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Dissolution of Evaporites and its Possible Impact on the Integrity of the Waste Isolation Pilot Plant (WIPP) Repository

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FOREWORD

The purpose of the Environmental Evaluation Group (EEG) is to conduct an independent technical evaluation of the potential radiation exposure to people from the proposed Federal radioactive Waste Isolation Pilot Plant (WIPP) near Carlsbad, in order to protect the public health and safety and ensure that there is minimal environmental degradation. The EEG is part of the Environmental Improvement Division, a component of the New Mexico Health and Environment Department -- the agency charged with the primary responsibility for protecting the health of the citizens of New Mexico.

The Group is neither a proponent nor an opponent of WIPP. Analyses are conducted of available data concerning the proposed site, the design of the repository, its planned operation, and its long-term stability. These analyses include assessments of reports issued by the U.S. Department of Energy (DOE) and its contractors, other Federal agencies and organizations, as they relate to the potential health, safety and environmental impacts from WIPP.

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DISSOLUTION OF EVAPORITES AND ITS POSSIBLE IMPACT ON THE INTEGRITY OF THE WASTE ISOLATION PILOT PLANT (WIPP) REPOSITORY

SUMMARY

The dissolution processes in the bedded salt of southeastern New Mexico in the vicinity of the Waste Isolation Pilot Plant (WIPP) are devided into shallow dissolution and deep dissolution. The dynamic interrelationship of deep dissolution with the formation of breccia pipes, brine reservoirs, regional dissolution and regional land subsidence through examples are described. Crude estimates are given for the age of formation of the two known breccia pipes. A review of radiological consequences of breaches of the repository as a result of the dissolution indicates that in the majority of the cases the radiological consequences of a breach of the WIPP as a result of the deep dissolution processes are being addressed by the scenarios already studied or by ones in preparation. However, the degree of the reliability of the models used in the breach scenarios is subject of ongoing investigations. In other possible dissolution scenarios, the release of radionuclide through the geosphere to the biosphere may take periods of time that are orders of magnitude longer than the half-life of the most toxic of the long-lived radionuclides in the WIPP repository, Plutonium 239.

INTRODUCTION

The purposes of this report are: (1) to investigate the dissolution of evaporites and its possible manifestation (formation of breccia pipes, brine reservoirs, regional dissolution and subsidence) in the bedded salt of southeastern New Mexico in the vicinity of the WIPP site, (2) to postulate conditions under which breaches of the repository might occur, (3) to address radiological consequences of such breaches, and (4) to indentify areas that need further investigation.

The dissolution of evaporites is the change of their state from solid form to liquid form by contact with unsaturated water. The dissolution of evaporites in the bedded salt of southeastern New Mexico, Delaware Basin, may have started around the time of their deposition and is continuing today. The extent and activity of the dissolution processes both now and in the future are of importance in evaluating the adequacy of the WIPP site. The dissolution of evaporites produces dissolution residues and may lead to collapse features such as breccia pipes, and may also be responsible for brine reservoirs. Other features that may be related to dissolution are some of the surficial sinks or depressions in the Basin.

The dissolution of evaporites begins by unsaturated water dissolving the soluble materials and continues as long as unsaturated water and evaporites are in contact. The residual solid matrix is weaker structurally and more porous than the original evaporite bed. This porous residual matrix gradually crumbles and consolidates under the overburden weight forming a new layer. All these processes may occur simultaneously at a given time within the Basin. The residual formations may provide a significant pathway of the radionuclides to the biosphere if a nuclear repository that is located within the bedded salt is subjected to dissolution. Mathematical models of radionuclide transport are utilized to evaluate the radiological consequences of the nuclear waste repository breach. Hydrogeologic and geochemical properties of the residual formations are of crucial importance in these models.

The cumulative effect of the compaction of the dissolved evaporites on overburden materials is represented by the land subsidence on the ground surface. The magnitude of this displacement varies while being transferred upward from an evaporite layer to the ground surface as a function of various characteristics of the overburden materials. The displacement increases if the materials above a given horizon are also subject to active dissolution and it may be dampened otherwise.

The dissolution of evaporites may be divided into two broad classes: (a) shallow dissolution, and (b) deep dissolution. Most scientists are in agreement on the mechanisms that control shallow dissolution and on its possible impacts on the integrity of the repository. However, it is the deep dissolution and its possible impact on the integrity of the repository that is a matter of controversy.

Acknowledgement -- Appreciation is expressed to R. W. Kopf (retired, U. S. Geological Survey) who kindly reviewed and commented on his hydrotectonic theory in this report.

SHALLOW DISSOLUTION

Shallow dissolution is the dissolving of surficially exposed evaporites by climatic precipitation and surface water. The evaporite formations subjected to shallow dissolution in the Basin are the Rustler Formation and upper part of the Salado Formation. The most pronounced remnants of this process are at Nash Draw two miles to the west of the outer boundary of the WIPP site, and the San Simon Swale, 20 miles to the east of the site boundary. The leading edge of the dissolution is referred to as the "dissolution front."

Bachman(1)* suggests that intermittent dissolution of the Salado Formation near its western boundary began at least as early as 140 million years ago and is presumed to be continuing today. He further states that, if dissolution continues to be no more severe than during the past 500,000 years, there is no reason to believe that the repository horizon will be threatened by dissolution for another 500,000 years. Bachman also concludes: "Dissolution is presently an active process over the Capitan aquifer system along San Simon Swale about 32 Km (20 mi) east of the WIPP site. However, this aquifer system does not underlie the site and there is no presently known aquifer system or process of dissolution in this area which is undermining the site."

Estimate of the Time to Breach the WIPP Repository as a Result of Shallow Dissolution -- The dominant variables influencing shallow dissolution are spacial and temporal variations of climatological variables such as precipitation and temperature; tilting of the basin; and chemical characteristics and solubility of the exposed evaporites in the path of the shallow dissolution. Bachman and Johnson (14) estimated that the average rate of shallow dissolution front movement towards the repository is vertically about 0.5 foot of salt per 1000 year and horizontally between six to eight miles per million years (43 ft/1000yr).

* Numbers in the paranthesis refer to the references listed at the end of the report.

The closest known shallow dissolution front is 1500 ft vertically above and two miles horizontally to the west of the repository (7). Assuming time invariancy and linearity of the processes, it will take 3.25 million years for the front to breach the repository, Figure 1. This period of time is several orders of magnitude longer than the 24,000 year half-life of Plutonium 239 and the associated detrimental effects will be negligible.

DEEP DISSOLUTION

Deep dissolution is the dissolving of evaporites by unsaturated water deep within a geologic formation. It may be divided into two groups: (a) local or point source dissolution; and (b) regional or blanket dissolution. Deep dissolution may be closely related to the formation of breccia pipes and brine reservoirs. The brine density flow may be the main mechanism for the connection of an aquifer to the salt beds of Salado, thus producing deep dissolution (5). The unsaturated water of pressurized aquifers below the evaporites may rise through fractures and/or interfacial boundaries dissolving the salt and form denser brine that sinks back into the aquifer. The local or point source deep dissolution at its extreme may be represented by surfaced breccia pipes or breccia chimneys. The regional or blanket dissolution includes the dissolution of evaporites in large areas of the Basin forming possibly more permeable strata and brine reservoirs.

The extent to which deep dissolution is active at present and could be active in the future is a matter of controversy among geologists. Anderson (5) suggests that deep dissolution may be an active process throughout the Basin wherever evaporites exist, and where there is a source of unsaturated and pressurized water as well as a pathway and driving force to move the water into the evaporites. Anderson (5, 6, 8) believes that the brine density flow mechanism through faults and fractures connecting the Delaware Mountain Group the Capitan Reef and Castile formation is the main mechanism for deep dissolution. He considers the thinning of halite beds in some localities and Total Dissolved Solids (TDS) concentration gradient in the artesian groundwater of the DMG aquifers as partial evidence to support his hypothesis. In summary, Anderson (6) believes: "The horizon selected for the repository, ..., is the one with the most active history of dissolution. If dissolution proceeds as it has in the past, the WIPP site will be breached at the horizon of the repository before the overlying salt is removed by surface ground-water flow. Hence, estimates of site stability based upon the rate of movement of a surface dissolution front (U.S. Department of Energy, 1980, p. 7-98) may not be pertinent."

Bachman (1, 8), however, believes that the mechanism of brine density flow, given the recent past geohydrologic and climatic conditions in the region, is not adequate to explain all the relevant features in the Delaware Basin. In addition, Bachman does not believe this mechanism alone can account for the removal of large quantities of brine in the subsurface within the Basin due to the tightness of underlying aquifers. Bachman and other scientists (1, 9) disagree with Anderson's hypothesis based on their belief that a) the halite beds in the Castile Formation were originally deposited in individual subbasins within the larger Delaware Basin protected by relatively impermeable enclosing beds of anhydrites; and b) that if there has been any dissolution it occurred through surface erosion when the beds were nearer the surface after Permian and before Cretaceous time.

Based on a combination of surface geology, historical and present earthquake records, surveys (electrical resistivity, seismic reflection, gravity, aeromagnetic), and well logs, Barrows (8) has concluded that (a) there are no breccia pipes at the proposed WIPP site and no deep-seated tectonic faults penetrating the Salado within a mile of the proposed repository site; (b) there is some fracturing in the Castile Formation in the vicinity of WIPP but no evidence of displacement; and (c) the mechanism of large-scale near-saturated brine removal through DMG aquifer and the San Andres Limestone is not plausible owing to low permeability of those strata.

Local Dissolution -- At the extreme, the manifestation of local dissolution may be the generation of a breccia pipe. There are two distinct theories on the formation of breccia pipes. Stanton (2) relates their formation primarily to deep dissolution processes and believes they are formed gradually by subsidence of overlying formations in cavities generated by the deep dissolution. According to this interpretation, a breccia pipe caused by collape should contain breccia which has been displaced downward from one-higher strata and the diameter of the pipe should decrease upward.

The second theory by Kopf (3, 4) suggests tectonic as the primary triggering mechanism for the development and reactivation of some breccia pipes. According to this hypothesis, termed "hydrotectonics" (Kopf, 15) some breccia pipes are pressure relief tubes formed by powerful upward hydraulic injection of muddy tectonic breccia which then undergoes reversible surges generated by fluctuations in volume of chambers along an underlying regional undulatory thrust fault or decollement in which the tubes are rooted. If the reversible surges continue, the top of the pipe may become higher and, if it perforated the upper plate, will form a broad low mound of mud on the land surface called a "mud volcano". Later subsidence may leave a cone- or basin-shaped topographic depression in the center of the mound.

It is interesting to note that breccia pipes formed by Kopf's hydrotectonic hypothesis may be recognized by one or more of the following characteristics: (1) part of a breccia pipe may contain a mixture of fragments, some of which have been displaced upward and other downward from their original stratigraphic position; (2) the deformation of any particular stratum increases toward the pipe; (3) the diameter of parts of a breccia pipe may vary and appears to reflect variations in solubility and tectonic competence of strata locally forming the walls of the pipe; and (4) preceeding periods of local uplift and subsidence of the Earth's surface activated by renewed reversible surges within a directly underlying hydrotectonic pressure-relief tube may be recognized and dated by comparing the normal thickness of sedimentary deposits in the region with the thickness of the same strata exposed in the walls of the pipe -- strata that were later penetrated by the top of the upward-growing pressure-relief tube (Kopf, written commun., 1981).

Regional Dissolution -- Regional or blanket dissolution includes the dissolution of the evaporites in large areas of the Basin and brine reservoirs. It is important to note that in both theories discussed brine reservoirs also may be hypothesized the initial phase in the formation of breccia pipes. In Stanton's theory (2), a brine reservoir may be the nucleus of the initial cavity that causes gradual subsidence of the overburden materials. In Kopf's hydrotectonic theory (3, 4), the intersection of near-vertical fractures may predetermine the site for relief of anomalously high positive and negative fluid pressures generated along a part of a presumed deeply underlying active thrust fault. Once formed, the pipe may act as a vertical aquifer which penetrates underlying and overlying more or less flat lying aquacludes, and which allows brines to move vertically from one aquifer to another, or if the pipe penetrates all overlying strata, allows the brines to reach the earth's surface. Continued thrust faulting may reactivate part or all of the overlying pressure relief tube at any time in the distant future.

The hypothetical consequences of events leading from the dissolution of the evaporites to the formation of a brine reservoir is depicted in Figure 2. The assumption in Figure 2 is that the unsaturated water from pressurized aquifers within the Basin flows through a fracture (B) and/or along an interfacial surface toward layers of more soluble evaporites. Upon dissolving these exposed layers the more dense water moves downward and the brine density flow occurs. It is also assumed that there will be a critical cross section (A) due to heterogenity of the evaporite layers or pecularities of flow boundary layer phenomena. This assumption is not necessary for the formation of a brine reservoir. However, it will help to demonstrate the dynamic nature of various processes within the evaporites breached with unsaturated water.

Any possible obstruction of the critical cross-sections A and B will curtail brine density flow and will generate a brine reservoir. If the obstructions do not occur the process will be generating regional dissolution (extensive areas that behave like aquifers). The obstruction could be caused by the precipitation of returning denser brine and/or by collapse of the upper strata inside the critical cross-sections. The brine within the partly or completely isolated volume become more saturated with available constituents of the exposed evaporites. The enlargement of the brine reservoir may be renewed if the obstructions ease, such as dissolution of the collapsed materials in the critical cross-section (A) by the brine.

The regional deep dissolution of the evaporites may be a major mechanism for the removal of salt and the associated land subsidence in the Basin. If due to regional deep dissolution, the transfer of salt outside the Basin must be accomplished through the Bell Canyon aquifer, a member of the Delaware Mountain Group aquifers that underlies the evaporites. Figure 3 illustrates diagrammatically the movement of groundwater in the Basin.

Estimates of Salt Removal and Ages of the Known Breccia Pipes

The approximate maximum capacity of the Delaware Mountain Group aquifers for the removal of salt may be crudely estimated from the present hydrogeologic conditions. This estimation is based on the hypothetical configuration, as illustrated in Figure 4, approximately one meter width of the basin in the direction of DMG flow. Assuming hydraulic conductivity K = .016 ft/day[13] and hydraulic gradient $dh/d\ell = 2.2 \times 10^{-3}$ and 10^5 m as the length of the Basin[5], a value of 1.1×10^3 gr/day of salt removal per one meter width of the Basin is obtained. This value is equivalent to a uniform vertical removal of 1.8 meters of salt per million years. The contribution of local or point dissolution has been neglected in the calculation.

Excellent opportunities exist for the study of the history of regional deep dissolution and the associated subsidences due to the presence of breccia pipes and Karst domes. Independent of the hypothesis regarding the formation of the anamolies, these vertical columns, especially surficialy exposed breccia pipes, represent a much less soluble and more resilient material than the adjoining evaporites. The resiliency is caused by the collapse of younger non-evaporites within the boundaries of each pipe. In addition, associated with the outcrops of each column on the ground surface is a small catchment basin. These small watersheds collect and direct surface water, which contains younger sedimentary materials, toward their center after any major storm. While migrating downward the fresh meteoric water dissolves any remaining evaporites within their passageways. Dissolving soluble evaporites causes more cavities that will be filled with more of the younger non-evaporite and/or less dissolvable salts. These processes, being a function of storm formations, occur very fast time-wise compared with regional dissolution and associated deformations which are controlled by groundwater flow. Therefore, it may be reasonable to assume that breccia columns a short time after their formation are composed of younger, more resilient materials and to a large extent non-evaporites or evaporites with low solubility.

Figure 5 depicts possible changes in the configuration of the layers of the bedded-salt and the ground surface in the immediate vicinity of a breccia pipe as a function of time after the formation of the pipe (t=o). Of special consideration and interest are the slope of various layers toward the vertical breccia column. Before the formation of the pipe ($t=T_1 < o$) various layers of the evaporites are undisturbed (Figure 5-a). Immediately after the formation of the pipe (t=o), the amount of displacement is largest closest to the root of the breccia pipe and it decreases toward the ground surface. At the ground surface a catchment area is formed (Figure 5-b). The sediment-laden meteoric water collected in this small watershed the pipe. This process generates a ground surface more resistant to surficial erosion and, by dissolving more of the remnant evaporites within the pipe, a strengthening of the structural soundness of the column.

Figure 5-C represents the cross-section of the area of interest a long period of time after the formation of the pipe ($t=T_2>o$). During T_2 period a mound is gradually formed around the perimeter of the breccia pipe. The mound formation is mainly due to the regional subsidence of the bedded-salt. The surficial erosion by wind, precipitation and surface water may also aide this phenomenonsince the ground surface in the vicinity of the column is relatively more hardened. Of special interest in this regional subsidence is the reversal of the slope of some of the salt layers toward the vertical breccia column. This change of the slopes, if documented as a function of time, could give a good lead towards quantitative evaluation of the history of the subsidence and associated dissolution processes in the Basin.

There are two known surfaced breccia pipes in the northern Delaware Basin, Hill A and Hill C. Hill A has a relief of 12 to 15 meters and Hill C a relief of 30 meters (1). Assuming that: a) 1.8 meters per million years (p. 10, the maximum rate of the removal of the salt through DMG aquifers as a result of deep dissolution processes) approximates the rate of land subsidence per each million years, b) the breccia pipes are rooted on the DMG and neglecting contribution of Magenta, Culebra and Rustler/Salado contact in dissolution process, one obtains an estimated age of 6.7 and 16.7 million years for Hill A and Hill C respectively. Since shallow dissolution and surficial erosion may also contribute to the regional land subsidence, the rates associated with those processes should be added to a refined rate of land subsidence for a more accurate age determination.

<u>Radiological Consequences of the Breach of the WIPP as a Result of Deep Dissolution</u>--An agreement does not exist among geologists on deep dissolution and its impact on the integrity of the WIPP repository. One way to evaluate

the possible radiological consequences of the breach of the repository as a result of deep dissolution is to assume a breach does occur and then to quantify the effects by using mathematical models.

The leading edge of the regional deep dissolution is called the dissolution front. The dissolution front may be in the form of fingers or wedges penetrating the stratiform evaporite. At the time of the closure of the repository, one can assume that the closest of these dissolution wedges is at a distance of X meters from the repository perimeter, moving towards it at a long-range average rate of r meters per year. This indicates that it takes $t_1 = X/r$ years for the dissolution wedge to reach the repository after its closure, Figure 6. After time t_1, the brine penetrates the repository and starts to dissolve, mobilizing and transporting the radionuclides towards the biosphere. The period of time associated with dissolution and/or mobilzation of the radionuclides in the wastes is t_2. The time for the mobile radionuclides to go through the regional dissolution remnants is assumed to be t_3, while t_4 is the period of time the radionuclides move from the outflow of the dissolution remnants to the biosphere. Therefore, $T = t_1 + t_2 + t_3 + t_4$ is the total period of time, after the closure of the repository, at which the radionuclides will be present in the biosphere, Figure 6.

In the extreme condition, if path AB in Figure 6 is already well developed, then immediately after the closure of the repository the dissolution and mobilization of the radionuclide starts. After the dissolution of radionuclides, according to the brine density flow mechanism, the radionuclide-laden brine should be moving downward toward the DMG aquifers. However, there are sets of circumstances under which the radionuclide-laden brine may be moving upward toward the ground surface.

While moving upward, if the brine became intercepted by the Magenta and Culebra aquifers of the Rustler Formation, the port of its entry into the biosphere would be the outcrops of these aquifers in Nash Draw (10) and/or the Malaga Bend of the Pecos River. This type of liquid breach scenario is already addressed in part by the DOE (11, 13) and EEG (7, 12). At present there are efforts to refine the model as to: a) the effects of the fractures in the dolomitic Magenta and Culebra; b) the possibility of having much more permeable abandoned mine tunnels in potash as part of the radionuclide flow path to the biosphere; c) the significance of the outcrops of Magenta and Culebra aquifers in the Nash Draw seven miles closer to the repository than the Malega Bend of the Pecos River; and d) the effects of long-term climatic and hydrologic variations.

If the radionuclide-laden brine is pressurized similar to some brine reservoirs, or a catastrophic collapse occurs similar to a breccia pipe, then it is conceivable that the brine might move all the way upward to the ground surface. Various other credible scenarios may be visualized in this class of the breach of the repository. The radiological health ramification of these scenarios will be addressed in future EEG publications.

Another possible scenario that may be developed when path AB in Figure 6 is already well developed at the time of the closure of the repository is that the deep dissolution remnant has formed a new flow path, unknown and undetected by our explorations (Figure 7). It is expected that this flow path would flow northeasterly as DMG aquifers do and would have at least a flow path of 15 Km. This length is equivalent to 2/3 the flow path length of the Culebra and Magenta aquifers from the WIPP to Pecos River before entering the biosphere.

I suggest that the hydrogeological and geochemical properties of this new flow path would be similar to the Magenta and Culebra aquifers of the Rustler formation since they are the remnant of past dissolution processes. The two basic differences are the radionuclide flow path from the WIPP repository through the geosphere to the biosphere and the fracture permeability. The flow path in the postulated aquifer would be a minimum of 15 Km. The fracture permeability in the postulated aquifer would be most likely smaller than its corresponding value in the Magenta and Culebra because of the higher overburden weight. Therefore, the radiological health consequences of this breach of the repository is very close to the calculation done on the breach of the repository through Magenta and Culebra aquifers (7, 10, 12, 13).

Another extreme case consideration is to assume that the hydrogeological characteristics of the postulated flow path are similar to the Rustler-Salado interface. This possibility appears much less likely due to the fact that the repository is located completely within the Salado formation. This case is not addressed here but should be quantified when more data become available.

Another possible pathway within the geosphere for the release of radionuclides to the biosphere as a result of deep dissolution-caused breaching of the repository is the movement of radionuclide-laden brine through the Bell Canyon aquifer. The minimum horizontal distance of the flow path from the repository within the Bell Canyon aquifer is 15 km. Using Darcy's law, porosity of 0.16, hydraulic conductivity of 0.016 ft/day, and hydraulic gradient of 2.2×10^{-3} (5), one obtains a travel time of 600,000 years. Even by not taking credit for any other time delays, this period is twenty five times the half-life of Plutonium 239.

CONCLUSION

The radiological consequences of a breach of the WIPP TRU waste repository, as a result of dissolution processes were shown to be in two broad classes. Most of the possible scenarios that could happen as a result of the deep dissolution processes were shown to be addressed by the scenarios already studied or being investigated at the present. The remaining possible scenarios except one showed that the possible release of radionuclides through the geosphere to the biosphere would take periods of time in at least orders of magnitude longer than the half-life of Plutonium 239. The one not specifically addressed that is a postulated hydrologic pathway with the characteristics of Salado/Castile contact appears unlikely. However, it should be quantified when more data become available. To obtain a better understanding of the radiological health effects of the deep dissolution-caused breach of the repository, emphasis must be placed on better evaluation and refinement of the existing mathematical models and associated parameters.

In the majority of the existing scenarios the most significant pathway of the radionuclide through the geosphere to the biosphere is the dolomitic Magenta and Culebra aquifers. Being fractured, the mathematical modeling of the radionuclide transport through these aquifers is subject to a large degree of uncertainty. Other uncertainties that relate to this pathway which need further study are: a) the possibility of having much more permeable abandoned mined potash tunnels as a part of the radionuclide flow path and b) the outcrops of the Magenta and Culebra in the Nash Draw, seven miles before the Malaga Bend of the Pecos River. The problems associated with the quantifications of these uncertainties as well as the effects of long-term climatic and hydrologic changes and hydrogeological data requirements of the models presently are being addressed.

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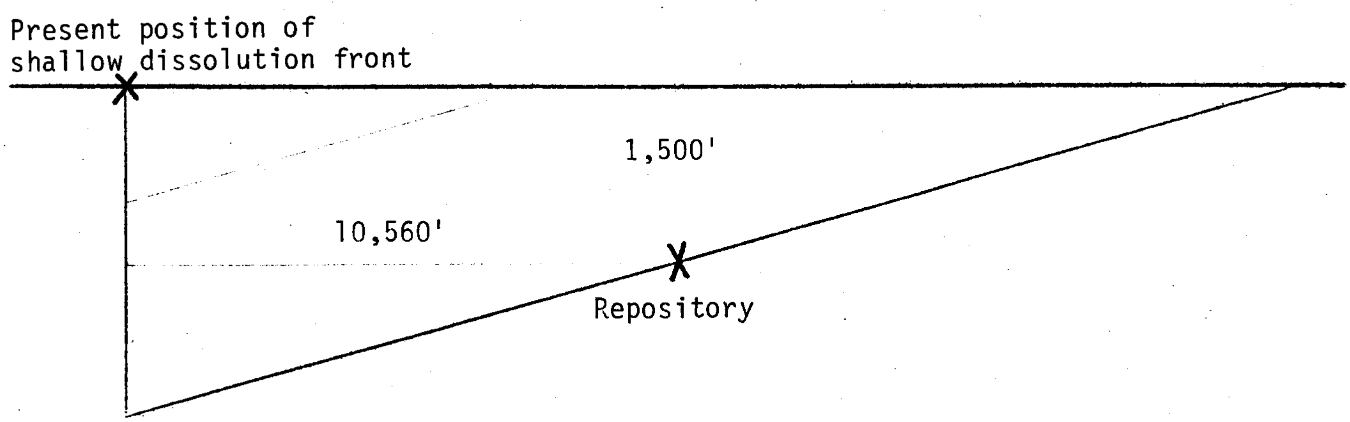
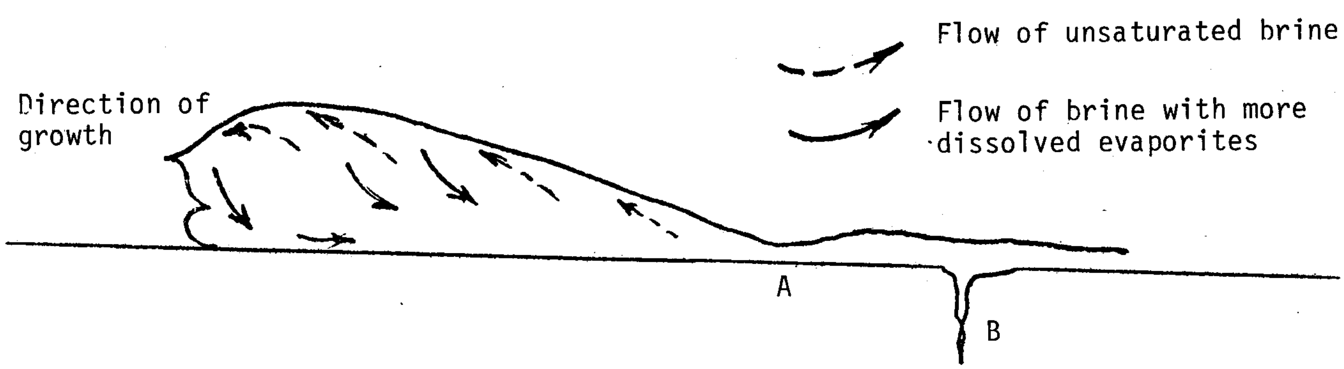


FIGURE 1 - Advancement of shallow dissolution front towards the repository.



A - A constriction in the flow path

B - A fracture connecting unsaturated brine to the evaporites

FIGURE 2 - A hypothetical sketh of a cross-section illustrating possible formation of a brine reservoir within Castile Formation as a result of deep dissolution.

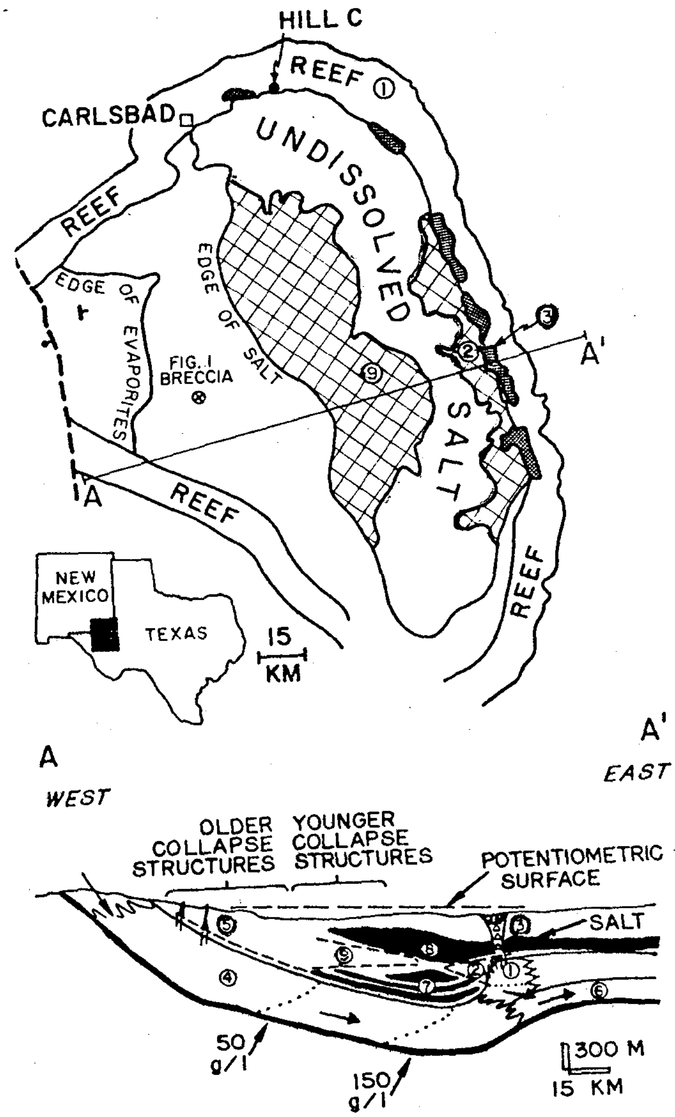
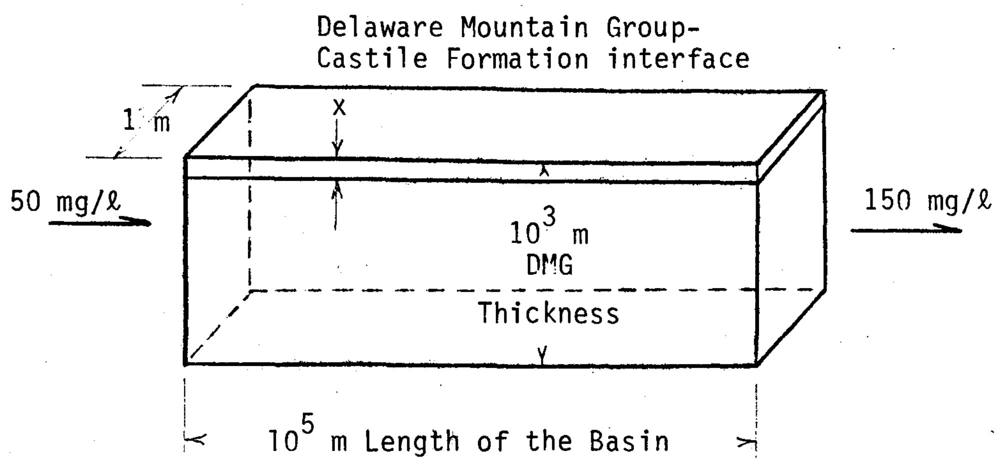


FIGURE 3 - Diagramatic sketch illustrating movement of groundwater in Delaware Basin as proposed by Anderson(5).



$V = K\ \Delta h/\Delta\ell$

$Q = V\ A$

$M = \Delta c \cdot Q$

$x = 1.8$ m/Myr

Where:

V = specific discharge. . . . . [L/T]

k = hydraulic conductivity. . . . . [L/T]

$\Delta h/\Delta\ell$ = hydraulic conductivity . . . . . [L/L]

Q = flow rate . . . . .[L^3/T]

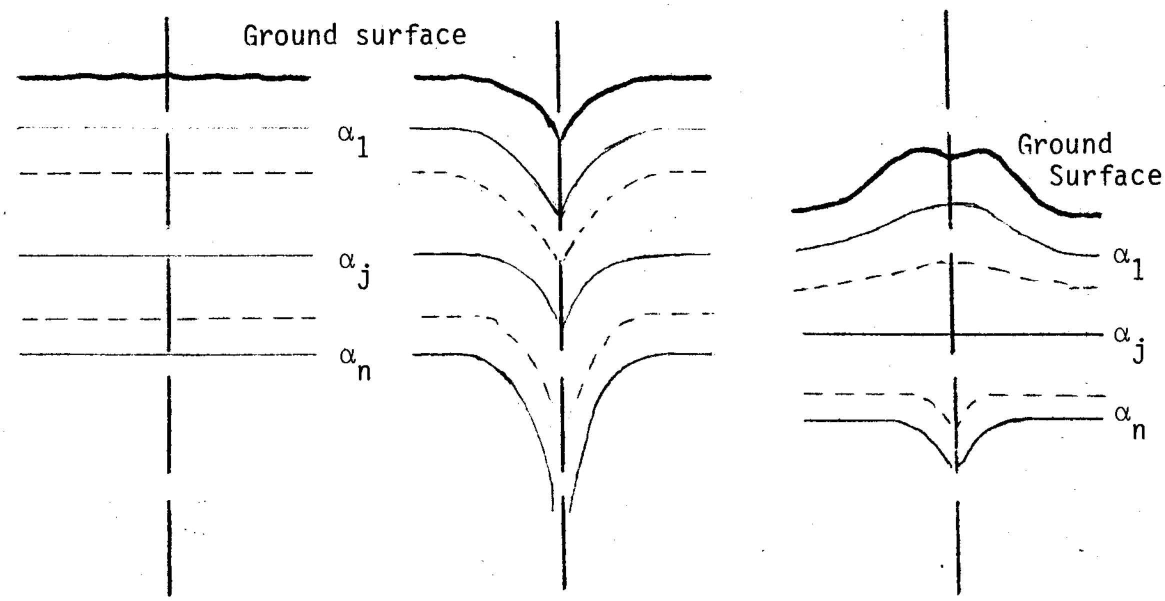
A = cross-sectional area. . . . . [L^2]

M = mass flow rate. . . . . [M/T]

Δc = change in the concentrations . . . . [M/L^3]

x = vertical thickness removal rate . . . . . [L/T]

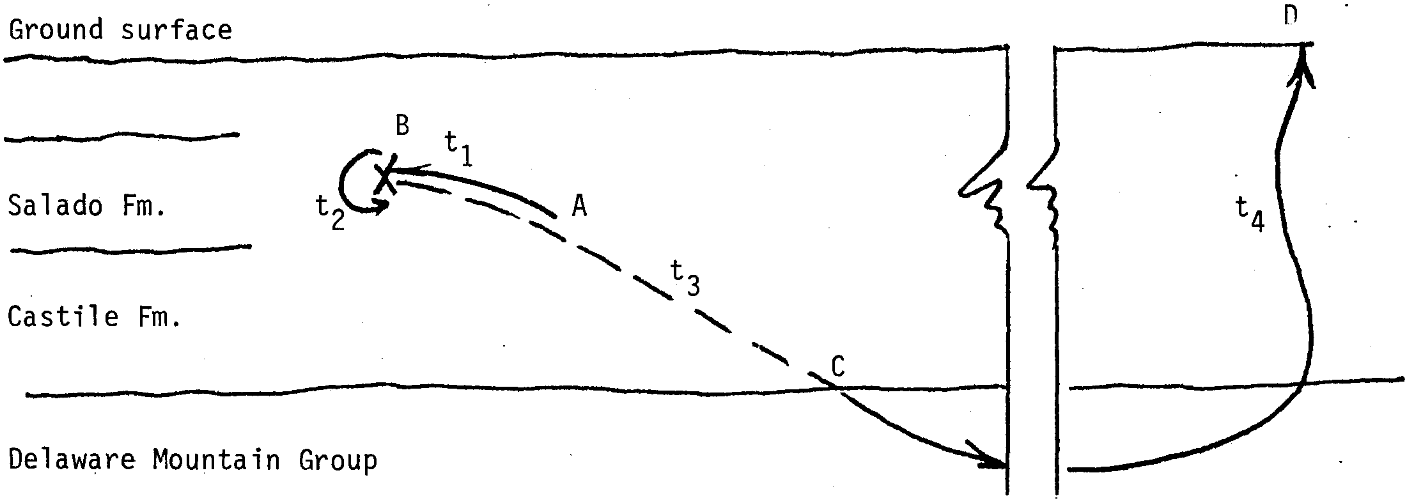
FIGURE 4 - A hypothetical 1m wide cross-section of the Basin parallel to the flow direction of Delaware Mountain Group aquifers.



$t = T_1 < 0$	$t = 0$	$t = T_2 >> 0$
Just before formation of breccia pipe	Formation of breccia pipe	At present regional subsidence
5-a	5-b	5-c

α_i, $i = 1, 2, \ldots, j, \ldots n$ are given horizons in the evaporite layers

FIGURE 5 - Possible changes in position of evaporite layers relative to a breccia pipe as a function of regional subsidence.



A - Position of a dissolution wedge at the time of closure of the repository B

C - Radionuclide-laden brine entering the DMG

D - Entrance of the radionuclides in the biosphere

FIGURE 6 - A hypothetical path of the radionuclides to the biosphere as a result of regional deep dissolution.

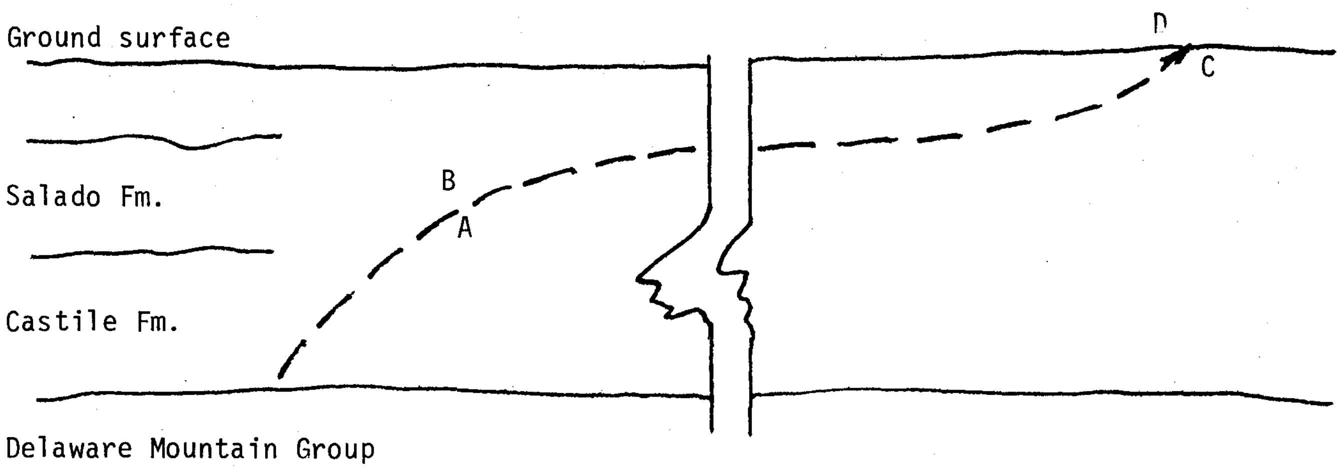


FIGURE 7 - A hypothetical direct flow path of the radionuclides to the biosphere as a result of regional deep dissolution.