Waste Isolation Pilot Plant

Compliance Certification Application

Reference 13

Anderson, R.Y., and Kirkland, D.W. 1980.
Dissolution of Salt Deposits by Brine Density Flow. Geology, Vol. 8, no. 2, pp. 66–69.

Submitted in accordance with 40 CFR §194.13, Submission of Reference Materials.

DATE: 02/28/96
DELIVERY DUE: 03/18/96

R E P R I N T

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WASTE ISOLATION DIVISION
P.O. BOX 2078
CARLSBAD, NM 88221

PURCHASE ORDER PO 72921

PAGE: 1 of 4

VENDOR: 156085
Information Express
Attn: Julie Sweetkind
3250 Ash St.
Palo Alto, CA 94306

PAYMENT TERMS: 1% 10 NET 30 DAYS
FOB: Destination Prepaid & Not Allowed
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This Order is issued under Westinghouse Prime Contract DE-AC04-86AL31950 with the U.S. Dept. of Energy. DPAS DO-B2 rating applies.

SHIP TO: Westinghouse Electric Corp.
Waste Isolation Division
For the U.S. Dept. of Energy
WIPP Site
30 Miles Southeast of Carlsbad
Carlsbad, NM 88220

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Waste Isolation Division
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P.O. Box 2078
Carlsbad, NM 88221

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Line Nmbr	Item ID / Description	Quantity Ordered	U/M	Unit Price	U/M	Total Price
1	71510-00123 PUBLICATION, BOOKS, BOOKLETTS, PAMPHLETTS. SEE NOTE FOR SPECS. ANDERSON, R.Y., DEAN, W.E., KIRKLAND, JR., D.W., AND SNYDER, H.I. 1972 PERMIAN CASTILE VARVED EVAPORITE SEQUENCE, WEST TEXAS AND NEW MEXICO. GEOLOGICAL SOCIETY OF AMERICA BULLETIN, VOL. 83, PP. 59-86	10.00000	EA	38.000	EA	380.00
2	71510-00123 PUBLICATION, BOOKS, BOOKLETTES, PAMPHLETTS. SEE NOTE FOR SPECS. ANDERSON, R.Y., AND KIRKLAND, D.W. 1980 DISSOLUTION OF SALT DEPOSITS BY BRINE DENSITY FLOW. GEOLOGY, VOL. 8, NO.2, PP. 66-69	10.00000	EA	11.000	EA	110.00
3	71510-00123 PUBLICATION, BOOKS, BOOKLETTES, PAMPHLETTS. SEE NOTE FOR SPECS. DACHMAN, G.O., 1976 CENOZOIC DEPOSITS OF SOUTHWESTERN NEW MEXICO AND AN OUTLINE OF THE HISTORY OF EVAPORITE DISSOLUTION, JOURNAL OF RESEARCH, U.S. GEOLOGICAL SURVEY, VOL. 4, NO.2, PP. 135-149. NO LONGER AVAILABLE PER USGS	10.00000	EA	10.000	EA	100.00
4	71510-00123 PUBLICATION, BOOKS, BOOKLETTES, PAMPHLETTS. SEE NOTE FOR SPECS. BROOKINS, D.G. AND S.J. LAMBERT. 1987 RADIOMETRIC DATING OF OCHOAN (PERMIAN) EVAPORITES, WIPP SITE, DELAWARE BASIN, NEW MEXICO, USA, 84: MATERIALS RESEARCH SOCIETY. ED. 771-780	10.00000	EA	22.000	EA	220.00
5	71510-00123 PUBLICATION, BOOKS, BOOKLETTES, PAMPHLETTS. SEE NOTE FOR SPECS. BROOKINS, D.G., J.W. REGISTER, AND H. KRUEGER. 1980 POTASSIUM-ARGON DATING OF POLYHALITE IN SOUTHEAST NEW MEXICO, GEOCHIMICA ET COSMOSHIMICA ACTA 44, 635-637. PERGAMON PRESS, JOURNALS DIV. MAXWELL HOUSE, FAIRVIEW PARK, ELMSFORD, NY 10523 (914) 592-7700	10.00000	EA	18.000	EA	180.00
6	71510-00123 PUBLICATION, BOOKS, BOOKLETTES, PAMPHLETTS. SEE NOTE FOR SPECS. CHOPPIN, G.R. 1983 SOLUTION CHEMISTRY OF THE ACTINIDES RADIOCHIMICA ACTA. VOL. 32, 4, 43 ACADEMIC PRESS 1250 6TH AVE. SAN DIEGO, CA 92101 (619) 699-6328	1.00000	EA	16.		
7	71510-00123 PUBLICATION, BOOKS, BOOKLETTES, PAMPHLETTS. SEE NOTE FOR SPECS.	10.00000	EA	11.000	EA	110.00

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Dissolution of salt deposits by brine density flow

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ABSTRACT

The origin of collapse structures and breccias that vertically penetrate or occur within impermeable evaporites has never really been understood. The density of the brine that develops as salt deposits are dissolved can generate continuous gravitational brine movement. If the source of the dissolving water is artesian, or continuous, a flow cycle is developed in which the salt itself supplies the density gradient that becomes the vehicle of its own dissolution. The Delaware Basin in western Texas and southeastern New Mexico provides a particularly good example of how brine density flow can produce dissolution chambers that collapse to form breccias. The potential for dissolution by brine flow is an inherent property of partly exhumed evaporites and may constitute a risk factor in the storage of radioactive waste in evaporite deposits.

INTRODUCTION

Breccias of several different types and geometries have long been recognized in evaporite basins that have been exhumed at some stage in their history. For example, leached residues containing angular blocks are known to accumulate at the upper surface of salt as it is gradually lowered by dissolving ground waters. More distinctive collapse breccias (Fig. 1) are also common in many evaporites, and the structure and character of these breccias have been correctly attributed to dissolution within the evaporites and collapse of overlying competent units (Landes, 1959). However, a mechanism to explain the commonplace occurrence of dissolution deep within largely impermeable evaporites has, until now, been unrecognized. The path of movement of dissolving waters that produce these features is poorly understood. A process of brine density flow is suggested to account for many of these deep-seated collapse features.

Recent studies in the Delaware Basin of western Texas and southeastern New Mexico, in connection with the development of a possible repository for radioactive waste, have identified hydrologic systems that appear to be responsible for the development of a variety of brecciated and collapsed dissolution features. These relationships between aquifers and dissolution effects have led to the formulation of the concept of brine density flow. The application of the brine density flow model to the dissolution of evaporites carries implications for the history and distribution of evaporites as well as for the use of evaporite deposits for the storage of radioactive waste.

BRINE DENSITY FLOW

The two requirements for establishing a brine density flow cycle are (1) a pressurized or artesian source of relatively fresh water and (2) a permeable fracture system or zone between the water source (aquifer) and salt mass that is normally isolated from ground water. Gravity flow of brine occurs when fresh water contacts the salt body and becomes more dense by dissolution of salt. The differential density between the brine and the fresh water causes movement of brine downward along separate and distinct pathways but in the same fracture system or permeable zone as the rising fresh water. The descending brine ultimately flows through the aquifer to a point of natural discharge and, because the system is under artesian pressure, the brine flow is continuously replaced by fresher water. Sustained flow results in the enlargement of dissolution chambers or an advancing front of dissolution. Subsequent collapse of competent beds causes brecciation.

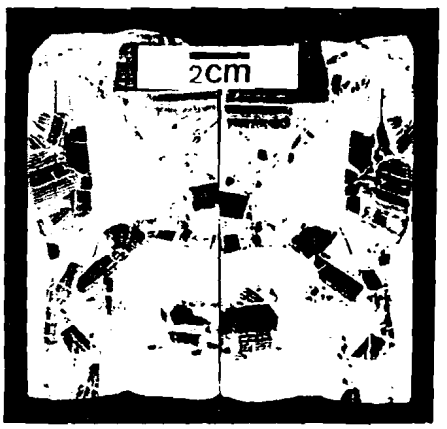

Figure 1. Collapse breccia from 130-m depth in breccia chimney located in Culberson County, Texas (see Fig. 4).

A model, simulating brine flow, was constructed in which a source (aquifer) was connected to an overlying chamber containing salt by a capillary tube 0.54 m long and 0.0015 m in diameter (Fig. 2). Water moving only through the capillary and driven only by brine density difference removed salt from the overlying chamber at a rate of about 1 g/min. A simple capillary results in a pulsating flow, with pulses

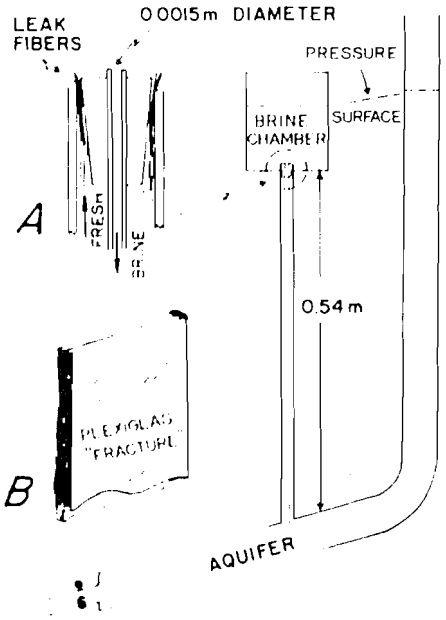

Figure 2. Laboratory apparatus used to observe brine density flow. Communication between aquifer and chamber is either by capillary and "leak fibers" (A), in which brine moves down capillary and fresh water moves upward around fibers, or by simulated "fracture" (B), in which brine descends and fresh water ascends in different parts of same fracture.

on the order of minutes, as fresh water and brine alternate in returning the system to pressure equilibrium after periods of flow. Continuous flow occurs when a two-way "leak system" is added so that the more viscous brine moves downward through the capillary tube, which is the more open part of the system, and fresher water moves upward between plastic fibers placed around the capillary (Fig. 2A). Pulsating brine flow also occurs in artificial "fractures" made of closely sandwiched plates of Plexiglas (0.1 × 0.6 × 0.001 m) (Fig. 1B). When the distance separating the plates is increased to about 0.001 m, continuous brine flow develops as the brine moves downward and fresh water moves upward in the "fracture" in separate and distinct pathways.

Brine flow in the models begins suddenly as the increasing density of the brine developing in the chamber attempts to equalize the pressure in the artesian system. Flow of brine in the simulated fracture begins as spatula-shaped "tendrils" and is maintained as a narrow column of rapidly descending brine (about 5 cm/s) surrounded by stagnant or slowly upward-moving fresher water. Flow of brine, however, is entirely within the field of laminar flow at the geometries to be expected in fracture systems. The fact that continuous two-way flow did not develop in the Plexiglas model until the plates were separated by 0.001 m does not mean that brine flow cannot develop in tighter natural fracture systems. Two-way flow develops readily in separated capillaries, and a concentration difference of brine of less than 2 g/l was sufficient to initiate and maintain continuous brine flow. Natural systems can be expected to contain a complex network of fractures to provide separate pathways for ascending and descending fluids.

The rate or vigor of brine flow varies directly with concentration (Fig. 3). Differential flow between the aquifer and the chamber, with concentration differences of 50 g/l, is about 20% slower at high concentrations than at low concentrations, presumably due to difference in viscosity. The amount of salt actually removed from the chamber varies exponentially with difference in concentration between the aquifer and chamber (Fig. 3). This effect is caused by the exchange of fluids between the two sources and shows that the rate of removal of salt from a chamber decreases significantly with increasing brine concentration in the aquifer. The potential for the development of brine flow after fresh water has contacted a salt body is principally a function of density differential and the permeability of the fracture system.

DISSOLUTION IN THE DELAWARE BASIN

The Delaware Basin provides a particularly good example of dissolution by means of brine flow, because the ongoing nature of the process makes it possible to observe the apparent relationship between existing aquifers and a variety of dissolution and collapse features. Also, the basin has a rather simple structure and hydrologic flow system.

Most of the basin is now part of a single block that was uplifted and tilted eastward, mainly in late Cenozoic time (King, 1948) to about 19 m/km. The anhydrite and halite beds of the Castile Formation are underlain by the shelf and basin aquifers of the Delaware Mountain Group (Fig. 4). The more permeable Capitan (reef) aquifer encircles the Castile evaporite and is overlain by the halite and anhydrite of the Salado Formation, the Rustler Formation, and younger nonevaporites that extend beyond the limits of the basin. Both of the aquifers are exposed to recharge in the uplifted western and southern parts of the basin. The potentiometric surface for fresh water in both aquifers is slightly above the ground level. The environmental head for brine would not rise to the surface but could be expected to rise from the basin and Capitan aquifers into the soluble evaporites. Both aquifers ultimately are drained by the San Andres Limestone (Hiss, 1975). Water flow in the reef aquifer parallels the reef but passes into the San Andres Limestone at the northeast corner of the basin. Water flow in the basin (Delaware) aquifers is generally down regional dip (Hiss, 1975).

Two genetically different types of brecciation have been recognized within the evaporite body in the Delaware Basin (Anderson and others, 1978): (1) dissolution breccia consisting of partly dissolved and broken anhydrite laminae enclosed in an anhydrite matrix, and (2) collapse breccia consisting of angular interlocking fragments of laminated anhydrite, limestone, and other rock types with little matrix. Collapse breccias develop directly above dissolution breccias after salt removal and chamber formation. The brecciated masses or bodies occur both as blanket type (interformational) beds or as chimneys and pipes (trans-formational breccias) similar to those observed in other evaporite basins (Landes, 1959).

Trans-formational Breccias

Mining operations at the Mississippi Chemical Company mine under Hill C (Vine, 1960; Fig. 4 here) have revealed the central core of a breccia chimney or "pipe." The downward deflection of marker beds adjacent to the pipe at the 360-m level indicates that the collapse

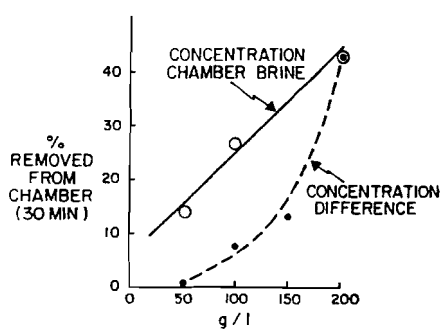

Figure 3. Relation of brine flow to concentration and concentration difference. Solid line is amount of brine removed from chamber per unit time with different initial concentrations and with aquifer concentration = 0; abscissa is initial concentration of brine in chamber. Dotted line is amount of brine removed from chamber per unit time with initial chamber concentration of 200 g/l and different aquifer concentrations. Abscissa is difference between concentration of brine in chamber and concentration of brine in aquifer.

chamber originates in the lower part of the Salado Formation where it rests above the underlying inner-reef margin of the Capitan aquifer (Fig. 4). Fracturing of anhydrite beds lying between the salt and the aquifer accompanied flexuring that took place during structural adjustments along the inner margin of the reef. This fracturing has allowed the undersaturated waters in the upper part of the reef aquifer to contact the overlying salt beds (Hiss, 1975, p. 118). Subsequent brine flow and chamber collapse is most likely responsible for the breccia chimney beneath Hill C.

The relationship between the reef aquifer and dissolution is best illustrated by a chain of large dissolution depressions (Fig. 4) that occur along the flexured inner-reef margin along the east side of the basin (Malley and Huffington, 1953). The base of dissolution in these features rests on the anhydrite beds capping the reef, as indicated by the absence of Salado salt in these structures. The area where there has been a loss of salt in the Castile and Salado Formations adjacent to the reef overlies an area where water of low chlorinity (1 to 5 g/l) occurs in the upper part of the reef aquifer (Hiss, 1975). In the northwestern part of the basin, the fresher water in the upper part of the aquifer is separated by a relatively sharp interface from water of higher chlorinity (>28 g/l) in the lower part of the aquifer (Hiss, 1975). More complete flushing of the reef aquifer in the eastern part of the basin may have resulted in a more uniform vertical density distribution (W. L. Hiss, 1979, personal commun.).

The potentiometric surface of the reef aquifer is higher than the position of beds containing halite, so the undersaturated reef waters can be expected to contact overlying and adjacent salt through permeable fractures. This configuration of aquifer, dissolution effects, and brine is essentially the same as found in the brine density flow model, and it is reasonable to conclude that brine flow from areas of dissolution above and adjacent to the fractured reef margin has carried the brine to the lower part of the aquifer where it has accumulated (Fig. 4).

Localized breccia chimneys or "pipes" also occur in the exhumed western part of the Delaware Basin, where they have developed above the predissolved position of the lower halite unit (Halite I) of the Castile Formation. The underlying aquifer of the Delaware Mountain Group has low permeability and a potentiometric surface that can be expected to raise water in permeable fractures to the level of halite beds.

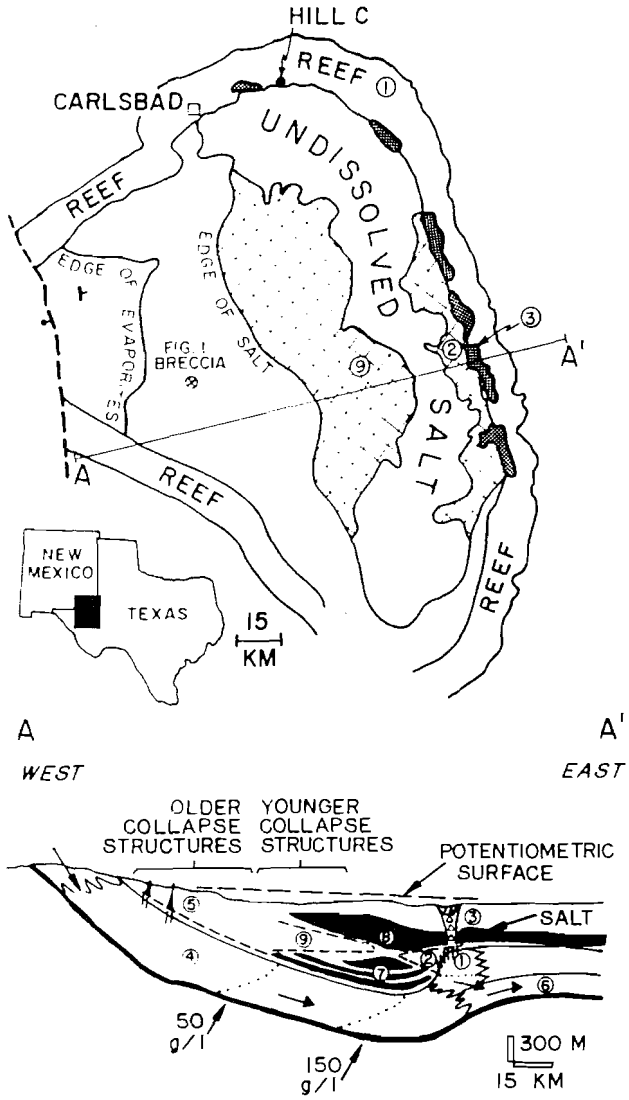

Figure 4. Diagrammatic illustration of Delaware Basin and evaporites. Undersaturated water from upper part of Capitan reef aquifer (1) moves laterally and vertically under artesian pressure through fractures to contact salt in an eastern dissolution wedge (2) and beneath reef-margin collapse structures (3). Undersaturated water from Delaware Mountain Group basin aquifer (4) moves upward under artesian pressure through fractures to contact salt beneath basin collapse structures (5). Brine from wedge (2) and from chambers beneath collapse structures (3, 5) drains downward into reef and basin aquifers (1, 4) and is removed through San Andres Limestone (6). Other features in diagram include salt beds of Castile Formation (7) and Salado Formation (8) and a western dissolution wedge (9). Unlabeled arrows indicate path of water flow in aquifers. (Modified from Hiss, 1975; Malley and Huffington, 1953).

Faulting and fractures in anhydrite between the basin aquifer and the overlying salt bed have given access to meteoric waters and hydrocarbons that nurtured a population of sulfate-reducing bacteria. Bacterial activity resulted in the biogenic replacement of anhydrite by calcite, increasing permeability of fractures by about 10% (Kirkland and Evans, 1976). Waters from the basin aquifer have moved upward along fractures and along these permeable zones of biogenic calcite. Where these waters have contacted overlying salt, dissolution chambers apparently have developed by brine density flow and have collapsed to form breccias (Fig. 1) and breccia chimneys (Fig. 4). The brecciated anhydrite in many of these chimneys has also been partly replaced by calcite from continued bacterial activity following collapse. Other younger collapse structures of similar spacing and scale occur in the central and eastern part of the basin, suggesting that localized dissolution and collapse above the basin aquifer may have occurred or may be occurring there as well (Fig. 4).

The chlorinity in the basin aquifer increases gradually from less than 10 g/l beyond the western edge of salt to about 150 g/l along the eastern margin of the basin (Hiss, 1975). Therefore, the potential for development of brine density flow in overlying fractures decreases eastward across the basin and is shifting eastward with exhumation and erosion of the tilted basin. The salinity gradient in the basin aquifer has been derived from the leaking downward of brines into the aquifer and is now balanced by slow leakage of brine from the aquifer into the San Andres Limestone (Hiss, 1975). The low permeability of the basin aquifer suggests that slow removal of brine from the aquifer might be the limiting factor in the development of overlying dissolution chambers. The hydrologic potential for dissolution and brine removal by the basin aquifer

can be calculated from available permeability data (Hiss, 1975) and the method of Lohman (1972, p. 10). This calculation shows that the upper 30 m of the basin aquifer can transport NaCl from the basin at the observed 150 g/l concentration at a rate of 14 $m^3 \cdot m^2 \cdot day$. This rate is sufficient to carry away the salt derived from 100 dissolution chambers of 1×10^6 m^3 from the New Mexico part of the basin in a period of about 30,000 yr, suggesting that removal of brine by the aquifer is not a long-term limitation in the formation of collapse structures.

Dissolution Wedges

Salt beds in the middle of the evaporite body (upper Castile Formation, lower Salado Formation) in the Delaware Basin have been dissolved over large areas and have left internal layers of dissolution and collapse breccias (Anderson and others, 1972, 1978). The relationship of dissolutional undercutting of salt to basin hydrology can best be observed along the eastern margin of the basin where the evaporite body abuts and overlaps the reef aquifer. An eastern dissolution "wedge" undercutting the evaporites has developed along the inner-reef margin and progressed out into the basin for distances of as much as 15 km (Fig. 4). The geometry of this wedge and the loss of salt from within the evaporite body show that the probable source of dissolving waters is the upper part of the reef aquifer, which is under sufficient head to move undersaturated water laterally. Thus, a brine flow cycle has been established in which the dissolving point of the wedge is supplied *laterally* with undersaturated water from the reef, and the brine produced by dissolution is drained down gradient into the lower part of the reef aquifer (Fig. 4).

A large western dissolution wedge is also present in the central part of the basin. It has apparently migrated eastward across the basin (Fig. 4). This remarkable feature has been produced by dissolving salt at preferred horizons from beneath overlying salt beds. Direct evidence for the wedge has been presented by Anderson and others (1978). The hydrologic controls for this western dissolution wedge are difficult to establish. Presumably, dissolving waters are supplied by surface drainage, and the resulting brine has leaked into the underlying aquifers. This wedge-like dissolution and lateral sapping of salt can be expected to eventually advance across most of the basin and leave beds of blanket dissolution and collapse breccia in its wake.

DISCUSSION

The brine density flow model and the examples of dissolution in the Delaware Basin suggest that similar processes may operate in other evaporite basins. The dissolution features of the Last Mountain Lake area of Saskatchewan (DeMille and others, 1964; Gorrell and Alderman, 1968), for example, are closely analogous to the over-reef dissolution and collapse in the Delaware Basin. Solution mining of salt, by means of artificial pressurized aquifer systems, which, in effect, is analogous to natural dissolution, produces breccias and collapse structures indistinguishable from natural collapse features (Jaron, 1970). Experience with solution mining also shows that the pathways of water movement at depth in evaporite beds may be complex and that dissolution effects can occur at considerable distances from the area of recharge of dissolving waters (D. J. Dowhan, 1976, unpub. report for Wyandotte Corp.).

We conclude that fracture systems that provide communication between pressurized and flowing fresh water aquifers and salt bodies have the potential for developing brine flow and a dissolution system. Localized dissolution chambers, which subsequently collapse to form trans-formational chimneys and pipes, can obtain a continuous flow of dissolving waters from remote horizons. Lateral dissolution and undermining of salt beds (wedges) can develop as a result of nearly horizontal brine flow and ultimately develop interformational or blanket breccias over wide areas.

The collapse breccias of the Delaware Basin (Anderson and others, 1978) and the breccias produced by solution mining (D. J. Dowhan, 1976, unpub. report for Wyandotte Corp.) show that various rock types above dissolved salt horizons may also develop voids and cavities that collapse to form breccias in stratigraphic units above and not directly related to the evaporites. In these instances, it may be possible to use certain breccias as indirect evidence of dissolution and to improve information on the past distribution of evaporites.

Most evaporite bodies are underlain by clastic or carbonate units that are likely to develop into pressurized and flowing aquifers upon exhumation. At burial depths favorable for radioactive waste repositories (500 to 1,000 m), many basins, as in the Delaware Basin, will have been partly exhumed and therefore may have a potential for developing deep-seated dissolution features from brine density flow. The near-random distribution of controlling fracture systems and the difficulty of identifying them in the subsurface make it hard to predict where the process will occur. It is suggested that estimates of the potential for deep-seated dissolution by means of brine flow should be added to factors considered in risk assessment programs for the evaluation of waste repositories in evaporites.

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