Some Aspects of Salt Dissolution in the Williston Basin of North Dakota

by Randy B. Burke

Introduction

Many mineral forms of salt occur throughout North Dakota, both on the surface and underground, both in crystalline form and in solution. On the surface, crystalline forms are found as alkaline salts around many ephemeral wet lands and as gypsum in the badlands. Also, the waters of many lakes throughout the northern part of the state are saturated with sodium sulfate. Glauber salt, the crystalline form of sodium sulfate, precipitates on the floors of many of these lakes in beds up to several feet thick (Murphy, 1996a). Potash salts occur beneath central northwestern North Dakota at depths as shallow as five thousand feet. Underground in the deep part of the Williston Basin, are pools of salt brines, some with concentrations of total dissolved solids over 300,000 milligrams per liter. Brines are commonly associated with economic minerals such as hydrocarbons and metalliferous ores in solution. In Canada, efforts are underway to extract metals from the brines. Hundreds of thousands of tons of glauber salt and potash are mined in Saskatchewan, where these resources are more abundant or more accessible than they are in North Dakota.

Beds of halite, (sodium chloride - NaCl), occur beneath the surface of more than one third of North Dakota (Fig. 1). Until recently, halite was mined by solution processes near Williston, North Dakota. Over a million tons of salt were dissolved from the Mississippian Charles Formation from a depth of more than 9,000 feet. The salt was precipitated from the brine solution and made into a host of products that included pellets for water softeners, table salt, and oil-field brines (Murphy, 1996b).

The combined maximum thickness of all of the halite beds in the subsurface of North Dakota is about 2,540 feet, almost a half mile thick (Fig. 2, LeFever and LeFever, 1995). This aggregate thickness of halite represents over 15% of the total thickness of all sediments in the basin. However, the halite occurs in numerous beds, and the location of their greatest thickness is in different parts of the State (Fig. 1). The thickness of the salt is highly variable, not only because of the way it was deposited in depressed areas, but also where salts are locally dissolved by ground water around the edges of the salt deposits. Tons of salt have been dissolved beneath hundreds of acres forming large subterranean caverns. Overlying rock has collapsed into these caverns, and the surrounding rock strata have bent and fractured. These fractures provide pathways for fluids including hydrocarbons. Recognition of the occurrence of dissolution-collapse features is a key to understanding the geology of the State. Furthermore, these features can have important economic consequences because oil and gas are commonly associated with them.

How Halite is Formed

Halite forms by precipitation from fluids saturated with sodium chloride, generally seawater. Seas transgressed into and receded from North Dakota many times, and often, marine waters became restricted in a subsiding Williston Basin. Reduced inflow of water and evaporation concentrated the seawater into a hypersaline brine that eventually precipitated the halite. A similar process of concentrating salt water in basins is occurring today in several places around the world like the Great Salt Lake in Utah, the Dead Sea in the Middle East, the Gulf of Karabogaz-Gol along the Caspian Sea, and Lake McLeod in western Australia.

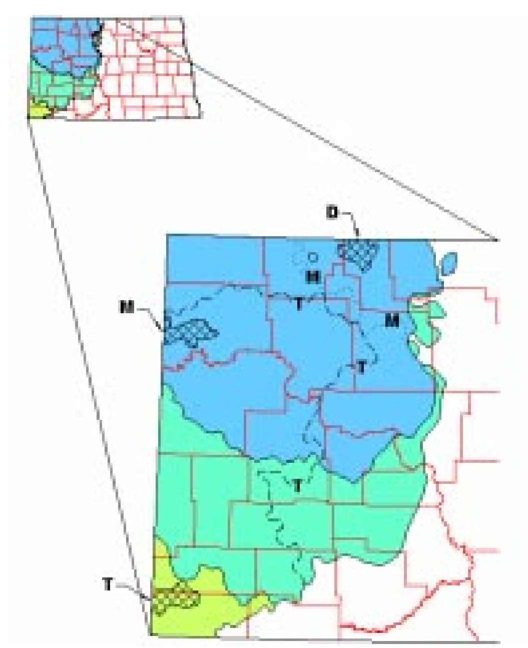

Figure 1. More than one third of North Dakota is underlain by halite beds. The darkest shading indicates the geographic distribution of Devonian (mostly) and Silurian (DS) halite. The intermediate shade shows the extent of Mississippian (M) halite beyond the DS group of salts, and the dotted line labeled with **M**s shows the extent of overlap of Mississippian salt with DS salts. The lightest shade shows the extent of Permian and Mesozoic halite beyond the extent of the DS and M salts, and the dashed line labeled with **T**s shows the extent of the overlap with other salts. The location where the salt is thickest for each grouping is designated by a cross-hatched pattern indicated by the letters **D**, **M**, and **T**, respectively.

Distribution of Halite in North Dakota

Western North Dakota is underlain by about 1,700 cubic miles (Anderson and Hansen, 1957) of halite (Fig. 1). This halite occurs in numerous beds that record deposition throughout geologic time (Fig. 2) from the Paleozoic through the Mesozoic. I have separated these beds into three groups: 1) Silurian and Devonian, 2) Mississippian, and 3) Permian and Mesozoic (Fig. 1). The location where the salt is thickest for each grouping is designated by a cross-hatched pattern. The distribution of thickest salt at different times is interesting because it indicates the location of the deepest part (depositional center) of the Williston Basin at those times and illustrates how the location of the depocenter has changed through time.

The rock layers (stratigraphy, Fig. 2) that comprise the three groups of salts delineated in Figure 1 consist of 28 different beds of salt (LeFever and LeFever, 1995). The Silurian and Devonian group consists of five different major units and includes the Devonian Prairie Formation, the thickest single salt in North Dakota at 640 feet. The Prairie also includes about 40 feet of economically valuable potash salts. The Mississippian group comprises 15 salt beds that range in thickness from 7 to more than 90 feet. The Permian and Mesozoic group of salts includes six distinct beds that combined are more than 1,050 feet thick. The Pine Salt is the thickest Permian-Mesozoic unit at about 250 feet.

The salt units are stacked, and there is considerable overlap in their distribution in west-central North Dakota (Figs. 1 and 3). Figure 3 is a schematic cross-section through the Williston Basin from Canada to South Dakota. One can see that the only salts present in the southwestern corner of North Dakota are some of the Triassic beds. The diagram also shows that there are isolated lenses of salt such as the Silurian salts throughout the section. Lenses of salt are common at the edges of the salt beds. Many of the lenses at the edges of individual strata result from the dissolution of salt along the depositional edge.

Dissolution of Salt

Halite is easily dissolved in fresh water. Fresh water enters the Williston Basin in several rock units that are exposed around the perimeter of the basin in such places as the Black Hills of South Dakota and the Big Horn Mountains of Wyoming (Downey, 1984). The strata carrying the water are called aquifers, and detailed knowledge about individual aquifers, their flow rates, and their flow paths is rudimentary. We do know that the water flows from the highlands in the south through the basin to the north and east into Canada and the Red River Valley, where water flows to the surface to form saline springs and seeps. On their journey through the basin, these waters have dissolved some of the halite.

Areas of dissolution occur most commonly along the edges of salt beds where fresh water comes in contact with

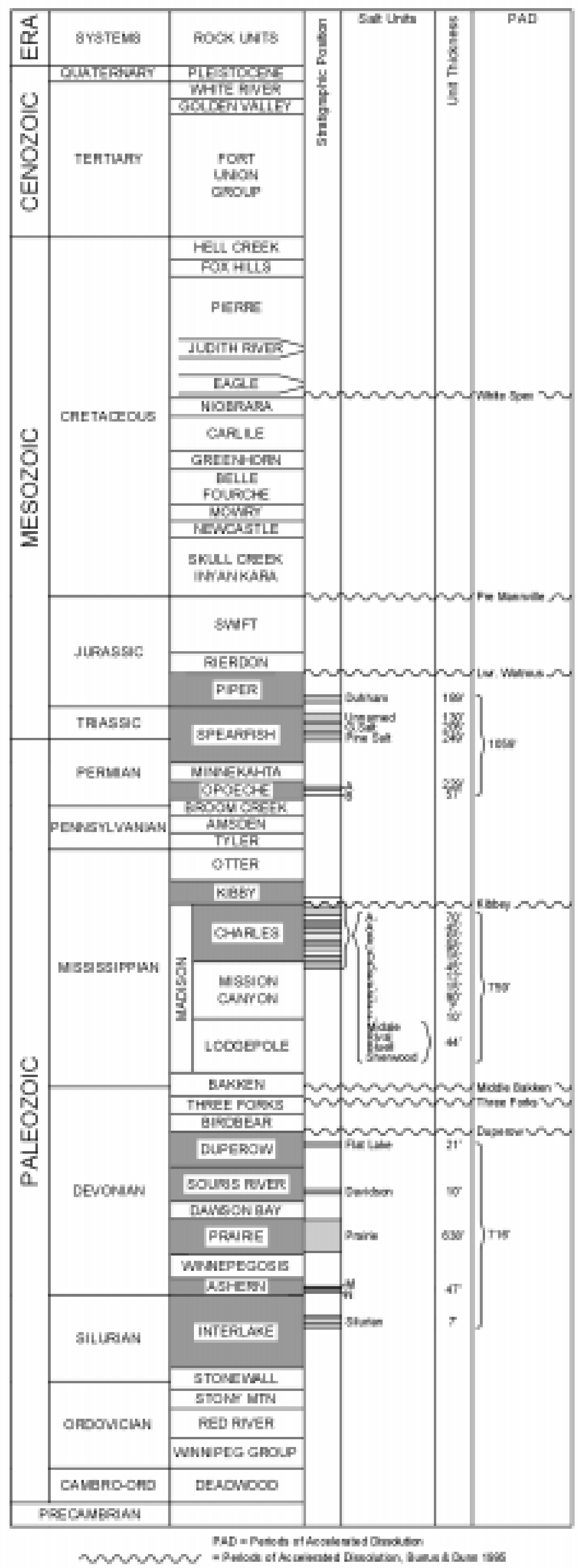

Figure 2. A stratigraphic chart of the rock units in the Williston Basin of North Dakota. Shaded units contain halite. The names of salt units and their maximum thickness are listed. Wavy (sinusoidal) lines indicate when dissolution of salt was accelerated (PAD) (modified from LeFever and LeFever 1995).

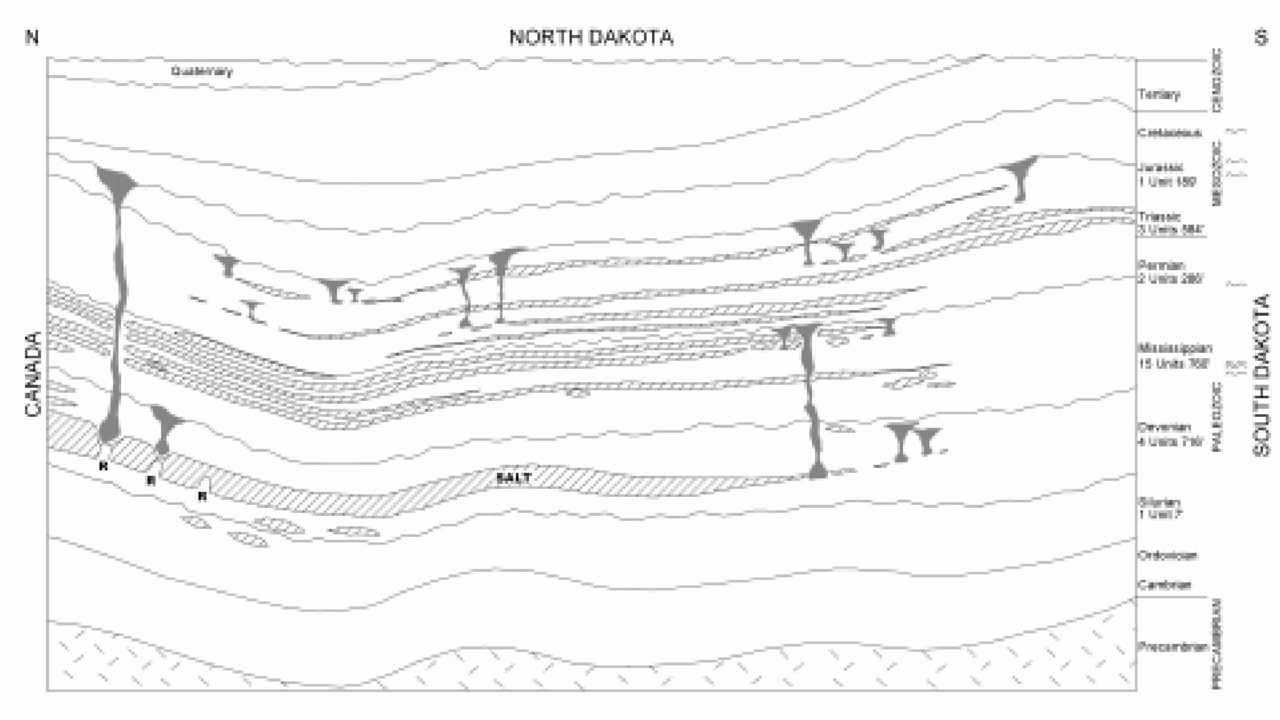

Figure 3. A generalized north-south schematic cross-section through western North Dakota showing the relative abundance, position, and distribution of some of the prominent halite beds (diagonally patterned units). The shaded, irregular, vertical elements with funnel-shaped tops represent dissolution-collapse structures (filled stopes and chimneys). The vertical extent of these stope-like features has been documented in some locations by increased thickening of the upper most unit as microbasin fill. Many of these microbasins are shown to have their upper termination at unconformity surfaces represented by the wavy lines running through the diagram. Major unconformities are surfaces of erosion or non-deposition representing long periods when the seas retreated and fresh water could recharge aquifers and move into the basin to dissolve the beds of salt. The wavy lines on the right side of the diagram indicate times of accelerated dissolution. Note that these usually correspond to major unconformities. The three small lumps on the left side of the diagram represent Winnipegosis pinnacle reefs (designated by **R**).

salt beds or where the salt is deposited around strata with high porosity and permeability that are particularly good aquifers. The latter case is illustrated in the Devonian strata by three small knobs on the left side of Figure 3 (labeled with **R**s) that represent Winnipegosis pinnacle reefs. The Winnepegosis reef deposits have very high porosity and permeability and serve as conduits (aquifers). These aquifers channel freshwater into the Prairie Formation and dissolve the salt, which envelopes the reefs. Dissolution of halite will continue until the freshwater supply is shut off or the water becomes saturated with halite. Much remains to be learned about the plumbing of this process, such as how the water is turned off and on, how sufficient volumes of freshwater are moved to the salt, and how salt-saturated waters are moved out of the system to allow for removal of hundreds of feet of salt over many square miles.

When salt dissolves, huge caverns form that can be tens to a few hundred feet high over large areas. The overlying strata collapse into a cavern when the weight of the overburden exceeds the strength of the rocks forming the roof of the cavern (Fig. 4). The material that collapses is a mixture of the many different rock types overlying the salt. It ranges widely in shape and size with some angular blocks many tens of feet on a side (breakdown blocks, Fig.4). Breccia, rocks composed of angular fragments of rocks (Fig. 5B,C,and D) is the most common rock texture associated with these collapse features (e.g. filled stopes). A stope is the new cavern formed in the rock above the salt when the roof collapses into a pre-existing cavern formed by dissolution of the underlying bed of salt. Above and around the perimeter of the stope, the rock layers fracture and fault (displacement along fractures) for great distance away from the stope generally following the draw angle (Fig.4). New porosity and permeability created by this fracturing and faulting provide additional pathways to trap or transmit fluids.

A general sequence of the rocks characterizing a collapse feature was proposed by Simpson (1978) (Fig.5). Deposition begins on the bottom of a cavern as the salt begins to dissolve and insoluble clay-sized material that occurs as impurities in the salt accumulate on the floor of the cavern in thin layers (Fig.5A). Higher in the sequence, angular and often rounded clasts of different types of rock gradually become

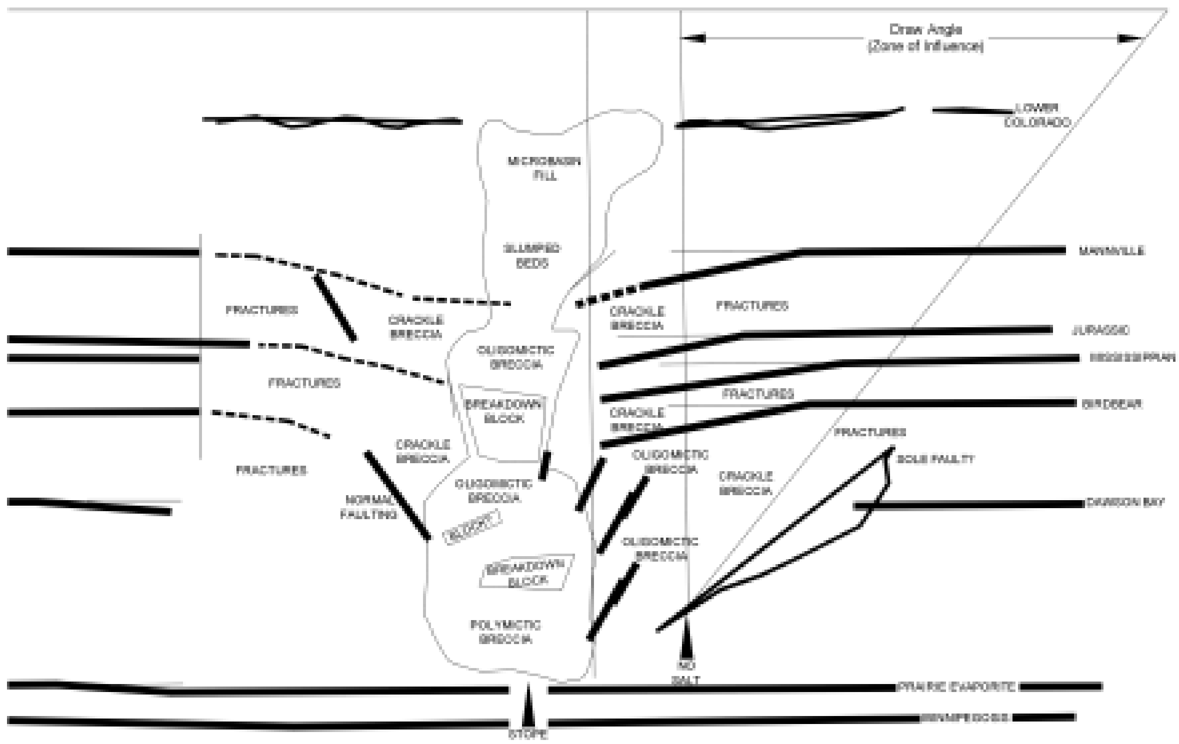

Figure 4. A schematic diagram illustrating the types and distribution of sedimentary textures and structural elements associated with a collapse structure (modified from Halabura and Potter, 2000). The stope is commonly tightly cemented, whereas the best porosity and permeability are found in the various fracture systems peripheral to the stope., or in the diagenetically altered host rock adjacent to fractures.

more common. This type of rock is called a polymictic breccia mostly because of the different rock types and the shape of the clasts (Fig. 5B). The polymictic breccia is gradually replaced by oligomictic breccia, angular clasts of the same rock type (Fig. 5C). Gradually the overlying rock is not broken into clasts but is merely fractured and expanded to form crackle breccia (Fig. 5D). All of the fractures, if they are not filled with cement, can provide excellent pathways for fluids to move through or into the rocks.

Some Implications

Dissolution of salt beds in the subsurface, the subsequent collapse of the overlying strata, and the disruption of surrounding strata are fascinating and complex geologic processes that create large, magnificent geologic structures. Once the strata are disrupted, fluids pass through or become trapped in the rocks. Fluids interact with the rock in many ways: new minerals can precipitate in voids and different minerals can dissolve, thereby creating new voids. Voids in rocks are ideal candidates for the deposition or trapping of economic minerals, both metallic and hydrocarbon.

Many oil reservoirs found in the Williston Basin are associated with salt dissolution and collapse features, e.g., Tule Creek in Montana, Hummingbird in Saskatchewan, and West Hope and Dolphin fields in North Dakota. But how does one locate undiscovered salt-dissolution collapse-structures? There are many pieces to this complex geologic puzzle and some of those necessary to predict where these salt dissolution features might occur include knowing: 1) the past and present distribution of all of the various salt beds, particularly where the edges now are and where their depositional edges originally were; 2) the location of basement structures and the timing of their movements throughout the geologic past; 3) the past and present hydrology of aquifers and aquicludes, including their flow rates, flow volumes, and chemistries; and 4) the stratigraphy of beds above and enclosing the salt units. Many salt-dissolution collapse-features, containing millions of barrels of oil and gas, are waiting to be discovered in North Dakota. Their discovery awaits not only a more detailed understanding of the geologic framework in which the process operates, but also, that of the salt-dissolution process itself.

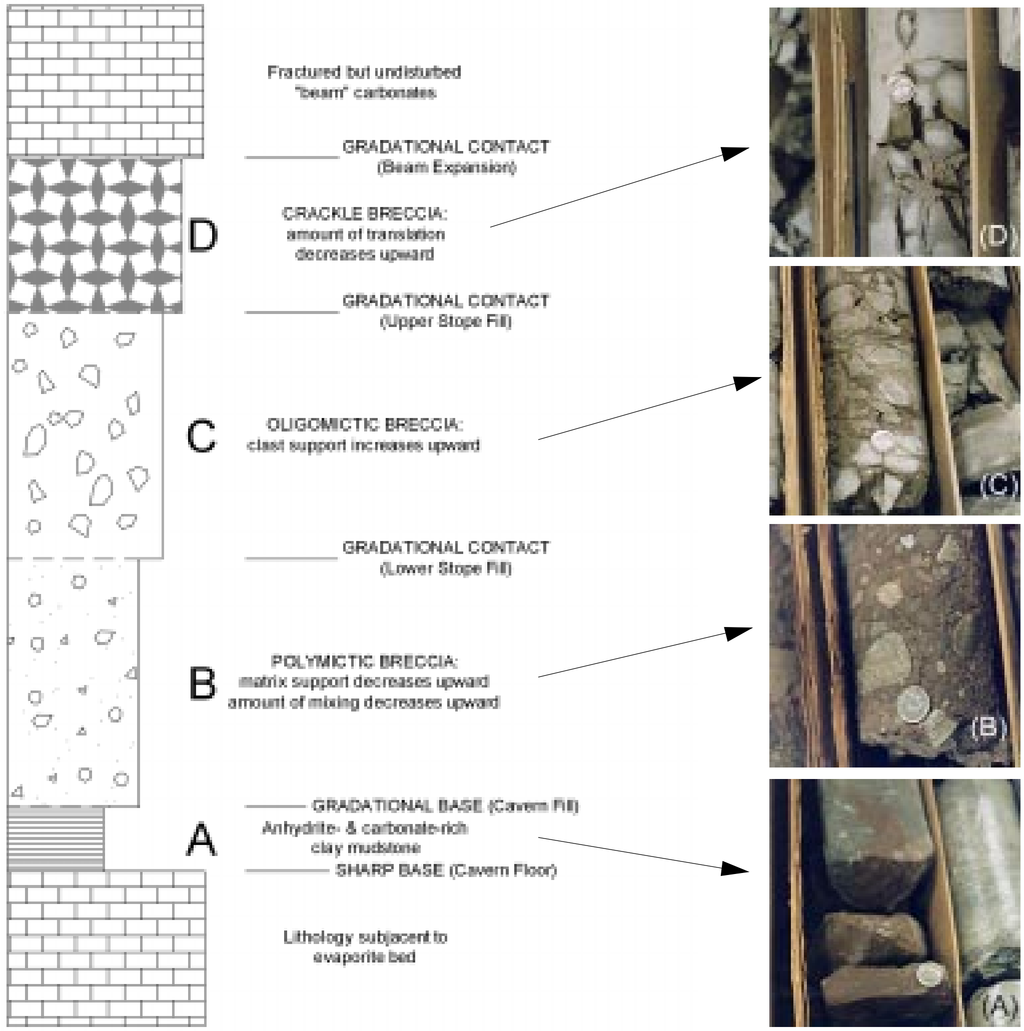

Figure 5. A diagram with accompanying photographs of cores illustrating the sedimentary sequence characteristic of dissolution-collapse structures (modified from Simpson, 1978). **(A)** The bottom of the profile is a mudstone that commonly is laminated and associated with clays and anhydrite. **(B)** A polymictic conglomerate/breccia overlying the mudstone is characterized by clasts of different lithologies and a range of shapes from well rounded to very angular. **(C)** Oligomictic breccia occurs above the polymictic conglomerate/breccia and is characterized by clasts of the same lithology and angular shapes. **(D)** Crackle breccia at the top of the profile illustrates exceptional porosity resulting from extensional forces in the rocks above and adjacent to the collapse cavern. Examples are mostly from cores of the Devonian Souris River Formation.

REFERENCES

Anderson, S.B. and Hansen, D.E., 1957. Halite deposits in North Dakota. NDGS Report of Investigations, no. 28.

Downey, J.S., 1984. Geohydrology of bed rock acquifers in the Northern Great Plains in parts of Montana, North Dakota, South Dakota and Wyoming. U.S.G.S. Professional Paper 1402E, 87 p.

Halabura, S.P. and Potter, D., 2000. Salt Dissolution and Collapse: Effects upon selected Western Canadian oil and gas pools. North Rim Exploration Ltd, Saskatoon, Saskatchewan, Canada, SITO Energy Ltd, Calgary, Alberta, Canada. Short course notes, 98 p.

LeFever, J.A. and LeFever, R.D., 1995. Relationship of salt patterns to hydrocarbon accumulations, North Dakota Williston Basin. *In* L.D.V. Hunter and R.A. Schalla, eds., 7th International Williston Basin Symposium Guidebook, Montana Geological Society, p. 69-88.

Murphy, E.C., 1996a. The sodium sulfate deposits of northwestern North Dakota. NDGS Report of Investigation, no. 99, 73 p.

Murphy, E.C., 1996b. Salt plant in Williston. NDGS Newsletter, v. 23, no. 4, p. 8-9.

Simpson, F., 1978. Solution-generated collapse (SGC) structures associated with bedded evaporites: importance of migration and trapping of hydrocarbons: Ontario Petroleum Institute Proceedings, v. 26, Paper 7.