Waste Isolation Pilot Plant

Compliance Certification Application

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Assessing Deep-Seatcd Dissolution-Subsidence Hazards at Radioactive-Waste Repository Sites in Bedded Salt

Peter B. Davies*

Department of Applied Earth Sciences, Stanford University, Stanford, CA 94305 (U.S.A.)

Abstract


Deep-seated salt dissolution and associated subsidence have occurred in many salt-bearing sedimentary basins. Because of its capacity for breaching the hydrologic integrity of a thick salt unit, the dissolution-subsidence process is a potential hazard requiring thorough assessment at proposed radioactive waste repository sites in bedded salt. In order to develop a better understanding of this potential hazard, a combination of field studies and theoretical analyses are used to delineate the physical processes that control dissolution and subsidence. This information is used, in turn, to develop strategies for assessing this hazard at any given bedded salt repository site.

A generalized hydrogeological model of dissolution has been developed consisting of a salt unit separated from an underlying aquifer by a low-permeability unit. This model suggests that local salt-removal rates can vary over many orders of magnitude, from microns per year to meters per year, depending on the hydrogeologic conditions beneath the salt unit.

Salt deformation is strongly rate-sensitive, so the rate of salt removal strongly influences the structural form of subsidence. Low salt-removal rates produce predominantly ductile subsidence, which is characterized by the gradual formation of a broad shallow depression that is narrower and deeper in successively lower horizons. On the other hand, high salt-removal rates produce predominantly brittle subsidence, which is characterized by the formation of a steep-walled chimney, filled with down-dropped, brecciated rock. Ductile subsidence depressions and brittle subsidence chimneys most likely represent the endpoints of a continuous range of structural forms.

Assessing potential dissolution-subsidence hazards at a given repository site begins with the identification and characterization of existing dissolution-subsidence features in the site area. Studies of existing features should be complemented by an evaluation of the potential for undetected or future dissolution activity, based on the deep hydrogeologic conditions at the site. Potential salt-removal rates predicted by this analysis are then used as an analysis of the structural character and timing of potential subsidence.

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INTRODUCTION

Salt dissolution, which occurs when unsaturated groundwater gains access to highly soluble halite, has occurred at depths of as much as 1500 m, in many evaporite-bearing sedimentary basins (Table I). In some areas, deep-seated dissolution and subsidence have occurred in the past and dissolution-subside activity is expected to continue. In many areas, dissolution has occurred at the base of, or within the lower part of, an evaporite section. In some areas, dissolution appears to be associated with either tectonic or non-tectonic fracturing that has provided, or enhanced, localized flow paths between halite units and nearby aquifers.

TABLE I

Examples of localized, deep-seated, dissolution-subside structures in halite salt deposits

<table>
<thead>
<tr>
<th>Name and location of structure</th>
<th>Type of structure and approximate dimensions</th>
<th>Comments/References</th>
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<tbody>
<tr>
<td>Crater Lake Collapse</td>
<td>Subsidence chimney:</td>
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<tr>
<td>Structure, Western Canadian</td>
<td>- Depth 900 m</td>
<td></td>
</tr>
<tr>
<td>Basin, Saskatchewan</td>
<td>- Diameter 240 m</td>
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<tr>
<td></td>
<td>- Expressed as a circular depression on the ground surface</td>
<td></td>
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<tr>
<td></td>
<td>- Approx. 43 m of subsidence has occurred near the ground surface</td>
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<tr>
<td></td>
<td>Structural depression:</td>
<td></td>
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<tr>
<td></td>
<td>- Depth 1200 m</td>
<td></td>
</tr>
<tr>
<td></td>
<td>- Elliptical shape 16 x 32 km</td>
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<tr>
<td></td>
<td>- Maximum structural relief 200 m, approx. equal to the total salt thickness</td>
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<td>- Maximum structural closure 90 m</td>
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<td>Structural depression:</td>
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<td></td>
<td>- Depth 1500 m</td>
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</tr>
<tr>
<td></td>
<td>- Irregular shape, 24 x 32 km</td>
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</tr>
<tr>
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<td>- Maximum structural relief 115 m is approx. equal to total salt thickness</td>
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<tr>
<td></td>
<td>- A cored exploration hole revealed that the entire salt section is missing; in its place is a layer of insoluble residue overlain by subsidence breccia</td>
<td></td>
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<tr>
<td></td>
<td>Subsidence chimney:</td>
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<tr>
<td></td>
<td>- Depth estimated to be in the range of 150 to 300 m</td>
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<tr>
<td></td>
<td>- Expressed as an 18 m deep sinkhole on the ground surface</td>
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Deformation of Pleistocene deposits indicates that the most recent subsidence occurred approximately 13,000 years ago. (Christiansen, 1971; Gobbell and Hojazi, 1971)

Subsidence chimney: - Depth 900 m - Diameter 240 m - Expressed as a circular depression on the ground surface - Approx. 43 m of subsidence has occurred near the ground surface - Structural depression: - Depth 1200 m - Elliptical shape 16 x 32 km - Maximum structural relief 200 m, approx. equal to the total salt thickness - Maximum structural closure 90 m - Structural depression: - Depth 1500 m - Irregular shape, 24 x 32 km - Maximum structural relief 115 m is approx. equal to total salt thickness - A cored exploration hole revealed that the entire salt section is missing; in its place is a layer of insoluble residue overlain by subsidence breccia - Subsidence chimney: - Depth estimated to be in the range of 150 to 300 m - Expressed as an 18 m deep sinkhole on the ground surface - Structural depression: - Depth 1200 m - Elliptical shape 16 x 32 km - Maximum structural relief 200 m, approx. equal to the total salt thickness - Maximum structural closure 90 m - Structural depression: - Depth 1500 m - Irregular shape, 24 x 32 km - Maximum structural relief 115 m is approx. equal to total salt thickness - A cored exploration hole revealed that the entire salt section is missing; in its place is a layer of insoluble residue overlain by subsidence breccia - Subsidence chimney: - Depth estimated to be in the range of 150 to 300 m - Expressed as an 18 m deep sinkhole on the ground surface

Subsidence deformation ranges from localized downwarping of higher strata, forming closed structural depressions, to extensive fracturing and downdropping of higher strata, forming roughly cylindrical chimneys of brecciated rock. Subsidence chimneys are commonly expressed at the ground surface as large sinkholes (Fig. 1). In some, however, the upward propagation of subsidence does not reach the ground surface. In others, relatively old subsidence structures are buried by younger deposits. Therefore, not all subsidence structures display a telltale surface expression.

Because of its capacity for creating hydrologic transport pathways between a radioactive-waste repository and the biosphere, the combination of deep-seated dissolution and subsidence is a hazard requiring thorough assessment. This assessment should include the following: (1) identifying and characteriz-
ing dissolution and/or subsidence features at both site and regional scales; (2) evaluating the potential for undetected or future dissolution-subsidence activity at the site; (3) characterizing the impact of subsidence relative to the ability of the repository to isolate waste from the biosphere.

Successful completion of these tasks requires a comprehensive knowledge of geologic and hydrologic conditions in the site area, as well as a thorough understanding of the dissolution-subsidence process. This paper comprises a brief synopsis of the physical processes that control deep-seated dissolution and subsidence, followed by a discussion of strategies for assessing repository sites relative to the dissolution-subsidence hazard.

**Dissolution and Mass Transport of Halite**

Dissolution of halite that is in contact with unsaturated groundwater is the primary process controlling deep-seated subsidence in salt-bearing sedimentary basins. Halite has a very high solubility (359 g NaCl/ L H₂O at 25°C). The solubility of halite varies somewhat with temperature, pressure, and the presence of other solutes, but it is one to three orders of magnitude higher than the solubilities of anhydrite and limestone under normal groundwater conditions.

Halite dissolution is essentially instantaneous relative to the time scale of the transport process in the presence of water that is unsaturated with respect to sodium chloride. Therefore, the rate of solid salt removal is controlled by the convective and/or diffusive flux of sodium and chloride ions away from a halite-bearing formation. Transport mechanisms include molecular diffusion, free convection (driven by gravity acting on an inverted fluid density gradient), and by forced convection (driven by a regional flow system).

In order to illustrate the basic components of the dissolution and mass transport process, and to derive rough first approximations of salt dissolution rates under a variety of hydrogeologic conditions, the behavior of a simple NaCl-H₂O system has been analyzed (Davies, 1984, Sect. 3.1). The role of each transport mechanism can be analyzed by considering the hydrogeologic conditions shown in Fig.2. This generalized geologic section depicts a salt unit that is separated from an underlying aquifer by a low-permeability unit (aquiclude) such as shale or anhydrite. The aquiclude is cut by a vertical high-permeability pathway. By varying the dimensions and hydrologic characteristics of the aquifer, aquiclude and high-permeability pathway, a variety of dissolution and transport scenarios can be examined.

The nature of the vertical hydrologic pathway(s) between the salt unit and the aquifer is difficult to determine. The most likely source for a local, high-permeability pathway is fracturing of the aquiclude by faulting produced by tectonic movements, differential subsidence, or differential compaction. If the aquiclude is anhydrite, which has a higher solubility than limestone under many conditions, then fracturing may also be produced by dissolution at the base of the anhydrite with associated subsidence. Although locating and hydrologically characterizing fracture zones associated with subsidence structures in the field is extremely difficult, the role of such zones in the dissolution process can be analyzed by considering a variety of idealized pathways.

**Transport by diffusion**

Diffusion is a process whereby solutes move under the influence of their kinetic activity in the direction of decreasing concentration. Under one-
dimensional, steady conditions, diffusion in a saturated porous medium is described by a modified form of Fick's law:

\[ J = -n T^* D \frac{dC}{dx} = -D e \frac{dC}{dx} \]  

In eq.1, \( J \) is the mass flux, \( D \) is the diffusion coefficient (empirically derived), \( n \) is effective porosity, \( T^* \) is a tortuosity parameter that is a measure of the nonlinearity of diffusion pathways, \( C \) is solute concentration, and \( De \) is an effective diffusion coefficient.

The diffusion coefficient for sodium chloride in the NaCl-H2O system is 1.5 \times 10^{-9} \text{ m}^2/\text{s} (Weast, 1978, p.582). For clayey deposits, Freeze and Cherry (1979, p.333) cite \( De \) values of \( 10^{-10} \) to \( 10^{-11} \text{ m}^2/\text{s} \) as being typical for nonreactive chemical species. \( De \) values for coarse-grained material can be somewhat higher than \( 10^{-10} \text{ m}^2/\text{s} \), however, the coefficient for diffusion in a continuous body of water, \( D \), provides an upper bound on \( De \).

Unfortunately neither \( De \) values nor the combination of \( n \) and \( T^* \) are available for low-permeability evaporites such as anhydrite, which is the aquiclude separating halite units from underlying aquifers in some basins. Because it is a relatively dense, crystalline rock, the effective porosities of anhydrite rock masses are most likely very low, probably much less than 0.01. Porosity for other relatively tight crystalline rocks range from \( 10^{-1} \) to \( 10^{-5} \) (Snow, 1968, pp.84-85). If anhydrite is similar, then it has \( De \) values on the order of \( 10^{-12} \) to \( 10^{-14} \text{ m}^2/\text{s} \).

Mass transport by diffusion is a very slow process. For example, assuming a relatively conservative situation comprised of a halite unit separated from an underlying fresh-water aquifer by a 10 m thick aquiclude having a \( De \) value of \( 10^{-11} \text{ m}^2/\text{s} \), the regional halite removal rate is on the order of 5 microns per year. In most natural situations, the water in the aquifer has higher initial salinities and the \( De \) values of the aquiclude are most likely a few orders of magnitude lower. Therefore, in most situations, halite removal rates controlled by diffusion are much less than one micron per year.

**Transport by free convection**

Free convection is a more efficient mass transport mechanism than diffusion, so it is a potentially important mechanism for transporting dissolved salt, as recognized by Anderson and Kirkland (1980). In either a saturated porous medium or a continuous body of fluid, a state of instability exists if the density of fluid at a given horizon is greater than that of underlying fluid. Furthermore, if the buoyancy due to a density inversion is sufficient to overcome the resistance to flow provided by the fluid viscosity and porous medium (if present), then free convection will occur. Halite dissolution at the base of a salt unit gives rise to vertical density gradients, with dense solute-rich brine overlying less dense groundwater, which can cause free convection to occur.

In order to delineate the role of free convective transport in the salt dissolution process, two basic questions must be addressed. First, under what conditions will free convection occur, and second, at what rate can dissolved salt be transported by free convection?

These questions can be addressed by examining the behavior of a dimensionless free convection parameter, called the Rayleigh number. The Rayleigh number is derived from a dimensional analysis of the equation of motion (Rayleigh, 1916; Lapwood, 1948; Wooding, 1960). This type of analysis can be utilized to examine solute-driven free convection under a wide variety of idealized, hydrogeologic conditions, including free convection in unfractured units, in single fractures, and in fracture zones (Wood et al., 1982; Davies, 1984, Sect. 3.1.3). As an example of this type of analysis, the next three paragraphs focus on free convection in a discrete zone of highly fractured rock that transects an aquiclude unit separating a halite unit from an underlying aquifer.

For the analysis, a discrete zone of highly fractured rock has been modeled as a vertical channel of porous material (Fig.3). For this geometry, the Rayleigh number has the following form:

\[ Ra = \frac{\Delta C \rho g k h^2}{\mu D_k} \]  

where: \( \Delta C \) is the difference in solute concentration between the dissolution zone at the top of the fracture zone and the groundwater at the base of the fracture zone; \( \rho \) is a volumetric expansion coefficient; \( \rho_s \) is a reference fluid density; \( g \) is the magnitude of gravitational acceleration; \( k \) is intrinsic permeability; \( h \) is the height of the fracture zone; \( \mu \) is fluid viscosity; and \( D_k \) is the dispersion coefficient. In order for free convection to occur in a system with the geometry depicted in Fig.3, the Rayleigh number must exceed a critical

![Fig.3. Schematic illustration of the equivalent porous medium model used for analyzing free convection in a discrete zone of highly fractured rock.](image)
value of 40 (Beck, 1972). By setting eq.2 equal to this threshold Rayleigh number and solving for $k$, the minimum permeability required for the occurrence of free convection can be determined for a given fracture zone.

For example, consider an aquiclude 100 m thick separating a halite unit from an underlying aquifer containing groundwater with a dissolved NaCl concentration equal to one half the concentration at total saturation. For this case, the Rayleigh number exceeds the critical threshold and free convection will be active if the fracture zone permeability is greater than $10^{-17}$ m$^2$ (or hydraulic conductivity is greater than $4 \times 10^{-8}$ cm/s). The results of this and other fracture zone scenarios suggest that the threshold permeability for the onset of free convection is relatively low, and therefore, free convection will be a viable transport mechanism.

A rough estimate of flux of dissolved salt through a fracture zone can be calculated using an empirically derived relationship between the convection parameter, $Ra$, and a dimensionless mass transport coefficient, $Nu$, called the mass transport Nusselt number. The Nusselt number expresses the ratio of the total mass flux to the mass flux by diffusion alone. Because of the physical and mathematical analogies between heat and mass transport, Rayleigh–Nusselt relationships derived from heat transport experiments are commonly used to predict mass transport rates in physically similar systems (Eckert and Drake, 1969; Kreith, 1973).

In the absence of an empirically derived $Ra$–$Nu$ relationship for a physically identical system, estimates of mass transport rates through a porous fracture zone have been made using an empirically derived $Ra$–$Nu$ relationship from Elder (1967) for heat flux through a horizontal porous layer. This approach provides a reasonable first approximation of flux magnitudes because of the similarities between free convection in a porous medium with and without the presence of confining vertical walls. The presence of vertical walls has much less influence on free convection in a vertical channel filled with porous material than it does on free convection in a vertical channel filled only with fluid. This diminished influence occurs because viscous dissipation in a porous channel is primarily associated with flow through the porous medium rather than flow along the channel walls (Beck, 1972). The only effect of the walls is that they restrict the geometry of the convection cells. This restriction makes heat and mass transport through a vertical porous channel less efficient than transport through a comparable vertical section within a horizontal porous layer.

Mass transport by free convection is much faster than transport by diffusion alone. For example, consider a situation comprised of a 1-m wide fracture zone with a hydraulic conductivity of $10^{-4}$ cm/s transecting the aquiclude described in the previous section. The localized halite removal rate for this scenario is on the order of a few centimeters per year, which is orders of magnitude higher than the removal rate for diffusion alone.

Transport by forced convection

Once salt-rich brine passes from a fracture zone into an underlying aquifer, the mode of mass transport is altered significantly. Forced convection through the aquifer, driven by a regional head gradient, becomes the primary transport mechanism. However, if the vertical component of the external head gradient is small, the vertical component of flow may still be primarily driven by buoyancy (Prats, 1966; Bear, 1972).

Because groundwater flow in the vicinity of an influx of salt-rich brine is influenced by spatial variations in fluid density, rigorous modeling of this process requires solution of strongly coupled flow and mass transport equations. A simpler alternative, which yields an upper bound on aquifer transport capacity, is to compute the amount of dissolved salt required to bring the entire thickness of the aquifer to NaCl saturation.

Summary

The preceding paragraphs summarize the main components of the salt dissolution and transport process. In addition to the few example dissolution rate computations in this paper, a wider range of dissolution scenarios in Davies (1984, Sect. 3.1.5) shows that salt-removal rates can vary over several orders of magnitude, depending on the hydrogeologic conditions underlying the salt unit. The rate of dissolution is controlled by the transport capacity of the least efficient component of the mass transport system. For most cases, the rate limiting component of the system is transport through the aquiclue, either by molecular diffusion through an unfractured aquiclue, or by free convection through a fracture zone. An exception to aquiclue-limited transport occurs in situations where a high-permeability fracture zone is coupled with a low-capacity aquifer. In this case, transport is limited by the rate at which the aquifer can carry away the relatively high influx of dissolved salt.

Brittle versus ductile salt subsidence

Removal of salt by dissolution is the boundary condition that controls subsidence deformation. Because salt deformation behavior varies significantly with deformation rate, the salt dissolution rate (i.e., the rate at which support is removed from the lower part of a salt section) strongly influences the structural form of the associated subsidence.

Salt deformation behavior

Salt is characterized by its ability to deform either ductilely or brittlely, depending on temperature, stress state, and deformation rate. Most experimental and theoretical work on salt deformation has focused on ductile deformation, because this is the dominant mode of long-term deformation associated with conventional salt and potash mining (Hofer, 1965; Heard, 1972; Baar, 1977; Munson and Dawson, 1981). Ductile deformation also plays a central role in the development of salt domes and salt glaciers (Ode, 1968; Berner et al., 1972; Gera, 1972; Wenkert, 1979). At temperatures expected for the salt dissolution–subsidence process, the primary ductile deformation mechanisms for dry salt are dislocation glide at moderate differential stresses and moderate...
deformation rates, and dislocation creep at low differential stresses and low deformation rates.

If intercrystalline water penetrates the subsiding salt mass from below, deformation by intergranular liquid diffusion may be the primary ductile deformation mechanism at lower stress levels. Deformation by this latter mechanism is capable of producing strain rates that are orders of magnitude higher than are possible in dry salt at the same stress states.

At relatively high deformation rates, salt will rupture following relatively small ductile strains. This process is called creep rupture. Although little work has been done on the creep rupture of salt, extensive work on analogous rupture processes in similar polycrystalline materials, i.e., metals at high temperatures, provides some insight into the creep rupture process in salt (Nair and Singh, 1973; Carter, 1983). The amount of ductile strain prior to rupture is strongly influenced by confining stress and deformation rate. The deformation mechanism responsible for creep rupture is time-dependent nucleation and growth of fractures that form during creep deformation. Unfortunately, the available laboratory data on creep rupture in salt covers only a narrow range of stress conditions.

The wide variety of potential salt deformation behaviors, coupled with the broad range of potential salt removal rates, makes construction of a single, generalized model of salt subsidence impractical. Therefore, in order to gain more insight into the mechanics of the subsidence process, two basic types of subsidence are analyzed: (1) very slow subsidence characterized by predominantly ductile deformation; and (2) relatively rapid subsidence characterized by predominantly brittle deformation. These two types of subsidence represent the ends of a continuous range of subsidence processes.

**Ductile subsidence**

In order to develop a conceptual picture of the structural evolution of ductile subsidence, several relatively simple models have been developed. Modeling of geologic structures in salt has its roots primarily in research that has been directed toward understanding the development of flow structures such as salt anticlines and salt domes.

Nettleton (1934) introduced the concept that the formation of salt domes is "essentially the movement of very viscous fluids under gravitational forces". Even though the physical mechanisms of plastic salt deformation are complex and differ from viscous fluid deformation, viscous models have been quite useful in the study of geologic structures in salt (Biot and Odé, 1965; Ramberg, 1968, 1981; Berner et al., 1972; Barrows, 1983).

Following the basic methodology of these earlier studies, the creeping flow equations have been solved to model subsidence in a thick salt unit, caused by localized salt removal from the base of the unit (Davies, 1984, Sect. 3.2.2).

The results of the subsidence model suggest that constant removal of salt from a localized area at the base of a thick unit produces a flow field similar to that depicted in Fig.4. The flow field is characterized by an outward spread of subsidence at successively higher levels. Flow rates decrease with increasing distance from the salt-removal zone, and flow orientations have a small lateral component directed toward the axis of the developing subsidence depression.

The structural depression created by subsidence is characterized by broad, shallow downwarping of beds in the upper part of the unit, with downwarping becoming narrower and deeper at successively lower levels (Fig.5). The
depression extends laterally well beyond the outer margin of the salt-removal zone, so a vertical borehole could be located within the structural depression and still miss the salt-removal zone at the base. Because of the relatively subdued form of a developing subsidence depression, detection of such structures in the field can be extremely difficult.

The extensive drilling program at the Waste Isolation Pilot Plant (WIPP) site in southeastern New Mexico has revealed an anomalous, closed depression in the northern part of the site (Fig. 6). This depression persists through the upper few hundred meters of a several hundred meter thick evaporite section. The depression is broad and shallow in the upper portion of the section and narrower and deeper in successively lower strata. The structural characteristics of this depression suggest that it formed as a result of ductile subsidence caused by localized salt removal in the lower portion of the evaporite section. There is no deep-borehole data within the depression, however, a deep borehole in the central part of the depression has been planned as a means of further exploring the origin of this structure.

Brittle subsidence

In contrast to the ductile downwarping of beds produced by relatively low salt-removal rates, subsidence produced by high salt-removal rates is commonly characterized by the formation of a steep-walled chimney, filled with downdropped, brecciated rock. Such chimneys are structurally similar to subsidence chimneys in other rock types ranging from limestone to granite, produced by mechanisms such as limestone dissolution, block-cave mining and underground nuclear explosions.

Utilizing mechanical analyses of analogous mine subsidence and block-cave mining processes by Terzaghi and Richart (1952), Denkhaus (1960, 1964), Woodruff (1962), Obert and Duval (1967), and Stephansson (1971), a conceptual model for the development of subsidence chimneys in salt can be developed (Davies, 1984, Sect. 3.2.3).

Like mine excavation, salt dissolution causes a localized reduction in the vertical normal stress at the rock-removal zone. This localized decrease in support produces a redistribution of stresses, accompanied by local stress concentrations in the rock surrounding the dissolution zone. During the early stages of subsidence, downward flexing of strata overlying the dissolution zone leads to a combination of vertical tensile fractures at points of maximum flexure and horizontal tensile failures along bedding planes (Fig. 7). Continued dissolution produces additional subsidence, further fracturing of the rock mass, and upward propagation of the chimney structure. Within the intact

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**Fig. 6.** Structure contour map on the 124 Marker Bed at the WIPP site in southeastern New Mexico. Note the closed structural depression in the northern portion of the site. (Dashed line shows the location of the WIPP Zone VI boundary, crosses show the location of well control.)

**Fig. 7.** Conceptual model of rock failure during the early stages of brittle subsidence. Enlarged area on the right shows the occurrence of vertical tensile failures at points of maximum flexure and horizontal tensile failures along bedding planes.
rock above the upward propagating chimney, there is a tendency toward the development of an arch-like zone of rock in compression. By means of this arching, the lithostatic load is resolved into increased compressive stresses along the arch trend, transferring the load to the rock mass on either side of the chimney. Because of the arch-like geometry, high shear stresses in the arch abutment are oriented in a near vertical fashion (Fig.8). Upon further loading, near-vertical shear failures occur at the chimney boundary, thus producing near-vertical chimney walls.

An important by-product of the subsidence process is an increase in rock porosity and permeability. The volume of the rock that has been removed essentially translates into void space. This void space propagates upward and is distributed throughout the subsiding rock mass by means of the fracturing and subsidence processes previously described.

The upward propagation of void space does not necessarily involve the development of large open cavities, because reduction in vertical support may be sufficient to induce fracturing and subsidence.

An unusual potash mine exposure of a subsidence chimney in southeastern New Mexico has provided a rare opportunity to directly observe some of the subsurface structural characteristics of a subsidence chimney in bedded salt (Snyder and Gard, 1982; Davies, 1984, 1985). The chimney is steep-walled and contains down-dropped blocks and fragments of halite, anhydrite, polyhalite, and post-evaporite strata (Fig.9). Adjacent to the chimney is a broad transition zone containing both faulted and ductilely downwarped beds. The dissolution-induced morphology of halite clasts and the breccia matrix composition indicate that limited amounts of groundwater flowed through the chimney during or following subsidence. Hydrologic conditions in the underlying carbonate aquifer and the presence of trace amounts of oil from these carbonates suggest that the direction of groundwater flow was upward through the chimney.

**ASSESSING POTENTIAL DISSOLUTION-SUBSIDENCE HAZARDS AT RADIOACTIVE-WASTE REPOSITORY SITES**

Salt dissolution is a highly variable process, with dissolution rates ranging over several orders of magnitude under different hydrogeologic conditions and corresponding subsidence deformation ranging from ductile downwarping of strata to extensive downward displacements of fractured and fragmented rock. Because of its potential for damaging the hydrologic integrity of a radioactive-waste repository, the hazards associated with this process must be thoroughly assessed at any given bedded salt repository site.
Identifying and characterizing existing dissolution and/or subsidence features in the site area is the first step toward assessing this hazard. Based on the insights gained from the physical analysis that is summarized in the first part of this paper, the following paragraphs are a discussion of strategies for carrying out the hazard analysis one step further by: (1) characterizing the impact on a repository of brittle versus ductile subsidence; (2) evaluating the potential for undetected or future dissolution-subsidence activity at specific sites; and (3) characterizing dissolution-subsidence activity by projecting potential salt dissolution rates and determining the associated form of subsidence.

Brittle subsidence chimneys are perhaps the most striking form of subsidence caused by salt dissolution. If this type of subsidence structure were to propagate upward through a waste repository, it would create a vertical, permeable conduit for groundwater flow. This conduit, which could extend all the way up to the ground surface, would hydraulically connect aquifers lying above and below the salt unit with each other and with the repository. The direction, quantity and velocity of groundwater flow will depend on the hydraulic conductivity of the subsidence breccia and on the vertical head gradient between aquifers. Depending on the elevations of aquifer heads relative to the ground surface, a surface sinkhole at the top of a subsidence chimney may serve either as a ponding point for groundwater from underlying aquifers or as a collecting basin, channeling surface water downward into the chimney.

Although the hydraulic conductivity of the subsidence chimney is an important parameter controlling the quantity of groundwater flow through a chimney, adequately characterizing this parameter is difficult. The conductivity of a subsidence breccia is not constant in either space or time. Initially, the brittle subsidence process causes a local increase in conductivity by creating fractures and interconnected pore space between individual breccia clasts.

Conductivity may then decrease with time, however, if flow through the chimney is limited in quantity and is accompanied by reprecipitation of evaporite minerals. On the other hand, conductivity may increase with time if large quantities of water flow through the chimney, causing further dissolution of soluble clasts and the surrounding chimney wall. In this latter case, the original chimney structure may evolve into a much larger subsidence feature. In both cases, primary factors controlling changes in flow through the chimney with time are the initial conductivity of the subsidence breccia and the magnitude of the vertical head gradient.

Unfortunately, very little is known about initial conductivities of subsidence chimneys in bedded salt. Mercer (in Snyder and Gard, 1982, pp.67-69) reports permeabilities ranging from 0.9 to 0.11 millidarcies (9 \times 10^{-7} to 1 \times 10^{-1} cm/s expressed in terms of hydraulic conductivity), or less, from a series of drill stem tests in a subsidence chimney on the northern margin of the Delaware Basin in New Mexico. However, permeabilities at the time this chimney formed (Early to Middle Pleistocene) were most likely higher and were later reduced by a combination of recompaction of the subsidence breccia and by precipitation of interstitial halite.

Limited permeability data from subsidence chimneys in other rock types have also been reported. Stone et al. (1983) have utilized calibration of a groundwater flow model to indirectly determine hydraulic conductivities for two relatively shallow (50 m) subsidence chimneys that formed as a result of underground coal gasification experiments. They report conductivities of 7 \times 10^{-5} and 1 \times 10^{-4} cm/s for these two chimneys. Rosza et al. (1975) have utilized measurements of underground pressure responses to atmospheric pressure changes at the ground surface to estimate the permeability of subsidence chimneys above underground nuclear explosions in tuff and alluvium. They report permeabilities ranging from 7 to 99 darcies (7 \times 10^{-7} to 1 \times 10^{-1} cm/s). The conductivity data from these three studies suggest that initial conductivities of subsidence chimneys may range from moderate to high.

If dissolution rates are low enough, subsidence deformation will be ductile rather than brittle. Ductile subsidence is characterized by gradual, localized downwarping within the salt unit. If this type of subsidence were to occur at a repository, the effects would be quite different from effects of brittle subsidence. Although the repository horizon would be gradually lowered and deformed, the salt would remain intact. Because fracturing and brecciation of the salt does not occur, ductile subsidence is not likely to be accompanied by large increases in hydraulic conductivity. Therefore, during much of the subsidence, waste would remain isolated from the active groundwater flow system.

Hydrologic breaching of the repository would most likely not occur until the repository horizon was lowered to the level of active salt dissolution. At this point, waste would be released into the underlying aquifer. Because ductile subsidence is relatively slow, repository breaching by this process would require a much longer period of time than would breaching by brittle subsidence. This period of time may, in fact, be longer than the time required for the waste to decay to acceptable toxicity levels.

Having delineated the gross impact of brittle versus ductile subsidence on a waste repository, the next question that must be addressed is how to evaluate a specific site relative to the potential for undetected or future dissolution-subsidence activity. Although a well-designed exploration program, including air photo analysis, surficial mapping, geophysical surveys, and exploration boreholes, should locate well-developed subsidence structures, deep-seated structures that are in the early stages of formation may be difficult to identify. Even if the absence of early-stage structures could be proven, this would not guarantee that dissolution and subsidence could not occur at some point during the life of the repository.

Therefore, in addition to the task of exploring a given site for the presence of existing dissolution-subsidence structures, the exploration program should be aimed at evaluating the geologic and hydrologic conditions that could lead to the presence of undetected, early-stage structures, or to the occurrence of dissolution and subsidence at some time in the future.

One important factor in evaluating the potential for undetected early-stage structures, or for deep dissolution activity at some time in the future, is the
hydrology of the aquifer(s) underlying the salt unit. At a starting point, the flow system in deep aquifers should be analyzed on a regional (basin) scale. However, because deep dissolution is commonly a localized process, characterization of the hydrology of deep aquifers must also account for local variations in groundwater flux associated with relatively high-permeability trends such as carbonate reefs or channel sandstones.

Another aspect of the local hydrologic conditions that can significantly affect salt dissolution is the presence of fracture zones that provide localized pathways between an aquifer and the lower part of a salt unit. Because of their small size and great depth, precise location and hydraulic testing of such zones is essentially infeasible, but the possibility that such fracture zones exist can be evaluated using subsurface geologic data. These data may reveal structures such as faults that transect both the aquifer and the base of salt. Processes that could produce such faulting include tectonic activity, differential compaction above reef structures, and differential settlements within the basin.

If the salt units at a given repository site are underlain by deep aquifers, and if there is geologic evidence of structures that could provide localized groundwater access to the salt, then potential salt dissolution rates can be appraised. The dissolution rate is equal to the transport capacity of the least efficient component of the total mass transport system.

Because the transport capacity of local fracture zones cannot be assessed directly, a conservative range of transport rates in idealized fracture zones must be assumed. A conservative estimate of aquifer transport capacity can be made by assuming that the entire aquifer is brought into the dissolution process. Alternatively, a variable density flow and transport model could be utilized to make more accurate estimates of aquifer transport capacity. The end product of these computations is a range of dissolution rates for a variety of possible local conditions at the site.

The analysis of salt dissolution rates should be complemented by a structural analysis of subsidence deformation caused by removing salt. Salt deformation is a strongly rate-dependent process. Therefore, the rate of salt removal, i.e., the rate at which support is withdrawn from the overlying salt strata, will strongly influence the structural character of subsidence. In general, high dissolution rates will produce predominantly brittle subsidence, whereas low dissolution rates will produce predominantly ductile subsidence. Using the computed salt dissolution rates as a controlling condition, the goal of subsidence modeling should be to determine the structural character of subsidence and the time frame over which this subsidence develops.

Although the subsidence models described in this paper characterize many facets of brittle versus ductile subsidence, these models represent only the endpoints of a continuous range of subsidence processes. The primary difficulty, and primary challenge, in developing a subsidence model that is capable of examining the entire range of subsidence behaviors will be to develop the capability to identify the conditions under which the transition from ductile to brittle behavior occurs. At present there are few laboratory data on the creep rupture behavior of salt. Also, there are few geologic data that can be used to estimate the transition conditions. Further developments in both of these areas will significantly enhance our ability to predict the structural character of subsidence deformation at a given repository site.

While a coupled dissolution (transport) and subsidence model will be a useful tool for evaluating potential dissolution-subsidece hazards under many conditions, some factors that may influence dissolution or subsidence at a specific site may be difficult to incorporate into the model. For example, adequately characterizing and incorporating complex dissolution pathways through nonsalt interbeds may be difficult. Accounting for the interaction with other processes such as gravity-driven salt flow may be difficult as well. Therefore, the model results should be carefully and critically evaluated. The final analysis of potential dissolution-subsidece hazards should incorporate all field and process information, not just that which can be readily incorporated into a numerical model.

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