

### 3.2.4 Sears Island Station, Sears Island, Maine

At Sears Island, Maine a fault zone was discovered by trenching across a bedrock low that was determined from refraction seismic studies. Nine borings probably penetrated the zone during the initial site exploration, but a fault was not inferred from interpretation of any of the borings. The zone was a wide near-vertical zone of highly weathered rock, and shear movement was not inferred until two trenches were excavated through the zone.

### 3.2.5 Millstone Station, Waterford, Connecticut

During the excavation for Unit 3, seven minor faults were discovered. Because the faults were all steeply dipping planes, only one boring had intersected a fault during the exploration program. No fault was inferred in this boring, although the rock condition was noted as being highly weathered and highly fractured.

3.2.6 Shearon Harris Station, Bonsal, North Carolina

A fault was discovered in the excavation for the radiation-waste building. A report on the characteristics and location of the fault is due for release during late spring, 1977.

3.2.7 Virgil C. Summer Station, Broad River, South Carolina

A near-vertical fault was discovered during the excavation. None of the borings in the site study intersected the zone.

3.2.8 Catawba Station, Lake Wylie, South Carolina

Four brecciated zones were discovered during the excavation. Several borings may have intersected the zones, but the boring logs lack descriptions of the rock.

3.3 Discussion of Results of Fault Investigations

Even though a boring may intersect a fault, there are many reasons why the fault may not be detected or recognized. Some of the reasons are outlined below.

3.3.1 Fractures are common in most rock. Most rock contains fractures, although the spacing of fractures may range from microns to tens of meters. Zones of closely-spaced and parallel to subparallel fractures are common within fault zones, but can also be found in non-faulted rock (e.g., cleavage fractures). Therefore, the presence of fractures alone does not necessarily imply the presence of a fault.

3.3.2 Severe weathering is often found in non-faulted rock. Some faults provide avenues for water movement and are planes of anomalously severe weathering. Open joints, or fractures, can produce the same effect, however, and so weathering cannot be used as a criterion for faulting without additional information.

3.3.3 Slickensides, or scratches, produced by shear movements, can be found on surfaces that are not throughgoing faults. Minor readjustments caused by crustal rebound or tectonic stresses can produce slickensided joints. Thus, the presence of a slickensided surface in a drill core does not necessarily denote a throughgoing or continuous fault.

3.3.4 Faults are not always planar. Faults commonly are not planes with the result that features found in one borehole can rarely be located on a plane established by similar features in three other boreholes. Therefore, if several of the above features are present in adjacent borings, it is not always possible to confirm or deny the presence of a fault by attempting to locate the features on a plane in three-dimensional space.

3.3.5 Secondary mineralization may result in misinterpretation. Secondary mineralization may exist throughout a fault zone with the result that, if all other evidence of shear displacement has been eliminated, a geologist may identify the zone not as a fault but merely as a vein of different rock type.

3.3.6 Not all faults juxtapose differing rock types. One of the best criteria for fault recognition in a boring is the contiguity of differing rock types that can be explained only by faulting, such as that of sandstone and shale in contact along a plane not parallel to bedding. In many instances, however, the movement along a fault is not sufficient or in the correct direction to juxtapose differing rock types. This problem is more obvious in igneous and metamorphic rocks, where bedding is absent or obliterated. Therefore, it is common that a fault is not recognized because the rocks on opposite sides of the shear surface are of identical lithology.

### 3.4 Tentative Recommendation

The study described above is limited to about a dozen nuclear power plant sites and, therefore, any conclusions based on this study should be considered tentative. A more extensive data acquisition program should be conducted so that the efficacy of exploration techniques relative to fault detection in a greater variety of geological terrains can be determined.

Even though limited in scope, this study indicates that the likelihood of unequivocal identification of a fault by means of a boring program is unlikely. There are two reasons for this. The first is that the boring must intersect the fault, an event of low probability when the fault has a steep dip and borings are vertical. The second is the difficulty of positively identifying a fault from the characteristics of the rock core obtained during the drilling.

Therefore, the tentative results of this study suggest that the probability of a pre-existing fault remaining undetected during the investigation phase of a repository site investigation approaches *unity*.

## TABLE 1 - PORTIONS OF INFORMATION SUMMARIES RELATIVE TO CERTAIN TOPICS PERTINENT TO DEVELOPMENT OF TASC MODEL

| Topic | WIPP Site and Salt Dissolution Review Meeting[(1)] | | Symposia on the Ochoan and Guadalupian Rocks of Southeastern New Mexico and West Texas[(2)] | |
|---|---|---|---|---|
| In-Situ Permeability | I-A-6 | (p. 4) | I-B-7 | (p. 2) |
| The Rate of Formation of Breccia Pipes | I-B-2-e<br>I-C-10<br>II-B-4 | (p. 2)<br>(p. 6)<br>(p. 7) | I-B-2, 3<br>I-D-4<br>II-D-1, 2<br>II-D-5 | (p. 1, 2)<br>(p. 3)<br>(p. 5)<br>(p. 5) |
| "Time Window" of High Permeability Breccia | I-C-6 | (p. 6) | I-B-6 | (p. 2) |
| Fracturing of Overlying "Barrier" Layers | II-B<br>I-A-7 | (p. 2)<br>(p. 4) | II-B-3 | (p. 3) |
| Influence of Aquifers Adjacent to Soluble Strata | | | II-C-2<br>II-E-3, 6<br>I-A-1-c, d | (p. 5)<br>(p. 6)<br>(p. 7) |
| Zone and Depth of Salt Dissolution | I-B-1-b, d<br>I-B-2-b<br>I-A-1-b<br>I-C-3 | (p. 1)<br>(p. 1)<br>(p. 3)<br>(p. 5) | II-D-4 | (p. 5) |
| Exploration Procedures | I-2-d<br>I-B-1 | (p. 2)<br>(p. 4) | | |

(1) Page numbers refer to pages in Appendix D.
(2) Page numbers refer to pages in Appendix E.

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## TABLE 2 - SUMMARY OF NUCLEAR SITE INVESTIGATION RELATIVE TO THE DETECTION OF FAULTS

| Site | Number of Borings Intersecting the Fault(s) | Observations and Interpretation in PSAR |
|---|---|---|
| North Anna<br>Mineral, Virginia | 11 | Noted the occurrence of rock fracturing and weathering, presence of chlorite and gouge. No faulting was inferred. |
| Robert E. Ginna<br>Ontario, New York | 6 | Three borings intersected main fault and three other borings intersected minor faults. All fault intersections recognized as such; however, the fault location was known prior to drilling. |
| Sears Island<br>Sears Island, Maine | 9 | All 9 borings intersected a zone of highly weathered phyllite. No faulting was inferred. |
| Millstone<br>Waterford, Connecticut | 1 | Boring encountered rock which was highly fractured and weathered. No faulting was inferred. |
| Shearon Harris<br>Bonsal, North Carolina | ? | Fault discovered during excavation. Report yet to be released. |
| Virgil C. Summer<br>Broad River, South Carolina | 0 | Fault discovered during excavation. |
| Catawba<br>Lake Wylie, South Carolina | Possibly Several | Boring logs list only rock lithologies with no details of other characteristics. No faulting was inferred. |

PRELIMINARY ESTIMATES OF THE PERMEABILITY AND POROSITY OF SALT FROM RESEARCH TO DATE (8 FEB 77)

I. Data From Literature

A. Gloyna and Reynolds, 1961 (Reactor Fuel Waste Disposal Project Study for AEC)

1. Permeabilities

a. Bedded salt 0.0 to 2.3 x $10^{-8}$ cm/sec

(1) Sample from 645 feet deep in Hutchinson, Kansas

(2) Confining pressures of test runs 500-2500 psi

(3) Results show permeability largely a function of net confining pressure.

(4) Noted in nearly all liquid tests that permeability decreased with the duration of the test.

(5) Brine solutions had permeability which averaged 32% of the non-reactive liquid K.

(6) Tests made on solid crystal showed no flow can occur through crystals themselves.

(7) Lab tests involved 7-14 days consolidation time; however this is not comparable to consolidation over geologic time.

(8) In-situ permeability most likely is lower.

b. Dome salt 0.0 to 1.5 x $10^{-4}$ cm/sec

(1) Sample from 700 feet deep in Grand Saline, Texas

(2) See Bedded salt (2) through (8).

2. Porosities

a. Hutchinson Salt (Bedded)

(1) Average .0059

(2) Range .0042 to .0076

b. Grand Saline Salt (Dome)

(1) Average .0171

(2) Range .0117 to .0225

c. Note: Lower porosity of bedded salt probably due to greater impurity content.

B. Gard, L. M., *et al.*, 1962. Project Gnome Final Report - Hydrologic and Geologic Studies (Samples from Gnome Shaft)

1. Porosities

a.

| Depth | Porosity |
|---|---|
| 715 | .027 |
| 720-725 | .011 |
| 1,013-1,015 | .051 |
| 1,019-1,023 | .012 |
| 1,120-1,123 | .071 |
| 1,130 | .017 |
| 1,147-1,152 | .008 |
| 1,173-1,178 | .032 |
| 1,177-1,181 | .027 |

b. Range .008 to .071

c. Average .028

C. BNWL 1900

1. Permeability Range: $5 \times 10^{-10}$ to $5 \times 10^{-6}$ cm/sec

D. Don Towse - Livermore: Recommendations for Repository Layer

| | Low | Medium | High |
|---|---|---|---|
| 1. Porosity | 0 | .05 | .3 |
| 2. Permeability | 0 | $9.7 \times 10^{-10}$ cm/sec | $9.7 \times 10^{-9}$ cm/sec |

II. Recommended Values

A. Permeability (Horizontal and Vertical)

1. Range - $10^{-10}$ to $10^{-4}$ cm/sec

2. Preferred Value - $10^{-7}$ cm/sec *

3. Rationale: The end points of the range represent the maximum and minimum (excluding zero) values reported in the literature reviewed to date. As no distribution of values was available, the geometric mean of the range was taken as the preferred value.

B. Porosity

1. Range - 0.004 to 0.07

2. Preferred Value - 0.01

3. Rationale: The end points of the range represent the maximum and minimum values reported in the literature reviewed to date. The distribution of values was used to determine a preferred value.

III. Bibliography

A. Gard, L. M., *et al.*, 1962. Project Gnome Report - Hydrologic and Geologic Studies: PNE - 130F.

B. Gard, L. M., 1968. Geologic Studies, Project Gnome, Eddy County, New Mexico: USGS Prof. Paper 589.

C. Gioyna, E. F. and Reynold, T. D., 1961. Permeability Measurements of Rock Salt: Journal of Geophysical Research, V. 66, pp. 3913-3921.

D. Towse, Don, 1976. Communication dated 12/14/76 from LLL.

E. Schneider, K. J. and Platt, A. M., 1974. High-Level Radioactive Waste Management Alternatives: BNWL 1900.

*This value was subsequently changed to $10^{-9}$ cm/sec.

# SALT DISSOLUTION AND COLLAPSE STRUCTURES

The following outline describes the mechanisms, occurrences, and approximate dimensions of various salt solution collapse structures found in the Delaware Basin in New Mexico and Texas, the Supai Salt Basin in Arizona, the Michigan Basin, and in local evaporite deposits in the Madison Group of southwestern Montana. To date, no detailed subsurface investigations of these features have been published. Air photo information (Arizona) and salt concentration variations in the Pecos River (New Mexico and Texas) evidence present salt solution activity in the Supai Salt Basin and Delaware Basin. In most cases, the breccia formed by these collapse events would be expected to cause a marked increase in the permeability of the immediate area.

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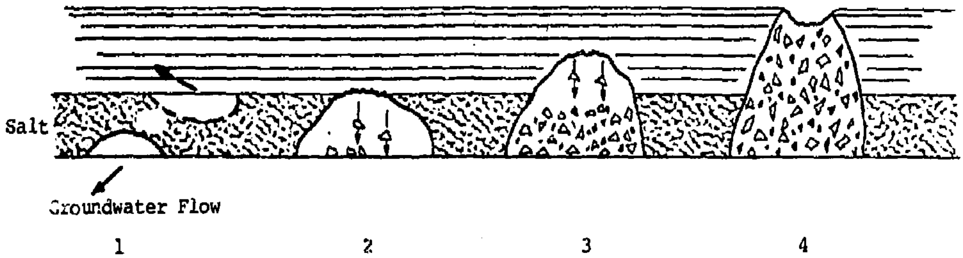
## FAILURE IN SALT

I. CASE 1 - Solution Collapse Producing Vertical Breccia Pipe

A. Schematic Diagram




B. Sequence

1. Initial cavity developed from solution by moving groundwater in an adjacent permeable unit.

2. With continued solution caving begins.

3. Upward migration of caving front occurs through overlying formations.

4. Breccia pipe may reach ground surface.

C. Occurrences

1. Delaware Basin. Frequent occurrence along Pecos River and 18-20 miles east of Carlsbad. Dimensions: Diameter-700-1200 feet; depth-500 to 800 feet (Figs. 1 and 2).

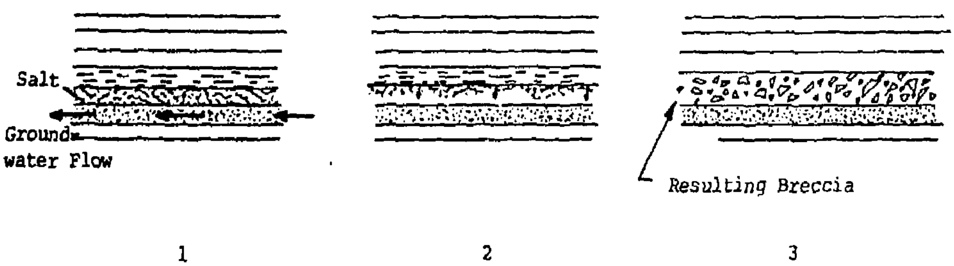
2. Michigan Basin. Frequent occurrence in Mackinac Straits Region and in random localities around margin of Basin. Dimensions: Diameter-10's to 100's of feet; depth-700 to 1500 feet (Mackinac Straits area) (Figs. 3 and 4).

3. Supai Salt Basin. No dimensions given.

4. Windsor, Ontario. Brinefield subsidence. Dimensions: Diameter-500 feet; depth-1000+ feet.

II. CASE 2 - Solution Collapse Producing Horizontal Breccia Zone

A. Schematic Diagram




B. Sequence

1. Initial ground water flow in adjacent permeable unit.

2. Solution of overlying or underlying salt bed.

3. Collapse of overlying unit.

C. Occurrences

1. Delaware Basin. Solution breccia zone at the base of the Rustler Fm. Maximum thickness-150 feet.

2. Michigan Basin. Occurs in the megabreccia blocks in the Mackinac Straits Region. Average thickness-several inches (Fig. 3).

3. Madison Group in southwestern Montana. Thickness range-inches to 100 feet.

4. Other reported occurrences in the Missippian rocks of western Canada and the Devonian rocks of Alberta and Manitoba.

III. CASE 3 - Solution Collapse Producing Linear Trough Subsidence and Brecciation

A. Similar to CASE 1; Linear rather than circular.

B. Sequence

1. Groundwater flow along adjacent linear permeable zones (i.e., concentration of sandstone or fractured rock).

C. Occurrences

1. Delaware Basin

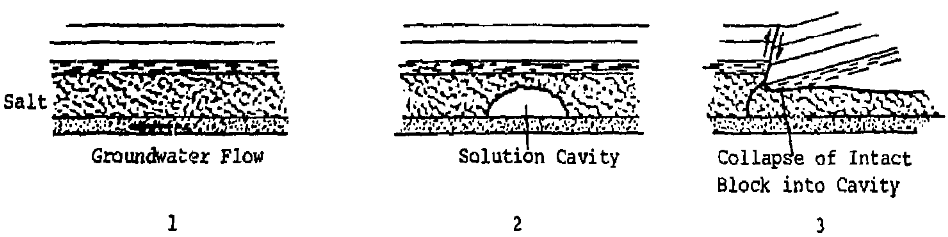
a. Shallow east-west troughs in gypsum plane on east side of Delaware Basin. Dimensions: Width-200 feet to 1 mile; length-0.5 to 10 miles; depth-not reported (Figs. 1 and 5).

b. Large trough parallel to the Pecos River from Carlsbad, New Mexico to Toyan Lake, Texas. Dimensions: width-1000's of feet; length-120 miles; depth-1300 feet (Fig. 6).

2. South limb of the Holbrook Anticline in the Supai Salt Basin (Figs. 7 and 8).

IV. CASE 4 - Solution Collapse Producing Megabreccia

A. *Schematic Diagram*




B. Sequence

1. Groundwater flow through adjacent permeable unit.

2. Solution of salt-producing cavity.

3. Collapse of intact block producing steeply dipping fault.

C. Occurrences

1. Mackinac Straits Region of the Michigan Basin. Dimensions: blocks 10's to 100's of feet with fault boundaries; dimensions of fault boundaries not reported (Figs. 3 and 4).

V. MISCELLANEOUS INFORMATION

A. General

1. Breccia fragments are generally angular and range in size from clay to 20 foot blocks.

2. Breccias are both indurated and non-indurated resulting in zero permeability to very high permeability. However, immediately upon formation, the permeability is a function of the grain size distribution and packing arrangement of the angular fragments.

3. Vertical extent of brecciation is a function of original cavity size and depth.

B. Maximum vertical fragment drop-600 feet, reported in Mackinac Straits Region by Landes (1945).

C. Multiple Events

1. Older alluvial filled sinks exposed in walls of younger sinks in Supai Salt Basin.

2. Breccia fragments within breccia in the Madison Group in southwest Montana.

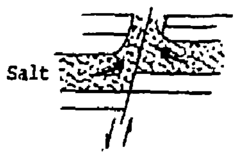
D. Present Activity Documentation

1. Comparison of air photos over a 17-year interval (Supai Salt Basin) showed new collapse features.

2. Increase in percentage of salt in solution in the Pecos River from the point where it starts across the Permian evaporites to point where it exits is evidence of present rapid solution.

E. Flow of Salt in Faults

1. Schematic Diagram




2. Flow is intermediate in character between fissure filling and salt dome. Flow of salt may force walls apart deforming the adjacent rock.

3. Large scale occurrences are frequently accompanied by the development of subsidence blocks in the adjacent area.

4. Halite rarely fractures except at shallow depths.

5. The ease of deformation of halite increases very markedly with rising temperatures.

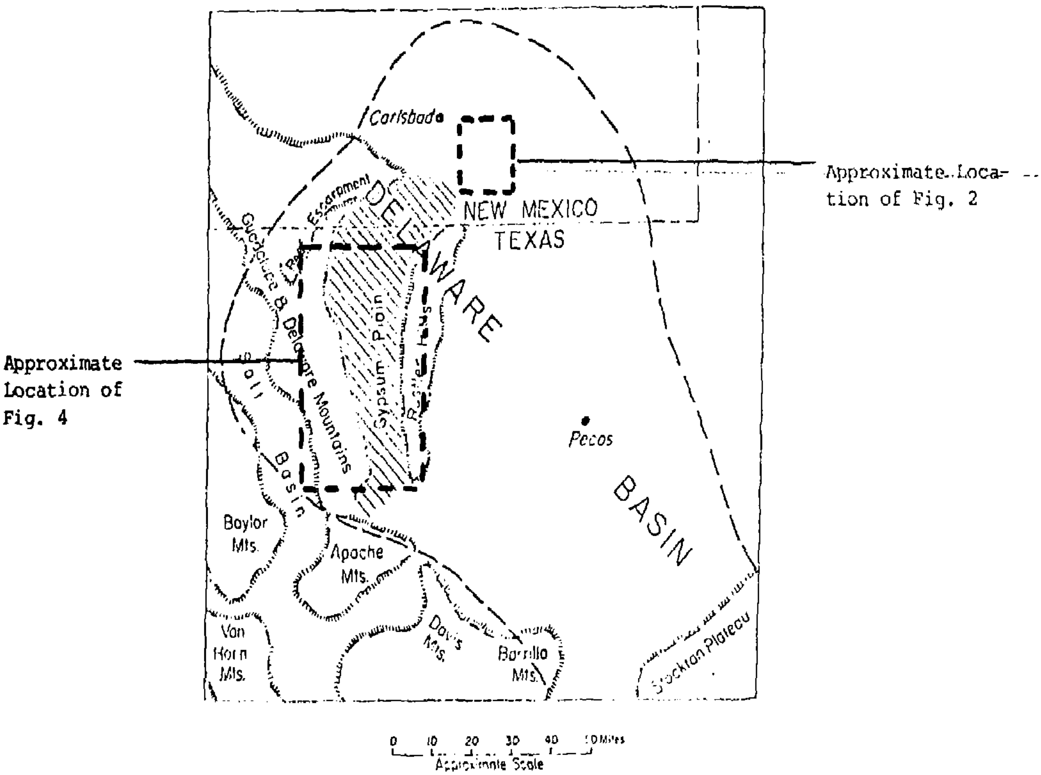



Fig. 1 - Index Map Showing the Locations of the Delaware Basin and Figures 2 and 4 (After Olive, 1957).

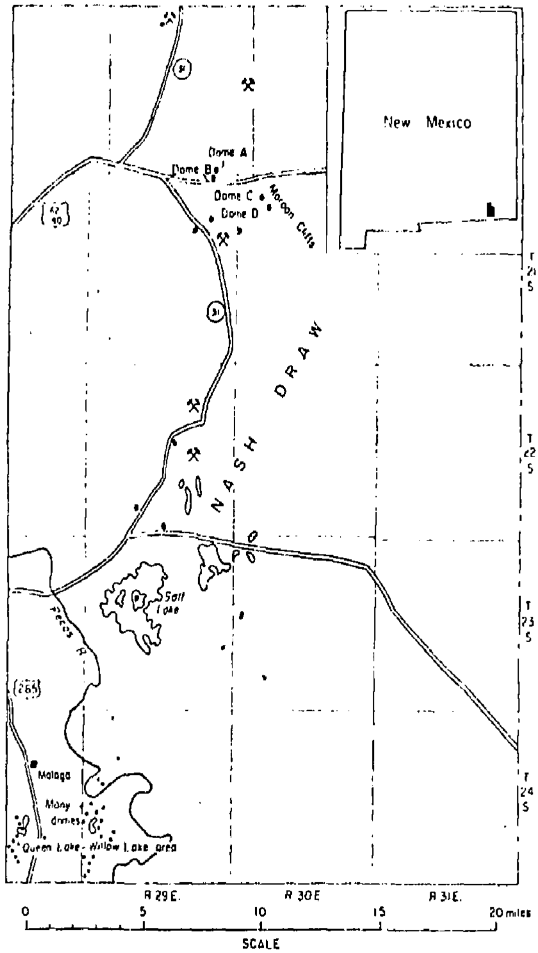



Fig. 2 - Index Map Showing the Locations of Domal Structures with Brecciated Cores in the Delaware Basin (After Vine, 1960).

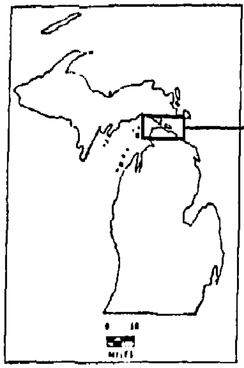



Fig. 3 - Index Map Showing the Location of the Mackinac Straits Region.

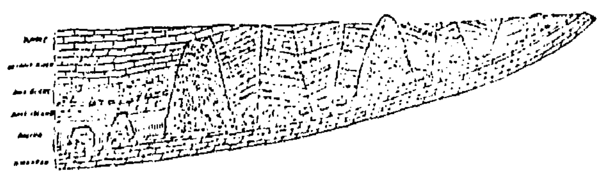



Fig. 4 - Hypothetical cross section of the Mackinac Straits Region showing collapsed formations above the Niagara limestone, breccia chimneys, and breccia stacks (After Landes, 1945).

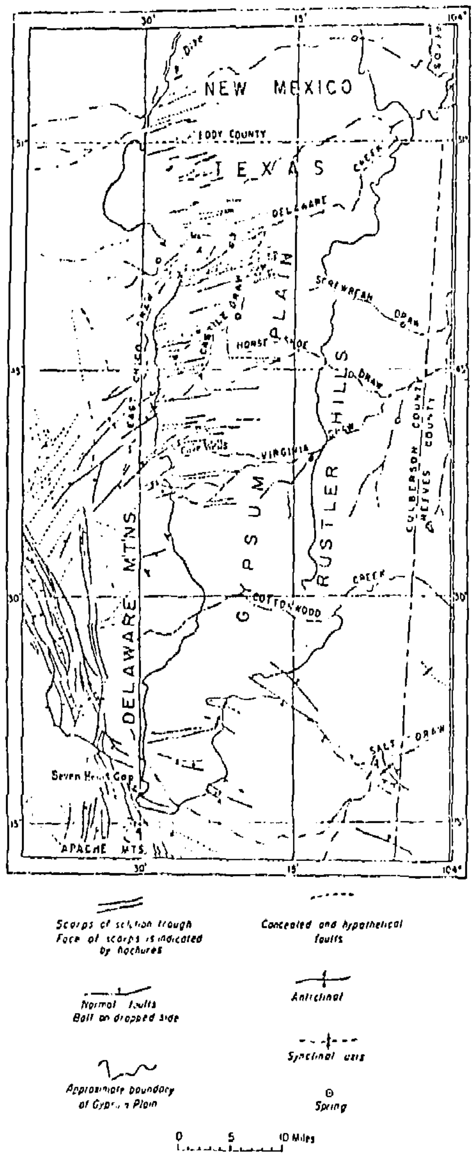



Fig. 5 - Map Showing Distribution of Solution-Subsidence Troughs of the Gypsum Plain in the Delaware Basin (After Olive, 1957).

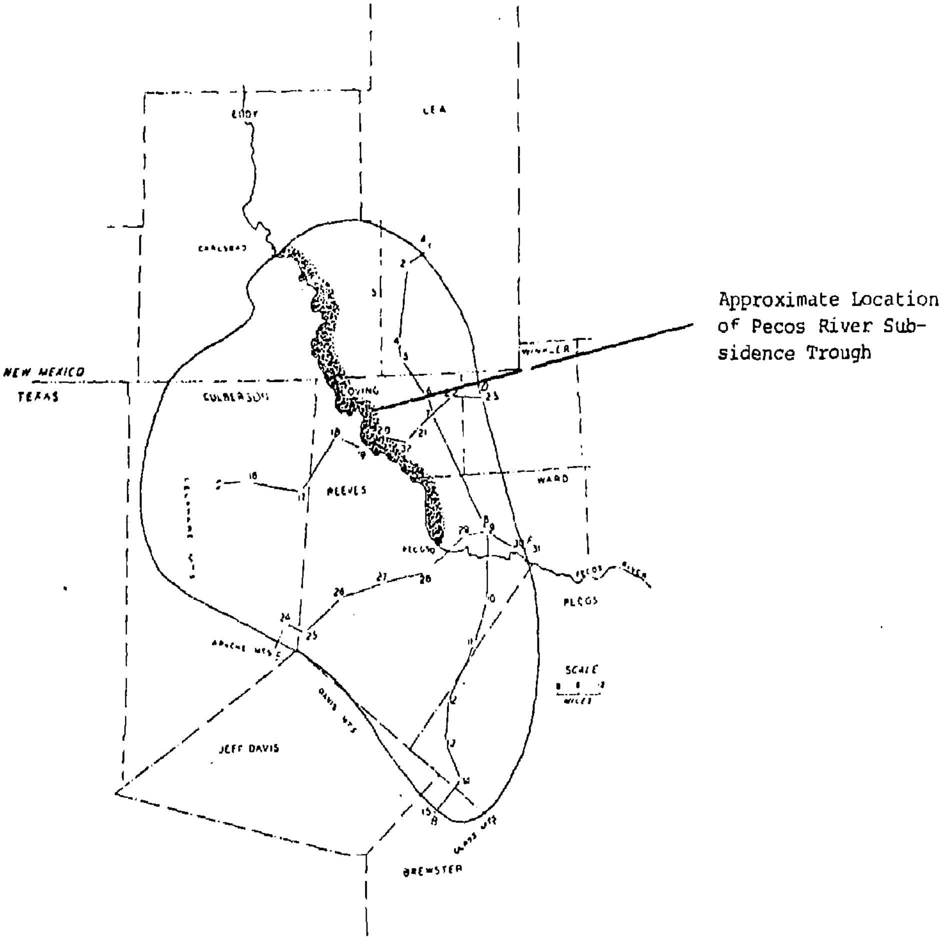



Fig. 6 - Index Map Showing the Approximate Location of the Pecos River Solution-Subsidence Trough (After Adams, 1944).

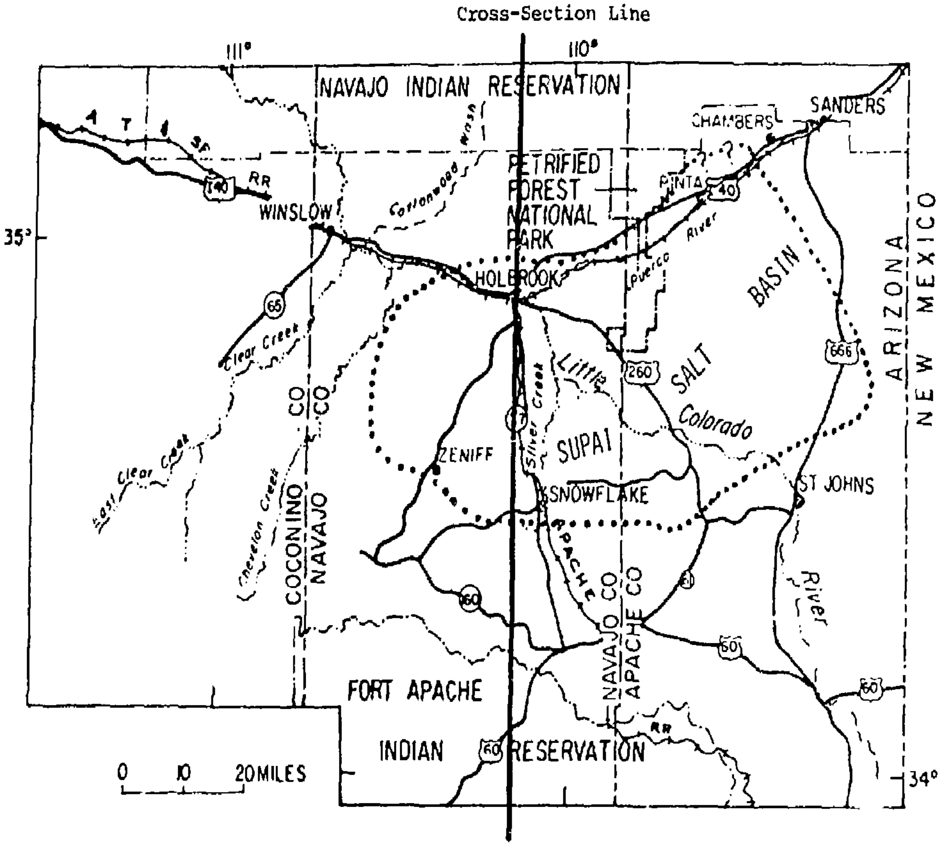



Fig. 7 - Index Map Showing the Location of the Supai Salt Basin (After ERDA 76-43).

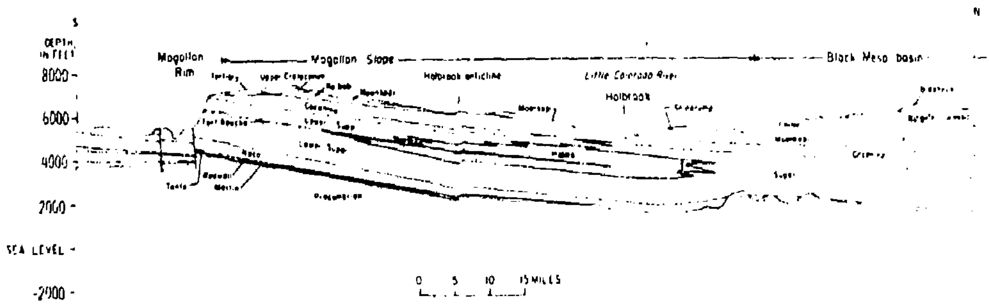



Fig. 8 - Generalized North-South Geologic Cross-Section Through Supai Basin (After ERDA 76-43).

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# PRELIMINARY INPUT FOR FAILURE EVENTS RELATED TO SALT SOLUTION

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PRELIMINARY INPUT FOR FAILURE EVENTS RELATED TO SALT SOLUTION

I. Recommended Values (See Sections II through VI for Data, Rationale and Assumptions)

A. Rate of "Critical Cavity"[1] Development

| Case | Number of Years Required To Produce 1 Critical Cavity/Square Mile |
|---|---|
| 1. 200 M Layer 4 | |
| a. Preferred Value | $4 \times 10^6$ |
| b. Range | $4 \times 10^4$ to $5 \times 10^8$ |
| 2. 1000 M Layer 4 | |
| a. Preferred Value | $9 \times 10^7$ |
| b. Range | $1 \times 10^6$ to $1 \times 10^{10}$ |
| 3. 20 M Layer 4 | |
| a. Preferred Value | $6 \times 10^5$ |
| b. Range | $7 \times 10^3$ to $9 \times 10^7$ |

B. Probability of Existence of Undetected Solution Cavity of a Size Which In the Lifetime of the Repository ($10^6$ years) Could Reach Critical Size.

Recommended Value - 1.0

C. Flow Distance Required To Reduce the Salinity To a Small Enough Value To Allow Radionuclide Sorbtion Activity To Begin

1. Preferred Value - 100 x Thickness of Aquifer

2. Range - 10 x Thickness of Aquifer to Infinity (Salinity is not low enough in steady state to allow radionuclide sorbtion activity to exist)

D. Permeability and Porosity of Collapse Breccias

1. Permeability

   a. Preferred - $10^{-1}$ cm/sec
   b. Range - $10^{-3}$ to 1.0 cm/sec

2. Porosity

   a. Preferred - 0.15
   b. Range - 0.05 to 0.20

---

[1] See II.B.1. for definition of "Critical Cavity"

E. Revised Preferred Permeability of Salt

$10^{-9}$ cm/sec

II. Rate of "Critical Cavity" Development

A. "Critical Solution"[2] Rates

1. 9 $ft^3$/sq mile/year

a. Average rate at which salt has been removed from Saskatchewan area in Canada producing 18 large collapse features and a 23,000 square mile area in which the salt has been totally removed.

b. Solution occurred from late Devonian to present.

c. Assumptions

(1) For specific collapse features, the resultant gravity faults bounding the large blocks dip an average of 70° toward solution cavity (Christiansen, 1967).

(2) Assumes that prior to solution, a relatively uniform thickness of salt (averaging 550 feet thick, based on adjacent areas) once underlay the 23,000 square mile area now devoid of salt.

(3) Assumes average constant rate of solution through geologic time, when, in fact, there is evidence that there were considerable variations in rate.

(4) Assumes average dimensions of the large scale features to be 60 square miles x 550 feet of salt based on data from Rosetown low (144 sq miles x 400 ft salt) and Saskatoon low (47 sq miles x 650 ft salt). Rosetown low is one of the larger discrete features in the area.

(5) Assumes equal distribution of features of the entire basin. However, in some areas, solution collapse features occur in clusters (Vine, 1960; Griswald, 1976; and Landes, 1945).

d. Information and data from References 3, 4 and 5.

2. $2 \times 10^2$ $ft^3$/sq mile/year

a. Average rate of solution for only the Saskatoon low (Saskatchewan, Canada).

---

[2] "Critical solution" is defined as that fraction of total solution which

b. Solution occurred Upper Cretaceous(?) to 12,000 years ago.

c. Assumptions

(1) See 1.c.(1) and 1.c.(3).

d. Information and data from Reference 3.

3. $3 \times 10^1$ $ft^3$/sq mile/year

a. Average rate of solution for only the Rosetown low (Saskatchewan, Canada).

b. Solution occurred Upper Devonian to present.

c. Assumptions

(1) See 1.c.(1) and 1.c.(3).

d. Information and data from Reference 4.

4. $7 \times 10^2$ $ft^3$/sq mile/year

a. Average rate of NaCl discharge in the Pecos River at the present time. (Delaware Basin, New Mexico and Texas.)

b. Use of this rate as the total amount of solution producing "critical" collapse features assumes the following:

(1) All discharge from the basin is occurring in the Pecos River. This would not account for possible groundwater discharge from the basin.

(2) All salt discharge is coming from critical zones, i.e., at depth. However, closer to some marginal portions of the Delaware Basin the salt horizons are at shallower depths. Therefore, the solution in these areas would not be termed "critical."

c. Information and data from References 1, 12 and 13.

5. $6 \times 10^{-2}$ $ft^3$/ sq mile/year

a. Average rate of solution producing surfaced collapse breccia pipes in the Delaware Basin as a whole.

b. Assumptions

(1) Assumes average collapse geometry of 1500 ft diameter, vertical walls, and 850 ft of salt removed. Diameter based on Vine, 1960 and Griswald, 1976 (only an estimation). Thickness of salt removed assumes total removal of the mean of the range of aggregate thickness for the Delaware Basin.

(2) Assumes salt removed beginning relatively soon after deposition (Triassic) to present time based on observations of the Canadian data (solution also began relatively soon after deposition) and on evidence of present solution (see A.4.).

(3) Assumes 100 surfaced collapse features in the Delaware Basin based on Griswald, 1976, estimate.

c. Information and data from References 1, 7 and 17.

6. $1 \times 10^2$ $ft^3$/ sq mile/year

a. Average rate of solution producing surfaced collapse features in the Delaware Basin for the collapsed area only.

b. Assumptions

(1) See 5.b.(1) and 5.b.(2).

c. Information and data from References 1, 7 and 17.

7. $5 \times 10^{-1}$ $ft^3$/sq mile/year

a. Average rate of solution for the Delaware Basin as a whole, producing surfaced collapse breccia pipes and three large areas of subsidence in southern and central Delaware Basin.

b. Assumptions

(1) See 5.b.(1), 5.b.(2) and 5.b.(3).

(2) Assumes (until detailed review of Maley and Huffington, 1953, is completed) that the volume of salt removed in the central and southern Delaware Basin features is comparable to the larger collapse features in Saskatchewan, Canada (i.e., the Rosetown low).

c. Information and data from References 1, 7, 10 and 17.

8. Recommended Critical Solution Values

   a. Preferred - 9 $ft^3$/sq mile/year

   b. Range - 6 x $10^{-2}$ to 7 x $10^2$ $ft^3$/sq mile/year

B. "Critical Cavity" Size

1. The "Critical Cavity" size represents the minimum volume of salt dissolution in the immediate vicinity (below) the repository necessary to cause collapse of the overlying strata, resulting in the connection of the repository to the aquifer (Layer 2).

2. Size

   a. Size is a function of the vertical distance to the aquifer and volume adequate to accommodate the volume increase of the overlying rock upon collapse.

   b. The volume used was that of a cylinder with (1) a diameter 1/3 of the height of the resultant breccia pipe (based on rough average of 1:3 diameter to depth ratio estimated for some breccia pipes in the Delaware Basin) and (2) a height 1/6 of the height of the resultant breccia pipe. This is to accommodate an assumed maximum increase in the porosity of the overlying rock to a value of 20 percent.

   c. Critical Cavity Sizes (Layer 4 varied, all other layers 200 M)

      (1) 200 M Repository Layer - 3 x $10^7$ $ft^3$
      (2) 1000 M Repository Layer - 9 x $10^8$ $ft^3$
      (3) 20 M Repository Layer - 5 x $10^6$ $ft^3$

3. Assumptions

   Assumes collapse breccia pipe formation is strictly a function of volume of salt removed. Other factors would include cavity geometry, roof rock strength characteristics and quantity and character of non-salt interbeds.

C. Rate of Critical Cavity Formation Calculation

1. Divide critical cavity volume by critical rate of solution resulting in the number of years required to produce one critical cavity per square mile. (See I.A. for resulting values.)

III. Probability of Existence of Undetected Solution Cavity of a Size Which In the Lifetime of the Repository ($10^6$ years) Could Reach Critical Size.

The estimate of a probability of 1.0 is based on two factors.

1. Though the theory exists for the geophysical (seismic) detection of solution cavities at depth, at present, the technology has not been developed to detect solution cavities at depths exceeding 1,000 to 2,000 feet (Cook, 1974).

2. With the estimated rate of production of critical cavities since the formation of existing deposits, there is a high probability for the present existence of several cavities in the near vicinity of a repository.

IV. Flow Distance Required To Decrease the Salinity To a Small Enough Value To Allow Radionuclide Sorbtion Activity To Exist

A. Factors

1. Volume and salinity of effluent solution.

2. Volume and character of water flow in the aquifer.

   a. Aquifer thickness
   b. Aquifer permeability and porosity
   c. Hydraulic gradient

3. Salt dispersion rate.

4. Chemistry of radionuclide sorbtion in the presence and absence of salt ions in water.

B. Though factors 1-3 can be accurately modeled, the unknown character of factor 4 eliminates the possibility accurately modeling this parameter at present (Towse, 1977).

C. A conjecture, based on dispersion, is

1. Preferred Value - 100 x aquifer thickness.
2. Range - 10 x aquifer thickness to infinity. (See I.C.2.)

V. Permeability and Porosity of Collapse Breccia

A. As no in-situ data has been reviewed to date, the hydrologic characteristics of a collapse breccia has been assumed to be similar to a clean sand and gravel mix (Terzaghi and Peck, 1967· Morris and Johnson, 1967).

1. Permeability

   a. Preferred - $10^{-1}$ cm/sec
   b. Range - $10^{-3}$ to 1.0 cm/sec

2. Porosity

   a. Preferred - 0.15
   b. Range - 0.05 to 0.2

VI. Revised Preferred Permeability of Salt

A. Upon recent acquisition of more information from Gloyna and Reynolds, 1961, and acquisition of Aufricht and Howard, 1961, the preferred value of salt permeability has been revised downward from $10^{-7}$ cm/sec to $10^{-9}$ cm/sec. This revision is a product of the weight of distribution of test values toward the lower end of the reported range ($10^{-10}$ to $10^{-4}$ cm/sec, excluding zero).

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WIPP SITE AND SALT DISSOLUTION REVIEW MEETING
SUMMARY OF INFORMATION - 5 APRIL 1977

PART I

28 March 1977: Field Review and Discussion of WIPP Site Area with Dr. George Griswald, Sandia Labs

I. Salt Dissolution in the Northern Delaware Basin

A. See Figures 1 and 2.

B. Salt Dissolution

1. The well known and better understood salt dissolution occurs as what is termed the salt dissolution "front."

a. See Figure 1.

b. As one moves east or down dip, the evaporite horizons subject to dissolution are stratigraphically higher.

c. Geophysical work is now successful in detecting the solution collapse/brine aquifer between the Salado and Ruster Formations using seismic survey and electrical resistivity.

d. C. L. Jones estimates the depth of present dissolution in this zone to be 300-400 feet, locally up to 1000 feet.

e. The "dissolution front" is frequently represented as a line on a map representing the forward edge of the region of salt removal. This representation may be over simplified, as there is some evidence of solution collapse features beyond this "dissolution front."

2. The less well understood salt dissolution occurs at what have been termed "breccia pipes."

a. See Figure 1.

b. The breccia pipes appear to be much deeper seated features than the dissolution front.

c. The evidence is as follows: (see Figures 1 and 2)

(1) One confirmed case, underlying Dome C, where the breccia pipe was encountered in a deep potash mine in the middle of the Salado Formation.

(2) One confirmed case in the Clayton Basin to the north where a potash exploratory hole cored 1200 feet of breccia before it was abandoned (Weaver Pipe).

(3) One unsurfaced, suspected case where the floor of a deep potash mine caved in.

(4) Two additional suspected cases from the geophysical work to date.

(5) Numerous areas with circular topographic form (sinks and domes) which are potential pipes.

d. Geophysical work to date has not been successful in detecting these features because they are deeper seated, more randomly distributed (no trends found to date) and may not always show surface expression. Geophysical work is to resume in the near future.

e. The depth of these features is unknown. They are suspected to go down to at least the bottom of the Salado Fm., perhaps well into or through the Castile in some cases. The originating permeable, water circulation horizons would be either fractured anhydrite units within the Castile or the Bell Canyon sandstone underlying the Castile.

3. The San Simon Swale (overlying the Capitan Reef) may be a larger scale block subsidence feature [analogous to the megabreccia blocks found in the Williston Basin and Michigan Basin].

II. Miscellaneous Information

A. Drill holes have encountered brine under very high artesian pressures from the Castile Formation.

B. Potash mining in the area has resulted in significant subsidence at the surface (3-4 feet) and very likely extensive fracturing of the overlying strata (in particular, the brittle dolomite aquifers on the Rustler Formation).

C. Natural gas and fluid removal from the underlying Pennsylvania and Perman Rocks may also result in subsidence of the overlying strata.

D. Brine inclusions up to 100,000 gallons have been encountered in the Salado Formation.

E. Four to five sets of air photos (going back to late 1930's) exist, but no comparative study has been completed yet.

F. May 3-7 there will be a New Mexico Geological Society Meeting at which a number of papers will be presented about this area and about dissolution features.

PART II

29, 30 March 1977: Salt Dissolution Review Meeting. The information presented here is a combination of the essential points of each presentation and specific new information to the project.

I. Regional Papers

A. "Salt dissolution in southeastern New Mexico" and "The San Simon Swale" - Charlie Jones, U.S.G.S.

1. Salt Dissolution:

a. May occur at the top, bottom, and edge of salt deposits.

b. Is generally shallow (400-800 ft), locally up to 1000 ft.

c. Is cyclic, dependent on diastrophism and climate.

2. Periods of dissolution in southwestern New Mexico.

a. Pre-Triassic.

b. Post-Triassic to Pre-Cretaceous.

c. Post-Cretaceous to Pre-Ogallala (Pliocene).

d. Post-Ogallala to Pre-Early Pleistocene.

e. Post-mid Pleistocene to Present.

3. C. L. Jones believes the maximum dissolution occurred Pre-Triassic (NOTE: There are several others who strongly feel it is Pleistocene).

4. C. L. Jones believes that there is no significant dissolution at great depths in this area. He believes only in the salt dissolution front as described under the WIPP Site in Part I. B. 1. of this report. (NOTE: There are others who feel the deep breccia pipes, as described in Part I. B. 2, of this report, are potentially a very real problem.)

5. Salt dissolution at depth of up to 3,000 feet has been documented in the Williston Basin.

6. Brittle fractures have been observed in a salt mine at a depth of 900 feet.

7. Agreed that potash mine subsidence which causes fracturing of the overlying strata may create increased groundwater circulation and possibly increased rates of salt dissolution.

8. San Simon Sink.

   a. Approximately one square mile in size and 30 feet deep.

   b. Last subsidence event is 1930's.

   c. Overlies the Capitan Reef.

   d. There is some structure in the salt due to down dip flow against the reef.

   e. Maximum calculated fragment drop is 500 feet.

   f. (Maximum calculated fragment drop known anywhere is 1500 ft which is in the Paradox Basin.)

9. Estimated several hundred sinks in New Mexico.

B. "Dissolution Breccia and Collapse Breccia in the Delaware Basin" - Dr. Roger Anderson, University of New Mexico.

1. Initial project involved detailed correlation of the Castile and Lower Salado lamina from drill core. Correlations made over a distance of up to 115 km.

2. Also encountered:

   a. Dissolution breccia consisting of small blocks of intact anhydrite in a clay and granular anhydrite matrix.

   b. Collapse breccia consisting of angular anhydrite blocks with no matrix. This collapse breccia is commonly found overlying the dissolution breccia.

   c. Breccia zones encountered in the west side of the basin (structurally higher) correlate with salt horizons on the east side of the basin.

3. Also encountered on the west side of the basin are buttes and stacks, some of which are composed of cemented breccias. These stacks may represent the erosional remnants of former breccia pipes. [There are some potentially analogous cemented breccia stacks which were former breccia pipes in the Mackinac Straights area of the Michigan Basin.]

C. "Dissolution in the Eastern Permian Basin" - Dr. Kenneth Johnson, University of Oklahoma.

1. In order for salt dissolution to occur, there must be groundwater flow adjacent to the salt. Flow paths include:

   a. Permeable sandstone.

   b. Cavernous gypsum, limestone, dolomite and salt.

   c. Fractures.

   d. Joints.

   e. Sinks.

   f. Collapse structures.

2. The saline water which is coming to the surface at springs and in rivers is young, implying that it is meteoric water.

3. Salt is presently being dissolved at depths of 200 to 800 feet below the surface, locally up to 1,000 feet.

4. Evidence for salt dissolution is:

    a. Abrupt thinning of salt.

    b. Irregular limits of salt.

    c. Salt outliers.

    d. Areas of complete salt removal.

    e. Abundant salt discharges in springs and rivers.

    f. Solution collapse features.

    g. Salt casts or molds in outcrop.

5. Salt occurs in cyclic sequences of dolomite, gypsum/anhydrite, salt, red shale and gray shale (from bottom to top).

6. Springs are usually fully saturated when they reach the surface.

7. Salt plains form from a combination of capillary evaporite and salt incrustation.

8. The two major rivers draining the Texas panhandle and western Oklahoma area discharge on the order of 5,000 tons of salt per day.

9. Collapse structures evidenced by:

    a. Folding.

    b. Tilting.

    c. Structures correlated with missing evaporite horizons.

    d. Fractures.

    e. Caverns.

10. In some areas salt dissolution and resultant collapse structures were formed during past episodes of salt solution and there is no evidence of present solution activity.

11. Solution-collapse may well be an autocatalytic process.

II. Salt Dissolution Around Boreholes

"Salt Dissolution in Oil and Gas Test Holes in Kansas" - Dr. Robert F. Walters, Walters Drilling Co.

"Growth and Shape of a Salt Cavity - Computer Model and Calibration from Detroit Mine Experiment" - Dr. Richard H. Snow, IITRI.

"Investigation of Salt Transport in Vertical Boreholes and Brine Invasion into a Fresh Water Aquifer" - Dr. R. M. Knapp, University of Texas and Dr. A. L. Podio, University of Texas.

"In-Situ Experiment" - Dr. George D. Brunton, OWI.

A. This series of presentations represented a series of computer modeling, lab experimentation and field reconnaissance studies in varying stages of completion. All were oriented to the potential effect of salt dissolution from water circulation in boreholes.

B. Field Investigations (Dr. Walters).

1. Study conducted for AEC and Solution Mining Research Institute.

2. Study covered the Hutchinson Salt of Kansas.

3. Compilation of boring logs. Combination of geophysical and caliper logs used. A very small percentage of the holes had information which was complete enough for use.

4. Maximum diameter from dissolution during drilling operation reported as 24 feet from a hole drilled in the 1930's. Holes drilled at later dates show much smaller amounts of salt dissolution.

5. Panning Sink.

a. Hole originally drilled for oil exploration.

b. Hutchinson Salt penetrated from 975-1,275 feet.

c. Later used as salt water disposal well.

d. Abandoned and plugged after derrick began to tilt.

e. Later developed sink: 300-ft-diameter and 80-ft in depth within a 12-hour period.

6. Subsidence cases known.

   a. Five associated with mining of salt.

   b. Eight associated with oil and gas operations.

7. Conclusions of study.

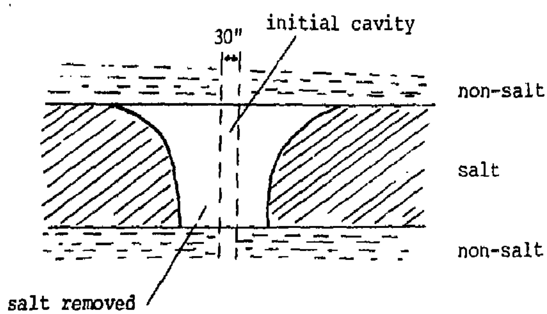
   a. Generally modern rapid rotary drilling using fresh water results in borehole enlargement to about three times the diameter of the drilled hole. Rotary drilling in the 1930's resulted in borehole enlargement some five times the diameter of the drilled hole. Both amounts are too small to cause surface subsidence.

   b. If the shallow aquifers above the salt are isolated, ordinarily no salt dissolution occurs after drilling ceases.

   c. "In boreholes with properly isolated shallow aquifers above the salt, the deeper aquifers below the salt, although possessing static fillup levels higher than the top of the salt, will equalize pressure by flowing up or down the borehole from one aquifer into another without flow across the salt face, hence without dissolving the salt." (A copy of the report documenting this conclusion has been requested.)

C. Results of Computer Modeling and Detroit Mine Experiment (Dr. Snow).

   1. Experimental set up and resulting cavity geometry.



2. Results of two week in-situ study - top diameter 3.2 m, bottom diameter 2 m.

3. Computer prediction based on inflow of one gallon of fresh water per day:

| Time | Top Diameter |
|---|---|
| $10^4$ years | 200 m. (no volume given) |
| $10^6$ years | 2,000 m. (no volume given) |

D. Computer and Lab Studies of Borehole Dissolution - (Drs. Kanpp and Podio).

1. Work is in progress.

2. Most of presentation centered on model and experimental set-up. Very little was presented on results.

E. In-Situ Experiment - (Dr. Brunton).

1. The experimental set-up for an in-situ study of borehole dissolution was described and then opened for discussion. The experiment would consist of a study hole connected to a water circulation system and a surrounding array of monitoring holes. As water is circulated through the study hole, the effects of dissolution will be measured by the monitor hole array.

III. "Brinefield Subsidence Investigation" - David J. Dowhan, BASF Wyandotte Corp.

A. Historical background.

1. Solution mining began 1940.

2. Benchmark surveillance began in 1950's, subsidence was measured in inches/year.

3. In recent years, accelerated subsidence prompted an investigation of the potential for collapse.

B. Investigation.

1. Added benchmarks and detailed surveying was conducted.

2. Several test holes were drilled.

C. Results.

1. Portions of the overlying strata were fractured and other portions intact.

2. Rock in the vicinity of the salt ranged from intact to a collapse rubble.

3. Insoluble residue was found at most previous salt horizons.

4. No large cavity was encountered.

5. It was concluded that no collapse would occur.

IV. "Geohydrologic Investigation of Gulf Coast Interior Salt Domes" - Charles G. Smith, Louisiana State University.

A. Investigation of salinity variations of ground water in the vicinity of selected domes.

1. Salinity measurements from electric logs of oil and gas wells.

2. Salinity plume indicates that a given dome is less likely to be hydrologically stable than a dome where no salinity anomalies occur.

3. Salinity plumes were encountered at four of the nine domes investigated.

4. Salinity plumes could also originate from the upward movement, along the dome, of deep aquifer brine water.

5. Estimates of the rate of salt dissolution from domes associated with groundwater plumes indicate that less than 30 meters of salt will be removed from the upper surfaces of the dome in 250,000 years.

V. During the proceedings of the conference, I noted a large concern and corresponding expenditure of time and money on the borehole dissolution problem. However, no consideration had been given to dissolution associated with the permeable fracture zone around a shaft. I discussed this with Dr. Ken Johnson of the OWI *Ad Hoc* Committee, and he agreed the subject warranted the Committee's attention and possibly further study.

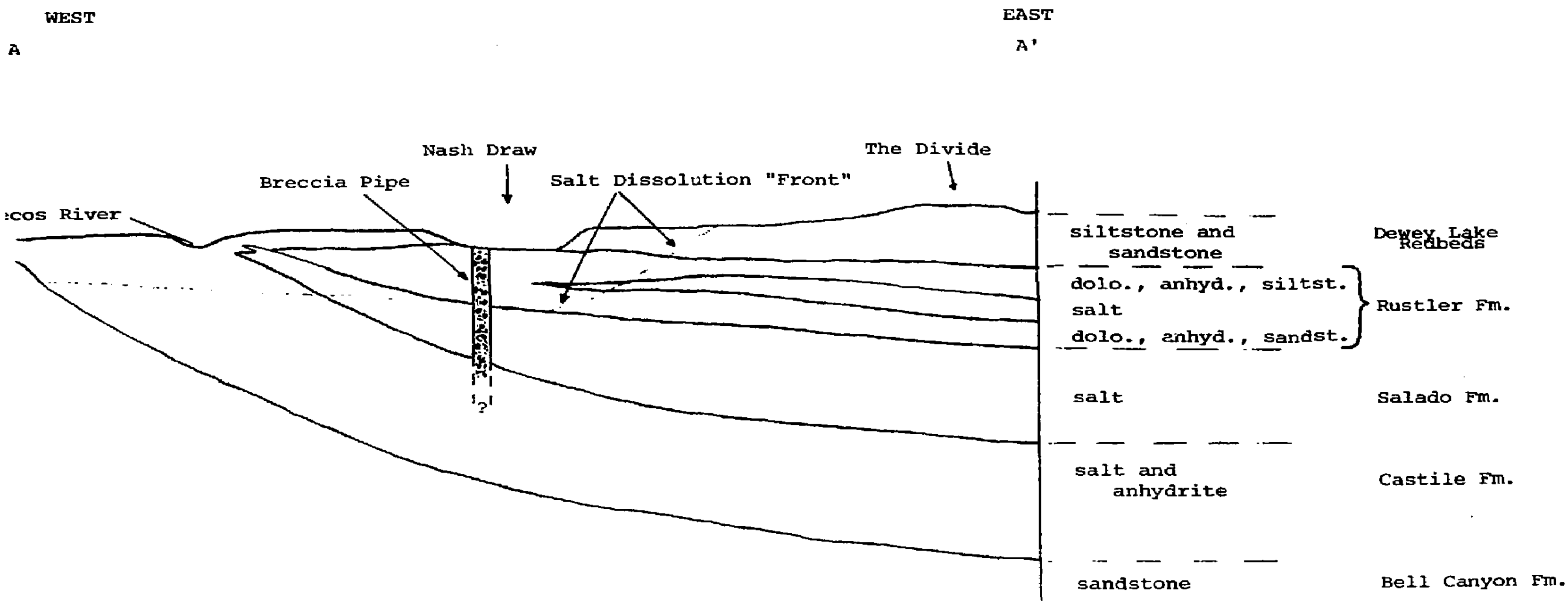



Figure 1. Schematic Cross Section– Northern Delaware Basin

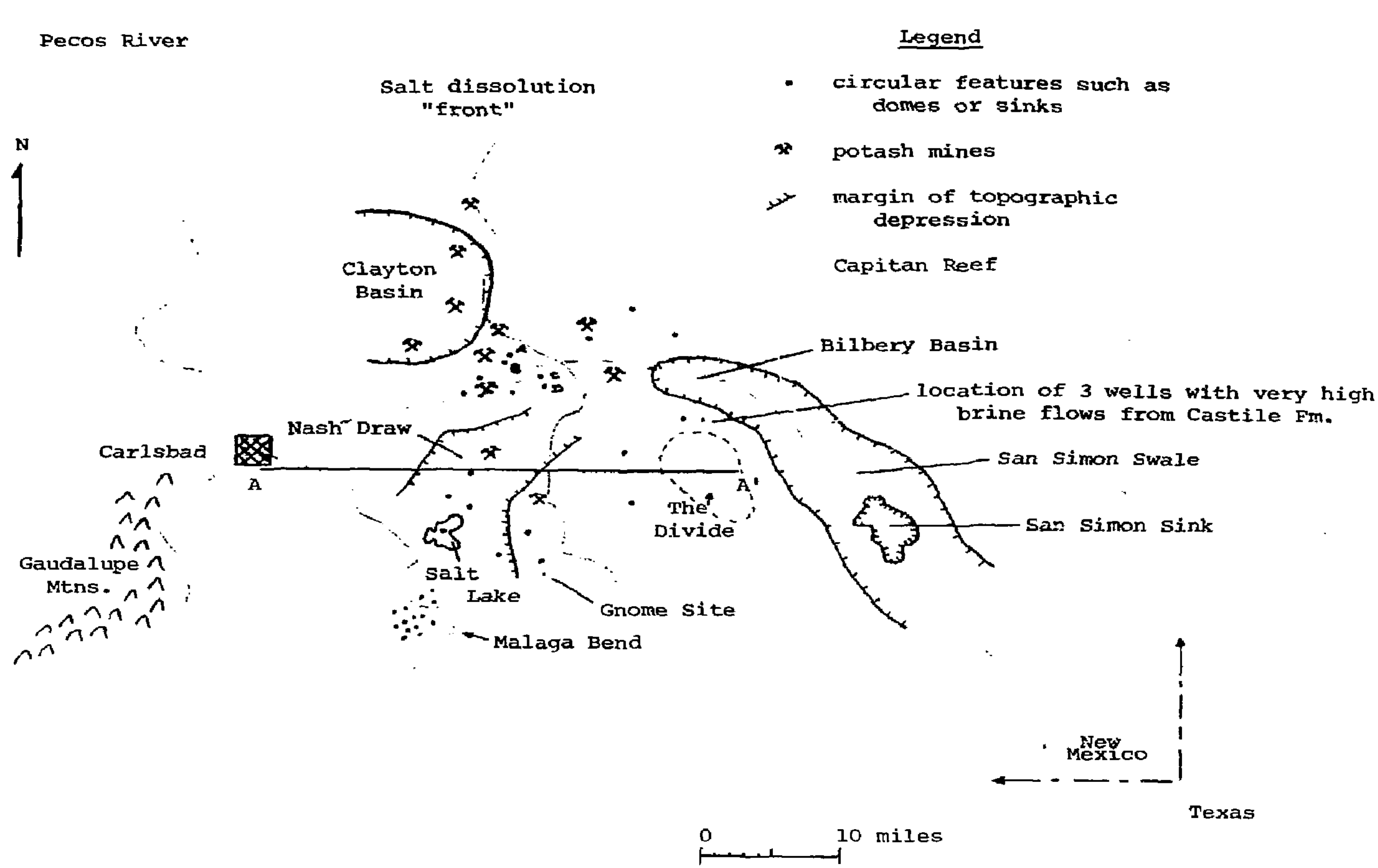



Figure 2. Location of Surficial Features- Northern Delaware Basin (after Bachman and Johnson, 1973; Bachman, 1973; Jones, 1973; Vine, 1960 and WIPP site review, 1977)

SYMPOSIA ON THE OCHOAN AND GUADALUPIAN ROCKS OF SOUTHEASTERN NEW MEXICO AND WEST TEXAS - AT CARLSBAD, NEW MEXICO

May 3-7, 1977

## Summary of Information

Part I - Potash Mines

I. Mississippi Chemical Corporation Mine

A. Introduction

1. The Mississippi Chemical Corporation potash mine is located off Route 31, in the Salado Formation underlying a northwest portion of Nash Draw and the adjacent area.

2. The potash horizon being mined is the 7th ore zone.

3. Depth of the mine is approximately 875 feet at the shaft and approximately 1100 feet (max.) to the east northeast.

4. The boundaries of the mine are determined by a combination of leased section limits and the depositional limits of the ore body being mined.

5. Except for the brecciated zone and the immediate vicinity (See B.), the beds are undisturbed, dipping 1-3$^{o}$ ENE.

6. Both conventional and continuous mining techniques are being utilized, each in a different portion of the mine.

7. This mine was the first in the area, early 1930's (then United States Potash Company).

B. Breccia Zone

1. A distinct brecciated zone was encountered at the east northeast extension of the 7th ore zone mine, directly underlying the collapsed domal surface feature, "Dome C" as described by Vine, 1960. (Depth - 1000$^{+}$ feet).

2. The approach to this zone is marked by a distinct steepening of dip. (see Figure 1).

3. The breccia consists of large and small blocks of anhydrite and small pieces of slickensided claystone, all within a large mass of recrystalized salt.

4. The contact of breccia dips steeply away from the breccia zone.

5. At the contact, the horizon adjacent to the breccia has been interpreted as 10th ore zone, normally about 100 feet stratigraphically higher.

6. The breccia is very tightly cemented by recrystalized salt.

7. In the vicinity of the breccia are numerous oil accumulations on the floor, walls, and ceiling. Many of these accumulations appear to be associated with fractures. This oil is interpreted as originating from a nearby, old oil exploration hole, drilled during a time period when oil was commonly pumped down a hole to help in pulling the casing. This interpretation has not yet been confirmed by geochemical analysis of the oil seeps.

C. Water

1. Generally speaking, the mine proper is fairly dry.

2. Occasionally white crystalline halite has accumulated on the walls and ceiling. These accumulations are commonly associated with clay seams and with holes drilled approximately 30 feet into the ceiling at intersections to check for pressurized pockets of gas and brine. The water is interpreted as originating from the clay seams and from brine inclusions within the salt. In pillars, the increase in pressure on the clay seams helps to force the water outward.

3. At the shaft, a sump at the top of the Salado Formation pumps an estimated 30-60 gallons per minute of briny water to the surface.

D. Miscellaneous Information

1. The near-future mine plans include mining a section under the uncollapsed dome, called "Dome D" in Vine, 1960.

2. Surface subsidence from long wall mining methods usually amounts to 2/3 to 3/4 of the height of the actual underground excavation. Tension cracks opening at the surface have been located in the vicinity of the Mississippi mine. The angle at which this collapse is propagated upward is usually 45$^{\circ}$ for the mines in the Delaware Basin.

3. Potash Company of America lost two shafts in the construction stage due to heavy water flows associated with adjacent sink features, above the Salado Formation.

4. The Mississippi Mine workings cross into the Nash Draw area without any noted rock deformation, evidencing that the salt dissolution causing subsidence of the draw is occurring at a higher horizon (at the top of the Salado Formation).

5. The distance from the present Mississippi mine workings to the outer boundary of the proposed WIPP site area is approximately 2½ miles.

II. Duval Corporation - Nash Draw Mine

A. Introduction

1. The mine is located off Route 128 in the southeast portion of the Nash Draw.

2. The 10th ore zone was toured.

3. The beds through the observed portions of the mine are undisturbed.

B. Water

1. The mine is fairly dry, though it is considered one of the wetter mines in the area.

2. The accumulation of white, crystalline halite on walls and ceiling is more frequent than the Mississippi mine and infrequent water dripping from the ceiling was observed.

3. It is a Duval company policy at the present time to not use longwall mining techniques, as one of the geohydrologic consultants to the company feels that mine flooding from the overlying aquifers is a significant risk associated with the resultant subsidence. The mining engineer disagrees with this view.

Part II - Symposium on the Ochoan Rocks

I. Introduction

A. Only those papers pertinent to salt dissolution in the Delaware Basin have been included in the following summaries.

B. The publication of these papers will not be available until November or December of this year.

II. Paper Summaries

A. The geochemistry of Delaware Basin groundwaters: Steven J. Lambert, Sandia Laboratories.

1. Subsurface samples of water from various formations were analyzed for solute content and for stable isotopes.

2.

| Water Sample Horizon | Total Dissolved Solids in Mg/l |
|---|---|
| Delaware Mtn. Sandstone | >300,000 |
| Castile Fm. | >300,000 |
| Potash Mine Seeps (Salado Fm.) | >300,000 |
| Rustler Fm. | 3,000-30,000 |
| Capitan Fm. | 500-200,000 |
| Morrow Fm. (Pennsylvanian) | 500-200,000 |

3. Stable isotope measurements indicate that Rustler and Capitan waters are indistinguishable from local meteoric waters. Salado, Delaware, Morrow and one of the Castile waters have undergone low-temperature isotopic exchange with oxygen and hydrogen bearing minerals. These waters have isotopic characteristics of neither marine (original Permian) nor meteoric water.

4. Meteoric water has been found at depth (e.g. 2800 feet). Not all deep water is saturated. Therefore, deep water has the potential for salt dissolution IF proper flow path adjacent to salt and discharge point were to exist. (Personal Communication).

B. Petrographic character and extent of an Oligocene basaltic dike system, northern Delaware Basin, New Mexico: J. P. Calzia and W. L. Hiss, USGS, Menlo Park.

ERTS imagery was utilized to facilitate the location of basaltic dike trend. An aside to this work was the location of a large circular feature in the central portion of the basin. This feature has been interpreted by the authors as a large, recent solution subsidence feature. A 1971 topographic map of the area on 10 foot contour intervals had shown no topographic depression in that area. (Further communications with the authors to find out more details about the feature are in progress).

C. Solution of Permian Ochoan evaporites, northern Delaware Basin, New Mexico: J. W. Mercer, USGC, Albuquerque and W. L. Hiss, USGS, Menlo Park.

1. The dating of salt dissolution episodes from Permian to Ogallala time (Pliocene) is largely conjecture based on stratigraphic and structure evidence for erosion, diastrophism and climate. This paper concentrates on Cenozoic solution, which is divided into two categories.

2. The first category is solution above and parallel to the Capitan Reef aquifer, forming a 8-12 mile wide trough filled with up to 1000 feet of alluvial material. Dissolution occurred initially at depth and was later facilitated by surface water from streams which developed in the collapse troughs.

3. The second category is salt-solution at the western margin of the Ochoan Series, the "salt dissolution front".

D. Development of dissolution breccias, northern Delaware Basin, New Mexico: Roger Y. Anderson, Kenneth K. Kietzke, and Doris R. Rhodes, University of New Mexico.

1. Dissolution breccia consists of subangular to somewhat rounded and elongate fragments of calcite laminated anhydrite in an anhydrite matrix.

2. Collapse breccias consists of angular fragments of laminated anhydrite which little or no matrix, sometimes found overlying solution breccias.

3. Breccia beds in the western Delaware Basin can be correlated with salt beds on the east side of the basin utilizing detailed lamination correlations of over- and/or underlying intact horizons.

4. The laminae and breccia core characteristics were then correlated with the corresponding geophysical log characteristics. Geophysical logs from holes in the Big Sinks area (see Figure 2) were correlated with the logs and core on each side. The interpretation of this work is that dissolution has occurred in the lower third of the Salado Fm. and in the underlying Castile Fm. This implies dissolution at a depth of approxmiately 3,000 feet. (Personal Communication)

5. This depression has been filled with Cenozoic alluvial material as described by Maley and Huffington, 1953.

E. Solution Features in the Delaware Basin evaporites: Alfred J. Bodenlos, USGS, Reston

1. Paper describes solution features west of the Pecos River.

2. Surface water percolating downward has produced many isolated depressions, sinkholes and shallow caverns.

3. Laterally moving groundwater has leached and removed the most soluble evaporite beds; overlying strata by collapsing into resulting voids have produced thin, areally extensive blanket breccias.

4. Groundwater moving upward from underlying aquifers (Bell Canyon ?) has dissolved large cavities in the evaporites; roof failures then have produced chimneys of breccia.

5. Breccia chimneys are found from the Pecos River to west of Gypsum Plain, with the following surface expressions:

   a) chimneys filled with post-anhydrite rocks form mounds of uncemented rubble or in higher hills contain steeply dipping post-anhydrite strata.

   b) chimneys filled with recemented anhydrite may be topographically featureless or may form low mounds.

   c) breccias altered to limestones form knolls, hills or high conspicuous buttes.

6. Breccia chimneys commonly are floored at the base of the Castile, implying the groundwater aquifer causing dissolution was the sandstones in the underlying Delaware Mountain group.

7. Some of the anhydrite-calcified breccias contain minable concentrations of sulfur.

8. Because of the large volume of groundwater required to accomplish the amount of dissolution evidenced by all these features, if has been concluded that the solution has occurred over a longer time period, e.g. from the Laramide (Cretaceous) onward, rather than from late Cenozoic onward as hypothesized by others.

F. Salt Anticlines in the Castile-Salado Evaporite Sequence, Northern Delaware Basin, New Mexico: Roger Y. Anderson, University of New Mexico and D. W. Powers, Sandia Laboratories.

1. Salt anticlines occur in a "deformation belt" along the NNW, N, NE, and E margins of the Delaware Basin. They are commonly associated with lows and missing halite.

2. These features also occur in some parts of the interior of the basin.

3. In ERDA #6, an exploratory hole drilled for the first WIPP site location, the following features associated with a salt anticline were encountered at 2500+ feet:

   a) the normal 1-3$^{o}$ dip increased to 60-70$^{o}$

   b) large volumes of brine and $H_2S$

   c) recrystallize and corrosion evidencing dissolution

   d) upper displacement of the middle anhydrite or the Castile Formation approximately 950 feet, placing it immediately below the lower Salado salt.

4. Extension fractures in the middle anhydrite suggest that it has been stretched above a mass of exceptionally thick salt of the lower halite unit of the Castile formation.

Part III - Symposium on Upper Guadalupian Rocks

I. Paper Summaries

A. Deep-sea channels in the Bell Canyon Formation (Guadalupian) Delaware Basin, Texas - New Mexico: Charles R. Williamson, University of Texas.

1. The setting of the sandstones of the Bell Canyon Formation is described as follows:

   a) blanket type, laminated silts deposited in deep water.

   b) saline density currents cut channels and deposit fine grained, well sorted sand in numerous elongate channels.

   c) channels come into the basin from the marginal areas, in particular, showing a strong NE - SW trend.

   d) the channels are 35-45 m deep, 4-5 km across and extend 40-60 km into the basin (nearly to the center).

2. Permeability of the sandstone ranges from .01-190 md ($10^{-8}$ - $10^{-4}$ cm/sec)

   Note: This paper is important to the solution question because these sandstones are a candidate for a ground circulation/salt dissolution unit in the Delaware Basin.

B. Movement of groundwater in Permian Guadalupian aquifer systems, southeastern New Mexico and western Texas: W. L. Hiss, USGS, Menlo Park.

1. The Delaware Basin system has been divided into three aquifer systems:

   a) the basin aquifer system consisting of the Bell Canyon, Cherry Canyon, and Brushy Canyon Formation - average permeability <10 md ($10^{-5}$ cm/sec).

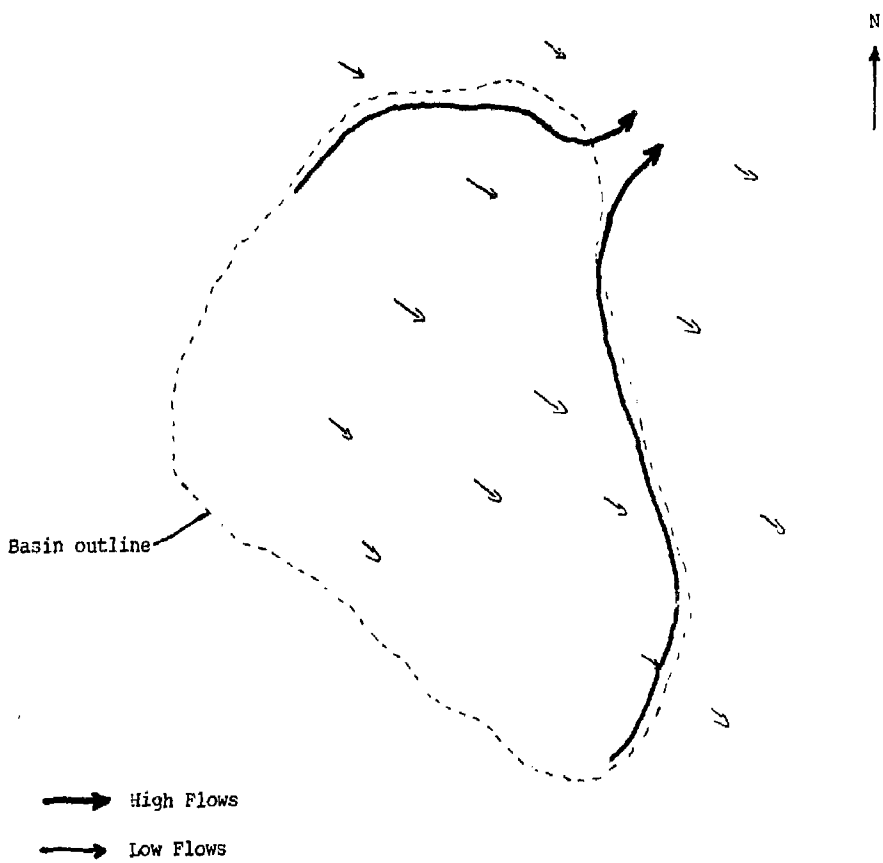
   b) the Capitan aquifer system - average permeability 2000 md ($10^{-3}$ cm/sec).

   c) the shelf aquifer system - average peameability <100 md ($10^{-4}$ cm/sec)

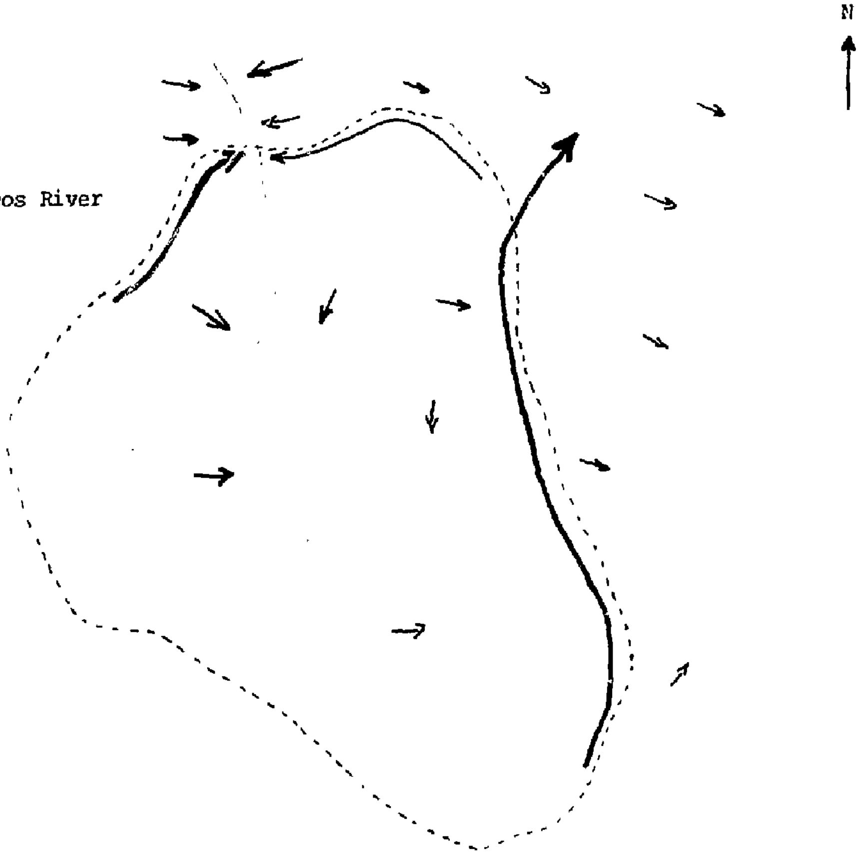
2. A number of submarine canyons cut across the Capitan Reef, restricting the highly permeable flow routes immediately east of Carlsbad.

3. Groundwater flow patterns are as follows:

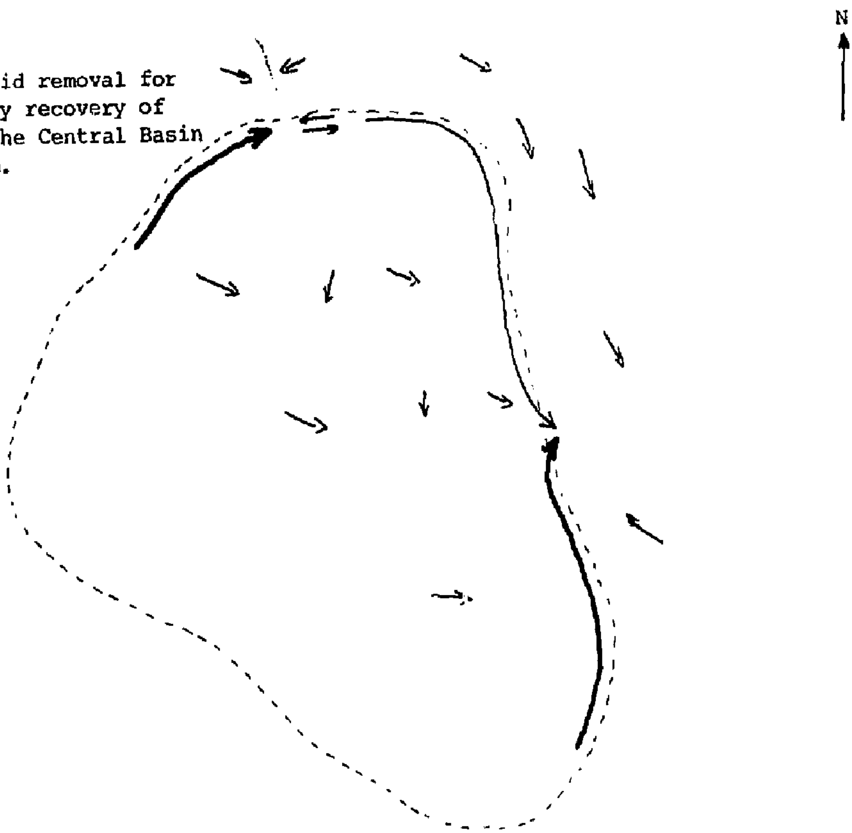
   a) pre-Pecos River



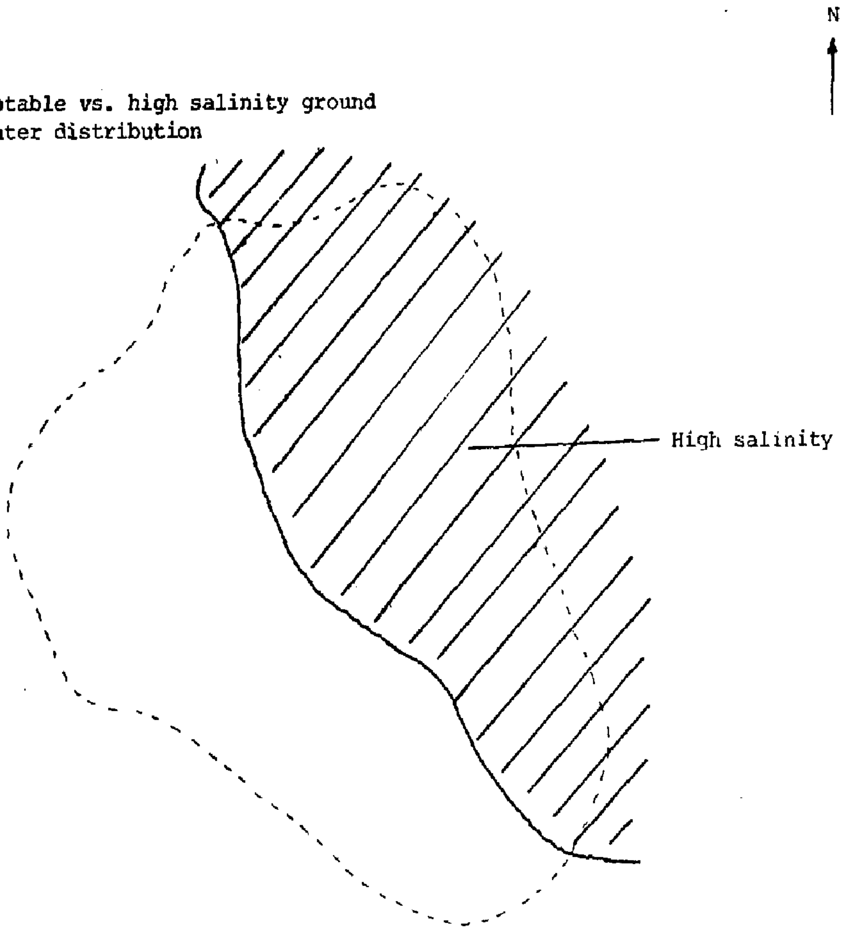
b) post-Pecos River




c) post fluid removal for secondary recovery of oil on the Central Basin Platform.



d) potable vs. high salinity ground water distribution



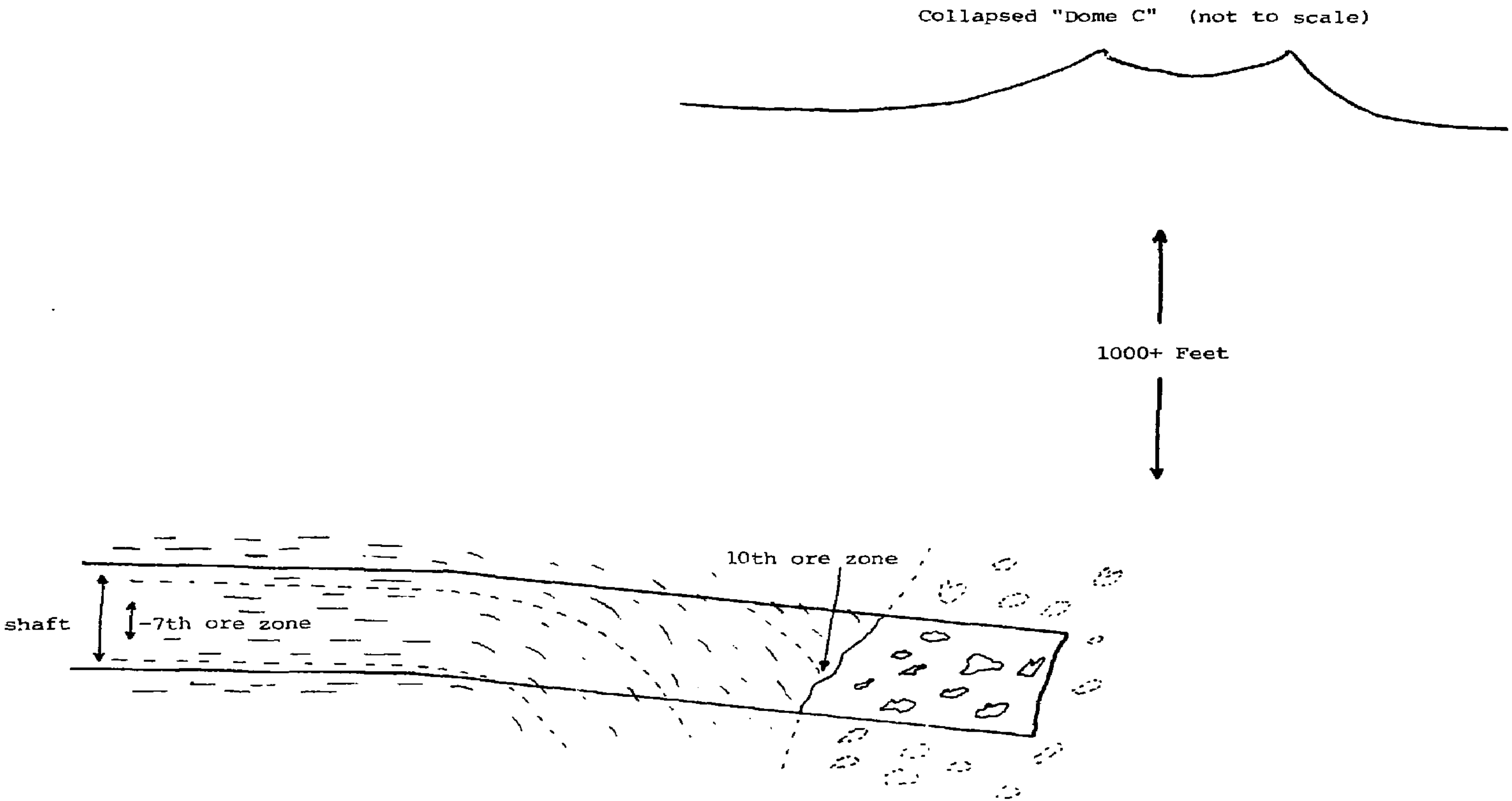



Figure 1. Skemat c Sketch of Mississippi Mine Breccia

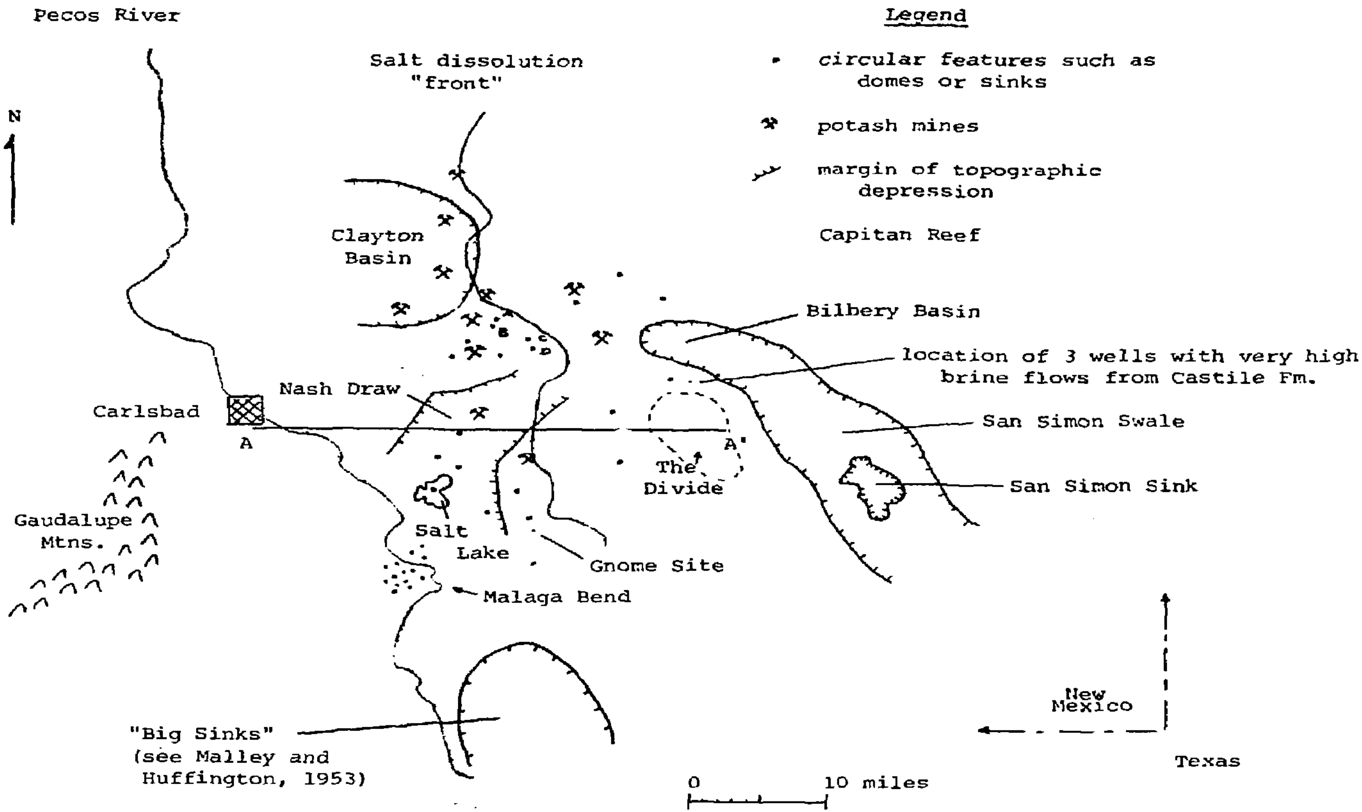



Figure 2. Location of Surficial Features- Northern Delaware Basin (after Bachman and Johnson, 1973; Bachman, 1973; Jones, 1973; Vine, 1960 and WIPP site review, 1977)