THE SODIUM SULFATE DEPOSITS OF NORTHWESTERN NORTH DAKOTA

by
Edward C. Murphy

REPORT OF INVESTIGATION NO. 99
North Dakota Geological Survey
John P. Bluemle, State Geologist
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On the Cover: An inch or two of mirabilite crystals is overlain by a crust of thenardite crystals along the western edge of Miller Lake. The mirabilite crystals, which extend out along the lake bottom, were pushed into a six-inch thick pile. The photograph was taken looking east in September, 1995.

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Abstract

The early explorers of the Nineteenth Century noted the presence of Glauber salt, a hydrated form of sodium sulfate, in many of the lakes in northwestern North Dakota. In 1934, the Federal Emergency Relief Administration funded an investigation of hundreds of lakes in Divide, Williams, and Mountrail Counties. Under this program, over 2500 holes were hand-augered through dried lake bottoms and thousands of samples were chemically analyzed. The FERA study concluded the seven major deposits contain 23 million short tons of Glauber salt. Unfortunately, very little of the basic data from this project remains. In the late 1940s, the U.S. Bureau of Mines augered 56 holes and analyzed a few hundred samples from fourteen lakes in the northwestern part of the state. The Bureau of Mines estimated that 30.4 million tons of Glauber salt is present in the fourteen deposits they investigated and the seven major deposits explored by FERA. The North Dakota Geological Survey augered and cored a total of 29 holes at five lakes in the northwestern corner of the state. The information from this study, along with that of the previous studies, resulted in a revised estimate of 46.3 million short tons of Glauber salt at fifteen lakes in northwestern North Dakota.

The layers of Glauber salt occur in lacustrine deposits that began forming at the end of active glaciation. These sediments are dominated by salt-bearing silts and clays. The salt layers range from a few inches to over 10 feet thick. Most salt beds occur within 30 feet of the surface, but in two lakes salt was found at depths of 50 to 70 feet. As noted by the early workers, these salt deposits occur in closed basins which often are within valleys or channels that have been overridden by glaciers and partly filled with sediment. The significant amount of relief that occurs at the base of the lacustrine units in at least two of these lakes likely are the result of kettles that formed when blocks of ice that had been overridden slowly melted.

Saskatchewan's sodium sulfate production peaked at over 500,000 metric tons in 1982. A dramatic decrease in the market has been due to a decrease in demand by the pulp and paper industry. In recent years, the detergent industry market has stabilized production at slightly over 300,000 metric tons. Continued demand from the detergent industry and increased demands for both food grade and nonfood grade sodium bicarbonate may create the proper economic climate needed to make a plant in northwestern North Dakota viable.

Acknowledgments

The author would like to thank Irving Grossman (New Jersey Geological Survey) for allowing me access to his vast library on sodium sulfate. Catherine Yansa (University of Wisconsin) provided a number of articles on sodium sulfate. In addition, Paul Guliov (Saskatchewan Energy and Mines), Bill Henry (Saskatchewan Minerals), and Sid McIlveen (Ozark-Mahoning) provided additional information on sodium sulfate and insight on the industry. A special thanks to Gillferd and Elaine Rust for providing information on the Sodium Corporation of America's site at Miller Lake. Jon Reiten, Montana Bureau of Mines and Geology, also provided information on lakes in northeastern Montana. Dennis Kittelson, of Westby, helped keep the drilling equipment running in the subzero temperatures. I also thank the following landowners who allowed me access to their property: Gillferd Rust, Anita Bjorgen, Eugene Herman, Claire Bjorgen, Brian Elm, Harlow Freund, Irving Wittmayer, Elwin Hazlitt, James Nordhagen, Bill Everett, Ralph Brown, Andy Johnson, George Olson, and the ND State Land Department. The Ozark-Mahoning Company (a division of Elf Atochem) graciously allowed an analysis of water from Grenora #2 to be used in this report. Sandy Slater and Susan Humble, Special Collections at the Chester Fritz Library, University of North Dakota assisted me in finding several historic documents related to Irvin Lavine and the FERA project. Chuck Fine, Department of Economic Development and Finance, has been working on the marketability of sodium sulfate and provided information and contacts in that area. Irving Grossman, Paul Guliov, and Jon Reiten critically reviewed the manuscript.

Author's Note

This project was undertaken without any allocated funds. Site-specific chemical data is crucial to obtaining accurate estimates of sodium sulfate reserves but due to the lack of funding, it was not possible to chemically analyze representative cores and cuttings. As a means of addressing this problem, resource calculations were based on the Glauber salt percentages and tonnage factors determined by a previous U.S. Bureau of Mines study (Binyon, 1952). Tables 3-5, 8-10, 12, and 13 contain the actual Glauber salt percentages of the layers (e.g., brine, intermittent salt, mud, permanent salt, etc.) as determined by Binyon. Tables 1, 2, 6, 7, 11, 14, and 15 contain the mean of all of Binyon's averages of the individual layers. At some sites the actual percentages of Glauber salt in the individual layers will be higher, while at other sites it may be lower. However, it is anticipated that the total resource will remain roughly the same if accurate chemistry becomes available for the other seven sites. Binyon based his calculations of the average tonnage factors on the chemical analysis of these materials. The overall tonnages of brine, salt, mud, and mud and salt were determined by dividing the cubic feet by these tonnage factors (32 for brine, 22 for the crystal bed, and 20 for mud and crystals).

Introduction

Sodium sulfate has long been an important industrial mineral in southern Saskatchewan. In North Dakota, there have been at least three commercial ventures that attempted to mine this natural resource between 1948 and 1961. In the early part of the twentieth century, sodium sulfate was used in the pulp and paper industry, glass, dye, textile and nickel industries, and to a lesser extent in medicinal and tanning preparations and the manufacture of sodium sulfide (Cole, 1926). Historically, the largest percentage of sodium sulfate produced was consumed in the production of kraft paper, a trend that continued until the early 1990s. In this country, mining of sodium sulfate deposits began in the 1880s near Camp Verde, Arizona and Natrona County, Wyoming (Tyler, 1935). Over the years, sodium sulfate has been mined in California, New Mexico, Texas, Utah, Washington, Wyoming, and North Dakota. Currently, sodium sulfate is being mined in the U.S. at Searles Lake, California; Great Salt Lake, Utah; and Cedar Lake, Texas. In addition, sodium sulfate deposits are mined in Canada, Mexico, Argentina, Chile, Iran, Spain, and the Russian Republics. The Searles Lake deposit is thought to have produced more sodium sulfate than any other deposit in the world (McIlveen and Cheek, 1994).

Occurrences in North Dakota

Sodium sulfate deposits have long been known to occur in North Dakota. In the spring of 1805, Lewis and Clark noted in their journals the appearance of Glauber's salts in the area between Washburn and Williston. Native Americans were known to have referred to the deposits as "summer ice" (Figure 1). Other explorers, Henry Brackenridge in 1811 and Maximilian in 1833, noted the occurrence of Glauber's salt in western North Dakota. Maximilian noted that the ground near Fort Union was covered with Glauber's salt which was being collected and stored at the fort. Glauber's salt is a naturally occurring compound of sodium sulfate named for the German chemist, J.R. Glauber, who first created it in his laboratory in 1658 by mixing sulfuric acid with table salt (sodium chloride). As a result of this experiment, hydrous sodium sulfate is commonly known as Glauber's salt (commonly referred to as Glauber salt) although the mineral name is mirabilite. The anhydrous mineral form is called thenardite, named for the French chemist Louis Jacques Thenard (McIlveen and Cheek, 1994). Naturally occurring sodium sulfate is generally found in the form of mirabilite or thenardite, with mirabilite the most common. In its pure state, Glauber salt is 56 percent sodium sulfate and 44 percent water (Lavine, 1935). In 1907, Daniel E. Williard, a professor at North Dakota State University, speculated that valuable salts may be present in the lakes in the northwestern part of the state because of the geologic similarity of this area to areas farther west that contained salt deposits (Lavine, 1935a).

In 1929, Oscar Quarne, while hunting ducks near his hometown of Grenora, was surprised to find that he could walk out into a shallow lake in the area (Grenora #1) supported by a layer of white crystals on the lake bottom. He sent the crystals to the University of North Dakota where the material was identified as Glauber salt. This identification aroused local interest and several men began prospecting around shallow lakes in the area. Their crude investigations uncovered 6- to 12-foot-thick beds of salt and disclosed that Grenora #1 contained an exceptionally thick deposit (Anderson, 1929). Quarne attempted to get title to the area for mining purposes but was thwarted by the State Land Department because approximately half of the lake is in section 16 (school lands). Quarne did succeed in arousing interest in these deposits, which led directly to the first scientific study of sodium sulfate deposits in North Dakota, in 1934.

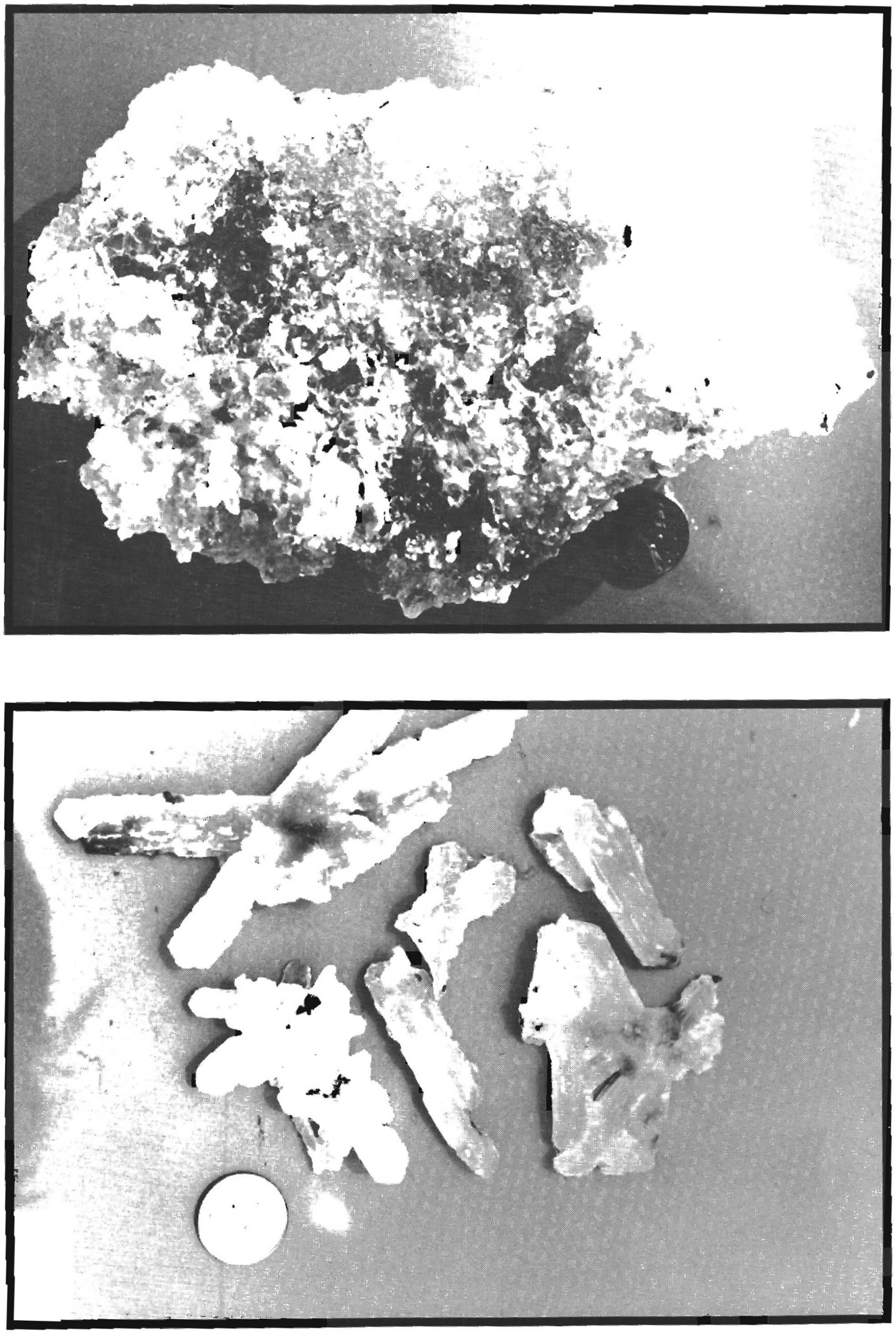

Figure 1. Mirabilite (Glauber salt) crystals from lakes in northwestern North Dakota. The crystals in the upper photograph are from the intermittent layer at North Lake, Divide County. The bladed crystals in the lower photo were found along the shore at Westby A, Divide County. Coins indicate scale.

Previous Work

Sodium sulfate was first discovered in Canadian lakes during an unsuccessful search for potash during World War I (Cole, 1926). In 1918, sodium sulfate was first mined at Muskiki Lake, Saskatchewan by the Canadian Salt and Potash Company. A substantial amount of work has been done on the deposits of sodium sulfate in the Canadian Provinces of Saskatchewan and Alberta (Cole, 1926; Rawson and Moore, 1944; Tomkins, 1948; Govett, 1958; Rueffel, 1970). Cole (1926) made an extensive study of these deposits in western Canada. His project included drilling and chemical analysis of samples from the lacustrine deposits beneath many of the lakes across the western portion of Canada. Tomkins (1948, 1954) presented the water chemistry of approximately 20 lakes in Saskatchewan and the developmental history of the 13 deposits that had been mined. More recent work on these lakes has centered on the sedimentologic history and geochemistry (Last, 1984, 1989a, 1989b, 1990, 1991, 1994; Slezak and Last, 1984; Last and Sleak, 1987).

In 1934, the North Dakota Geological Survey convinced the Federal Emergency Relief Administration (FERA) to fund a study of the sodium sulfate deposits of the state. Irvin Lavine, Professor of Chemical Engineering at the University of North Dakota, led a group to the northwestern part of the state to locate, map, and prospect the sodium sulfate deposits in the area. The work was supervised by the North Dakota Geological Survey and was sponsored by the Federal Emergency Relief Administration as a means of employment in this drought-stricken region (Lavine, 1935). By 1934, this area had suffered through six years of drought which had devastated crops but had also dried up many of the lakes making exploration much easier. From early July to late December, crews of men taken from the county relief roll (a total of 63 men) hand-augered over 2500 holes (some down to depths of 80 feet) and obtained and chemically analyzed thousands of samples from lacustrine deposits in shallow or dried lakes from Stanley in Montrail County to Alkabo in Divide County. Generally the men worked in two crews, a crew consisting of three to four men. Working conditions were terrible. Prior to freeze up, the men often stood knee deep in water and mud, many without hip boots or waders (Johnson, 1934). In some areas, the mud was so soft that planks were laid on the surface to help distribute the workers' weight so they would not break through the surface and wallow in the hydrogen-sulfide-laden mud. As fall progressed into winter, a warming house was brought to one of the lakes near Grenora to provide the men with some relief from bone-chilling cold winds that blew unrestrained across the frozen lakes. Correspondence from the crew chiefs to Lavine in Grand Forks indicates that they spent a good deal of their time looking for workers, due to the difficulty in finding men who were willing to tolerate these deplorable working conditions for very long (Skene, 1934; Walsh, 1934; Johnson, 1934). However, the comments in these letters conflict with Walsh's field notebook that indicates that none of the men working during a six-week stretch near Alkabo, missed a day of work (Figure 2).

The FERA study evaluated hundreds of dried lakes and determined that there were at least seven large deposits in northwestern North Dakota (Lavine, 1935). Lavine noted that all of the deposits were found in lakes that contained no drainage outlet, were the lowest depression that drained a large area, and were surrounded by a number of springs. Lavine observed that the salinity of these lakes increased through the summer as the lake temperatures rose and the salt became more soluble. In the fall, the water temperatures dropped and the salt-saturated brines precipitated sodium sulfate, initially as a sheet of crystals on the water surface that would settle to the bottom of the lake as it became too heavy (Figure 3). As noted by Lavine (p.4, 1935) "These crystals form during cold weather and disappear with a rise in temperature, sometimes changing the surface of the lake from liquid to solid, or vice versa, overnight".

Figure 2. A FERA crew pausing for a photograph. The four men were hand-augering a hole on one of the lakes near Grenora or Alkabo in the fall of 1934. Photo courtesy of University of North Dakota archives.

From the results of the drilling program, Lavine determined that the sodium sulfate at the base of the lake was present in two strata, a permanent layer and an overlying intermittent layer. The permanent layer had built up over thousands of years and in some instances was tens of feet thick. The intermittent layer was only a few inches thick and was deposited in the fall but wholly or partly went back into solution the following spring. That part of the intermittent bed that did not go into solution, either because of reduced amounts of available water or because it was protected by a layer of insoluble silt and clay, became part of the permanent layer. Because the intermittent layer was subjected to a repetitive cycle of going in and out of solution, Lavine found it to contain more of the soluble impurities, such as magnesium sulfate, than the permanent layer while the latter generally contained more of the metals such as iron and aluminum oxide. Sodium sulfate crystals are often present throughout the entire sequence of lacustrine strata beneath these lakes, occurring in both thin layers or lenses and as small crystals in a matrix of lacustrine silt and clay.

Lavine (1935) placed the seven deposits he studied (Grenora #1, Grenora #2, Miller, North, McCone, Stanley #1, and Stanley #2 lakes) into three general groups: Grenora, Alkabo, and Stanley (Figure 4). The major ion concentrations of the salt and muds were reported by Lavine as relative percentages of theoretical combinations. Based upon this chemistry, he determined that the intermittent and permanent crystal beds at these deposits ranged from 85 to 98 percent sodium sulfate. Lavine also determined that Miller Lake, at 4% insoluble material, contained the "cleanest" mineral deposit. He discovered during the drilling program that the permanent salt bed in these lakes generally averaged 3 feet thick and varied from a few inches up to 80 feet thick. The exception was Grenora (#2) where the bed averaged 12 feet thick. Based upon the general chemistry and lacustrine stratigraphy, Lavine and Feinstein (1935) estimated there were a total of 23.4 million short tons of Glauber salt in the seven deposits analyzed under the FERA project.

Judging from the inquiries and newspaper articles from across the state, there was considerable interest in the results of Lavine's study both by the citizens of North Dakota and from industry across the country. It is quite evident that the citizens of northwestern North Dakota were hoping that the establishment of a plant in that area might help ease the difficult economic conditions created by the

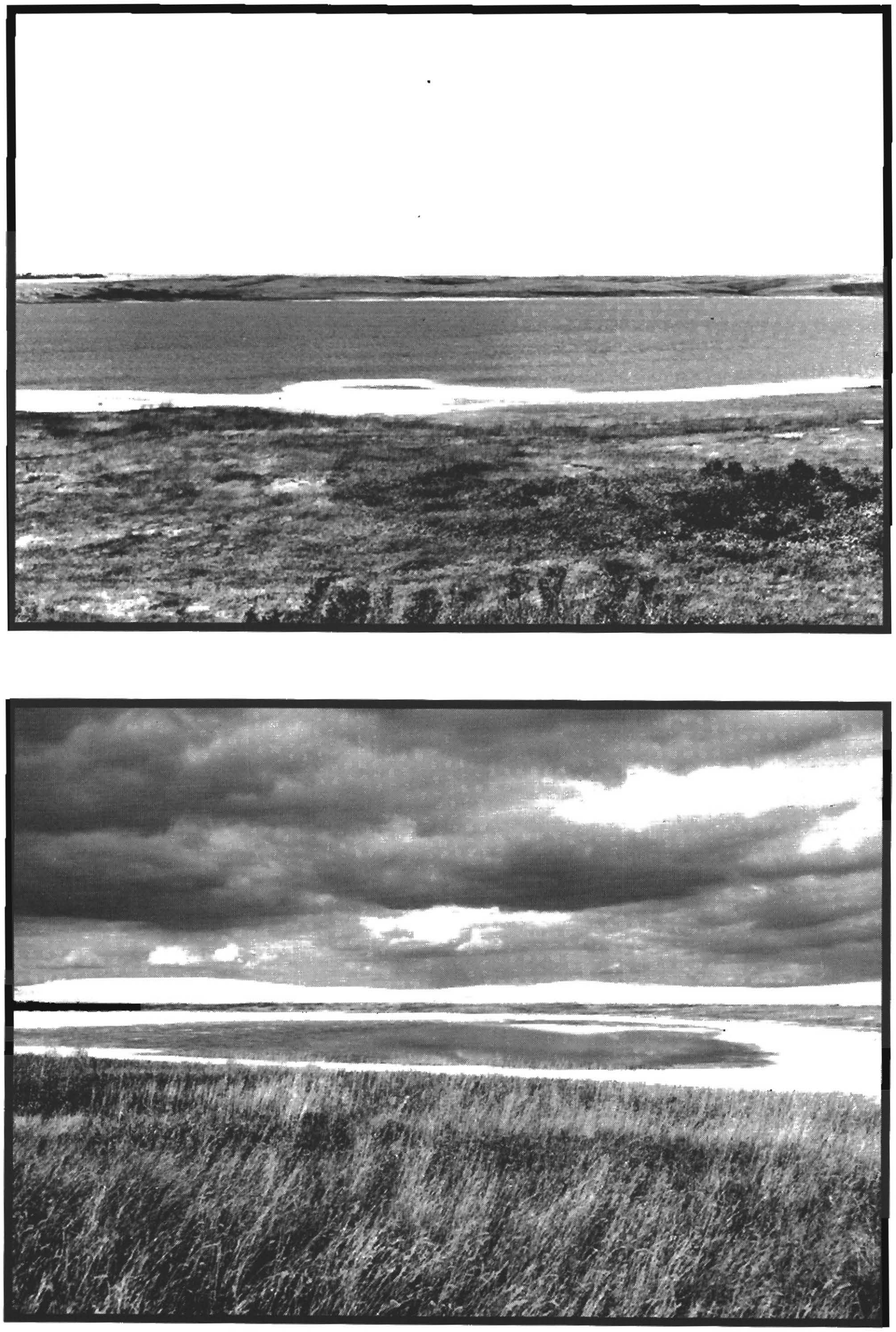

Figure 3. A ring of sodium sulfate exposed along the margins of lakes in northwestern North Dakota. The photographs were taken of White Lake, Mountrail County (upper), and North Lake, Divide County (lower), in the early fall of 1995. Most of the visible salt in these photographs is thenardite, anhydrous sodium sulfate.

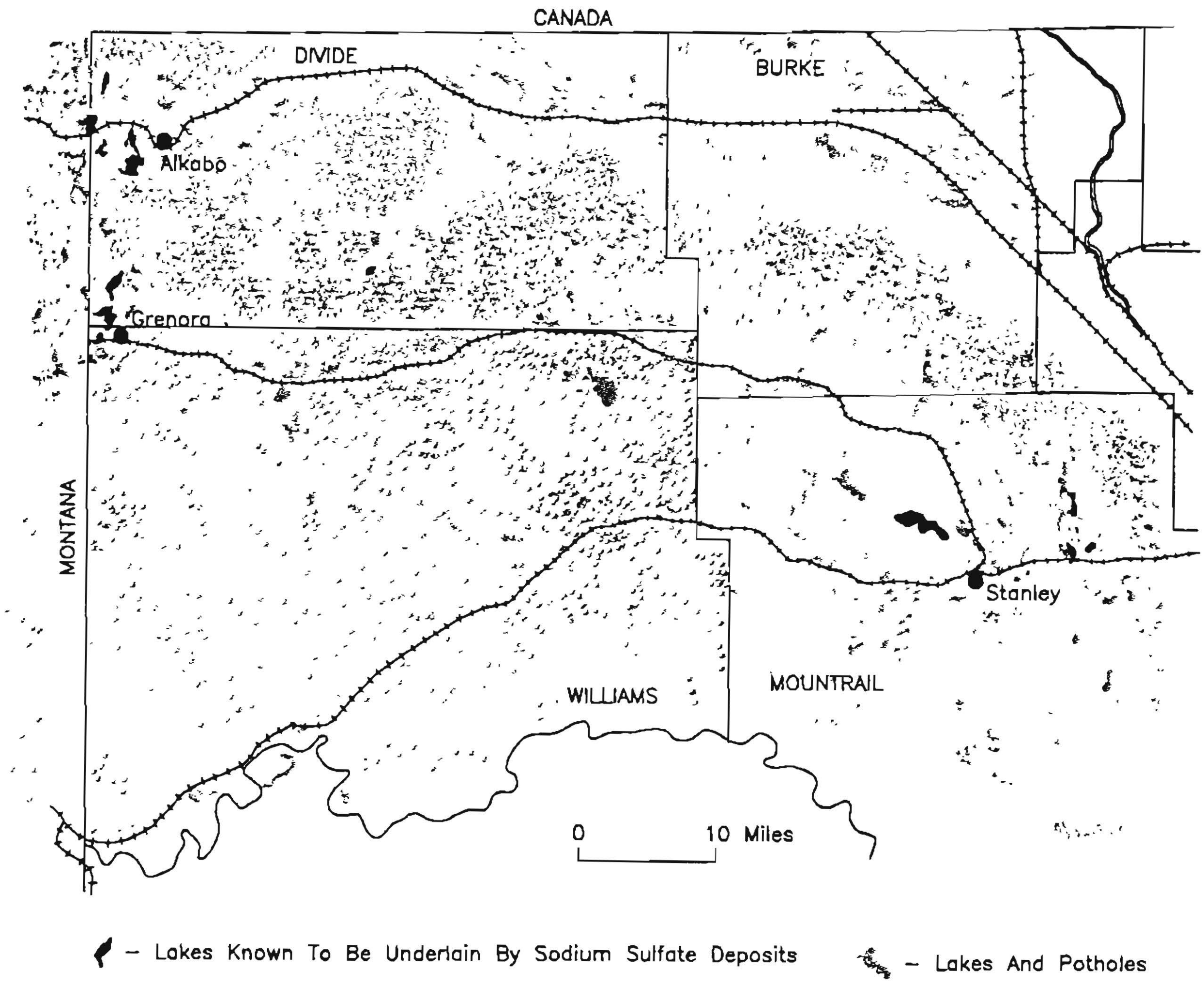

Figure 4 Distribution of the major sodium sulfate deposits in northwestern North Dakota.

drought and the economic depression. The level of interest and excitement for this endeavor culminated on August 24, 1934 when Governor Ole Olson, Irvin Lavine and others spoke before a crowd of several hundred at Grenora and at Grenora #1 during the dedication ceremonies for this project (Williams County Newsman, 1934) (Figure 5).

Unfortunately, most of the original field notes and records of the FERA project are missing. Only six of the original field notebooks have survived. One book contains a nearly complete listing of the drill logs for Grenora #2 and the other contains a partial listing of drill holes for the three lakes near Stanley (Stanley #s 1, 2, and A). On the FERA logs, sediments were differentiated as 1) crystal, 2) mud, 3) mud and crystal, 4) mud and slush, 5) and sand. The logs at Grenora #2 suggest that the workers generally did not penetrate the base of the lacustrine sediments, but almost always halted drilling 2 to 10 feet into a lacustrine clay underlying what they assumed to be the last crystal bed. It is likely that this same procedure was used at the other lakes.

Lavine and Feinstein (1935) published an abridged version of the FERA results and added a market study of the economics of producing these deposits. They felt that there were two main handicaps to producing these deposits: the duty-free entrance of sodium sulfate from Saskatchewan and high freight rates. The closest markets for sodium sulfate in the 1930s were Kraft-paper producers in

Minnesota, Wisconsin, and Michigan. A potential market was also noted for glass plants in Indiana and Illinois.

In the late 1940s, the North Dakota Geological Survey undertook another study of the sodium sulfate deposits (Grossman, 1949). This project was expanded to include additional lakes not studied under the FERA project. No drilling was undertaken under this project so estimates of sulfate reserves at the new lakes were based primarily on chemical analysis of lakes and springs and onsite observations of biota. Grossman noted that minute shrimp-like animals known as *Artemia salina* inhabit many of these saline lakes and that the salt tolerant plant *Salicornia rubra* commonly rings these lakes. Grossman reviewed the various theories concerning the source for these salts and noted that the chemical composition of the Fort Union strata was sufficient to supply the quantity of sodium and sulfate ions to produce these deposits.

In the early 1950s, Edward Tullis of the United States Bureau of Mines investigated several lakes in North Dakota, focusing attention on those not studied under the FERA project (Binyon, 1952). A crew hand-augered 56 holes in 14 lake basins, all but two of these lakes were in northwestern North Dakota. Most holes were less than 10 feet deep, although a few reached depths of 20 feet. For many of the lakes, the crews were able to stand on the dry lake bottom while on many others they had to wait until the lakes froze over before they could venture out on them. For lakes that were at least several feet deep, Binyon used a specially designed raft as a drilling platform. Binyon collected 266 samples and analyzed them for their salt content by mixing a given amount of sample with a given amount of distilled water. The resulting solution was then filtered and chemically analyzed. The raw chemical data were not reported. Instead, results were presented as theoretical compounds, generally salts, based upon their relative solubilities. Binyon used these theoretical combinations to estimate that the permanent salt beds ranged in concentration of Glauber salt from 44 to 70% (averaging 56%) and the intermittent salt beds contained on average 63% Glauber salt. In addition, the salt-bearing mud (or clay) ranged from 6 to 40% Glauber salt. As a result of these findings, Binyon determined that Lavine (1935) had over-estimated the amount of Glauber salt in these deposits by not accounting for the insoluble material and the pore water in his calculation of relative percentages. Binyon concluded that 30.4 million short tons of Glauber salt are present in the 21 deposits investigated by the FERA and the Bureau of Mines.

A few economic studies were conducted during the 1940s and 1950s to determine the marketability of sodium sulfate and the

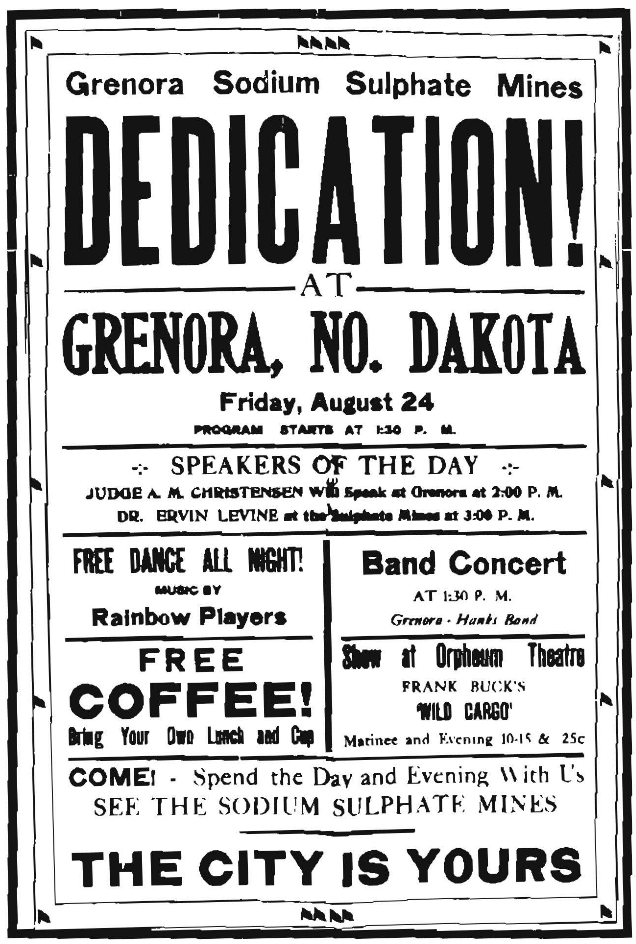

Figure 5. Poster announcing the August 24, 1934, dedication ceremony. The event was held to celebrate the commencement of the FERA project in northwest North Dakota.

economic feasibility of establishing a processing plant in northwestern North Dakota (Cooley, 1944; Burr et al., 1951). Cooley estimated several of the costs involved in operating a 50-ton-per-day salt plant near Grenora and provided a brief market survey. Burr et al did the most extensive market study that has been published to date on this subject. They determined from their study that a 50-ton-per-day processing plant was economically feasible but advised potential operators to diversify the end product as much as possible to be able to withstand any down turns in the main sodium sulfate market.

A few reconnaissance projects for sodium sulfate have been conducted in north-central and northeastern Montana (Sahinen, 1956; Ackerman, 1957). Sahinen obtained water and sediment samples from a number of lakes in Chouteau and Sheridan counties. Ackerman drilled for sodium sulfate on a few frozen lakes near Fort Benton, Montana. He determined from the solubility curve of sodium sulfate that a temperature of 40 degrees below zero (Fahrenheit) was required to sufficiently solidify the surface of the lakes for vehicle travel. He found that when the air temperature rose above 15 degrees below zero (Fahrenheit) the sulfate crystals began going into solution.

In the 1960s, Ted Freers and Hank Reed conducted a study of the sodium sulfate deposits for the minerals division of the Great Northern Railway. Freers recalls drilling in bitter cold temperatures on lakes in the Stanley area. Unfortunately, a search of the archives of the Burlington Northern Company has not produced any information on this project.

In 1977, the Ozark-Mahoning Company drilled nine holes through the lacustrine deposits on their holdings at Grenora #2 (McIlveen, 1977). In 1984, the company drilled eleven holes and installed several monitoring and supply wells in the Grenora Aquifer adjacent to Grenora #2 (Klahsen, 1984).

In addition to these mineral resource studies, several studies have been conducted on the geochemistry of the lakes in this area. Reiten (1991) obtained water samples from over 50 lakes in northeastern Montana and several in North Dakota (Nodak, VanVoast, Twin, Horseshoe, Westby B and C). From this study he was able to divide these lakes into 5 groups based on major ion concentrations. Donovan (1992) did a comprehensive study of lake geochemistry in northeastern Montana and northwestern North Dakota. Some of the North Dakota lakes studied by Donovan include: Skjermo, Miller, Grenora #1, Grenora #2, Stink, and Horseshoe. This study focused on the geochemical impact on these lakes from interaction with adjacent shallow and deep aquifers. A condensed version of this study was published by Donovan and Rose (1994).

Current Study

Little or no accurate information remains concerning the lacustrine stratigraphy of the seven deposits investigated under the FERA study. Therefore, the current project was initiated to gather this information, reassess the available salt resources and make this information available to industry for the purpose of encouraging the construction of a processing plant in northwestern North Dakota.

Observations, including water levels, biota, and temperature, conductivity and pH, were noted during periodic visits in the summer and fall of 1995 and the spring, summer, and fall of 1996. Water samples were obtained from six lakes (Miller, Grenora #1, Grenora #2, Horseshoe, White, and Stanley #2) in late September, 1995. Several additional lakes had been scheduled for sampling but were dry at the time.

The presence of these deposits under shallow or playa lakes makes exploration at best difficult and at times dangerous. Most previous projects have explored these deposits by hand-augering on dry lake bottoms in the fall or on the

Figure 6. A large spring, marked by open water, along the northwest edge of Stanley #2, Mountrail County. The photograph was taken looking southeast on March 8, 1996

frozen lakes in the early winter. At least one project used a homemade barge as a drilling platform. The North Dakota Geological Survey opted to drill these sites during the dead of winter when ice would support the weight of vehicles. Winter drilling was not without risks as the high salt concentration of the mud and brines makes for late freezing and in some cases unstable ice. Rawson and Moore (1944) determined that lake water containing 120,000 mg/l of total dissolved solids, the concentration of many of the lakes that were investigated, had a freezing point of 24.5 degrees (Fahrenheit). Additional concern was that large springs along the edges of many of the lakes can cause unstable ice any time of the year. Two springs, one on Stanley A and the other Stanley #2, created areas of open water in early March even though the area had undergone two successive weeks of subzero temperatures (Figure 6).

Twenty-nine holes were drilled and cored by the Geological Survey during three separate one-week periods during the winter, 1996 (the first week in January, the last week of February, and the first week of March). The holes ranged in depth from 10 to 54 feet (Appendix A). Coring was made difficult by sticky clay, noncohesive silts, and extremely indurated crystal salt beds. As a result, only one continuous core, hole no. 1 at Westby A, was obtained through an entire lacustrine sequence.

During the drilling program, temperatures ranged from 25 degrees above zero to 30 degrees below (Fahrenheit). The Geological Survey's 10-ton Mobil B-50 rig cored holes on several of the lakes during the first week in January (Figure 7). At time of freeze up, all of the lakes tested were dry except for Miller Lake which contained one to three feet of water, but no problems were encountered. Shortly after the first round of drilling was completed, the truck engine on the Mobil broke down and was not repairable. As a result, the last two weeks of drilling and coring were performed with a trailer-mounted Giddings probe. The Giddings probe performed well in the soft lacustrine clays and muds, but labored when augering through the beds of crystal salt. The fish-tailed auger bit would often loose its sharpened edge after drilling only a few feet, at

Figure 7 The North Dakota Geological Survey's drilling apparatuses used during the winter of 1996. A Mobil B-50 hollow-stem auger (upper photo) and a trailer-mounted Giddings probe (lower photo).

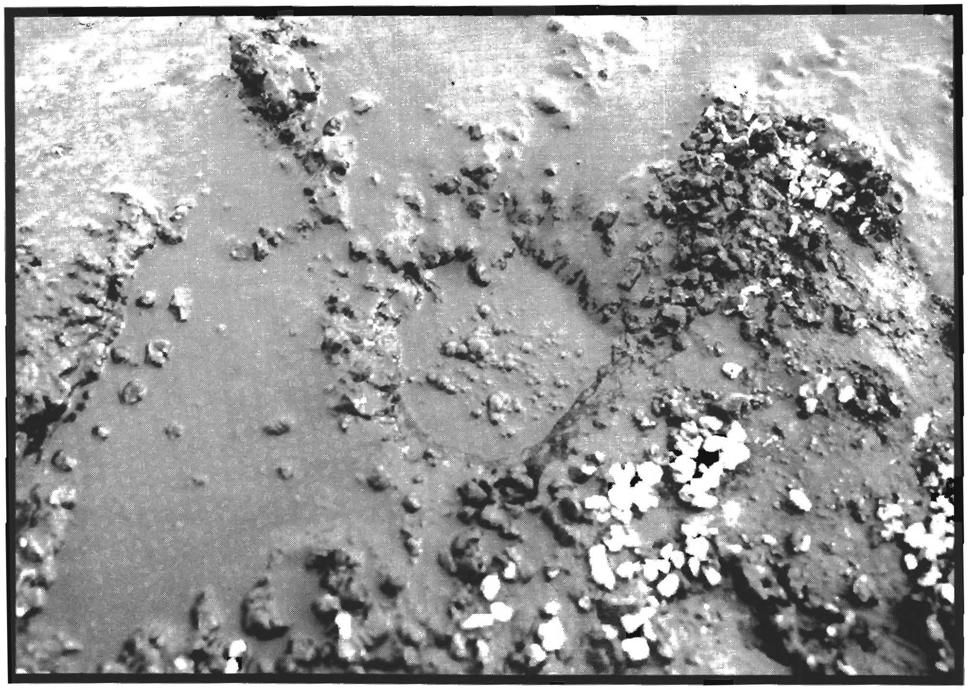

Figure 8. Gas bubbling at the surface of a 4-inch diameter borehole (hole no. 2) at Miller Lake, Divide County. Bentonite pellets, used to plug the hole, and mirabilite crystals. from the 24-foot hole, lay scattered on the ice.

times after only a few inches, into a crystalline bed. A hard rock bit with replaceable teeth performed slightly better when drilling through the salt section. The base of a thick crystal salt layer was often the most indurated portion of the bed. Several holes were abandoned after only making an inch or two of headway after drilling in salt for an hour or more. A thin-walled core barrel with a removable plastic sleeve insert was the only effective method for obtaining core of the sticky lacustrine muds and clays which often had the consistency of peanut butter. All cores and cuttings from this project are stored at the Geological Survey's warehouse in Bismarck.

Estimates of sodium sulfate reserves were generated by determining the extent and average thickness of the salt and salt-bearing beds by means of stratigraphic correlation. As was demonstrated under the FERA project, closely spaced holes are needed to accurately define the lacustrine stratigraphy. However, the handful of holes that were drilled in each lake during this project was sufficient to generate resource estimates more accurate than the previous ones. It should be noted, however, that many more holes would be required to obtain a more precise estimate of resource tonnage. This project was funded through the regular agency budget with no special funds. As a result, no funds were available to pay for chemical analysis of the salt and clay beds. Therefore, the Glauber salt content for each of the beds was estimated by applying the average salt concentrations (9% for brine, 70% for intermittent salt beds, 54% for permanent salt beds, and 24% for salt-bearing muds and clays) as determined by Binyon (1952).

The most troublesome aspect of the drilling program was the gas in the organic-rich sediments beneath the lakes. Miller and Grenora #1 were the worst, but gas was encountered to some degree in all of the lacustrine sediments (Figure 8). Although no analytic or volumetric tests were run on the gas, it was assumed to be a mixture of methane and hydrogen sulfide. Methane would be expected as a by-product of the decay of the highly organic mud. Hydrogen sulfide likely has resulted from the activity of sulfate reducing bacteria. The odor of hydrogen sulfide was present throughout the drilling of each of the holes, from the near-surface black organic muds to the basal lacustrine clays. The concentrations of gas were strongest in the darkly colored organic mud and clays immediately beneath layers of crystal salt. At times, the gas bubbled with enough vigor to splatter mud out of the hole. It was difficult under these conditions, even on a very windy day, not to be overcome by gas fumes. An investigation into the quality and quantity of this gas and its economic potential may be warranted. The samples and cores themselves give off a strong odor of hydrogen sulfide, even those samples left exposed to the air for several weeks. A combination of the high salt and hydrogen sulfide content of these sediments proved highly corrosive to the metal on the drill rig and soil probe.

North Dakota Deposits of Sodium Sulfate

Numerous lakes in North Dakota contain thin layers of sodium sulfate or become brines in the fall as a result of concentration by evaporation. For ease of discussion, the 15 main sodium sulfate deposits are discussed by area (Grenora, Alkabo, and Stanley) as designated by Lavine (1935). In order to present as complete a document as possible, drill hole information from the FERA project, the U.S. Bureau of Mines report (Binyon, 1952), and Ozark-Mahoning Company have also been included in this report.

Geology and Hydrogeology of the Grenora-Alkabo Area

Due to their close proximity, the geology and hydrogeology of the Grenora and Alkabo areas will be discussed together (Figure 9). A number of studies have investigated the surface and near-surface geology of this area (Alpha, 1935; Alden, 1932; Witkind, 1959; Howard, 1960; and Hansen, 1967). The northwestern corner of the state is underlain by glacial sediments, primarily till, which ranges in thickness from several tens of feet to over 600 feet in preglacial channels in this area (Figure 10). All of the surficial landforms in this area were formed in Late Wisconsinan time during the northeasterly retreat of the terminus of the glacier in this area (Hansen, 1967). South of this area, in central and north-central Williams County, glacial drift at the surface has been mapped as both Middle Wisconsin (?) and Early Wisconsin (?) (Howard, 1960). Drift thicknesses in the Alkabo area range from 100 to 200 feet and from 200 to 300 feet in the Grenora area (Armstrong, 1965). Two northeast-trending buried channels are present in this area. The

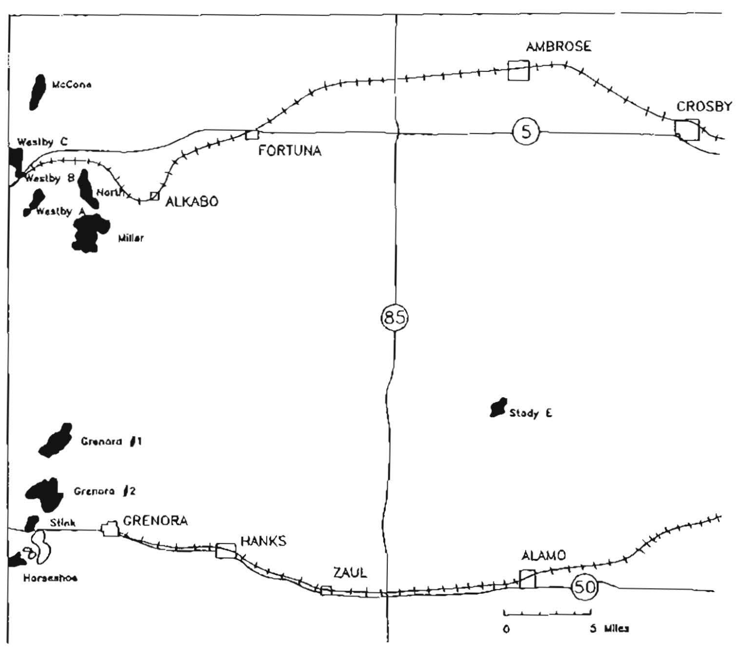

Figure 9. Distribution of sodium sulfate deposits in the Grenora and Alkabo areas.

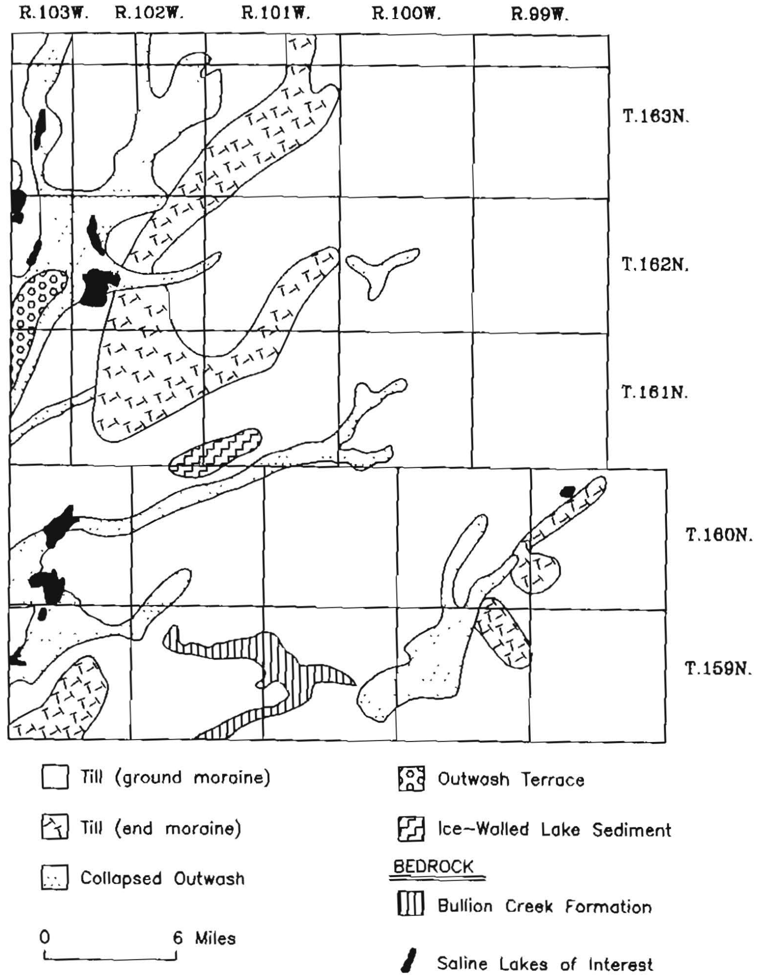

Figure 10. Geologic map of the Alkabo and Grenora areas in western Divide and northwestern Williams counties (from Clayton et al., 1980).

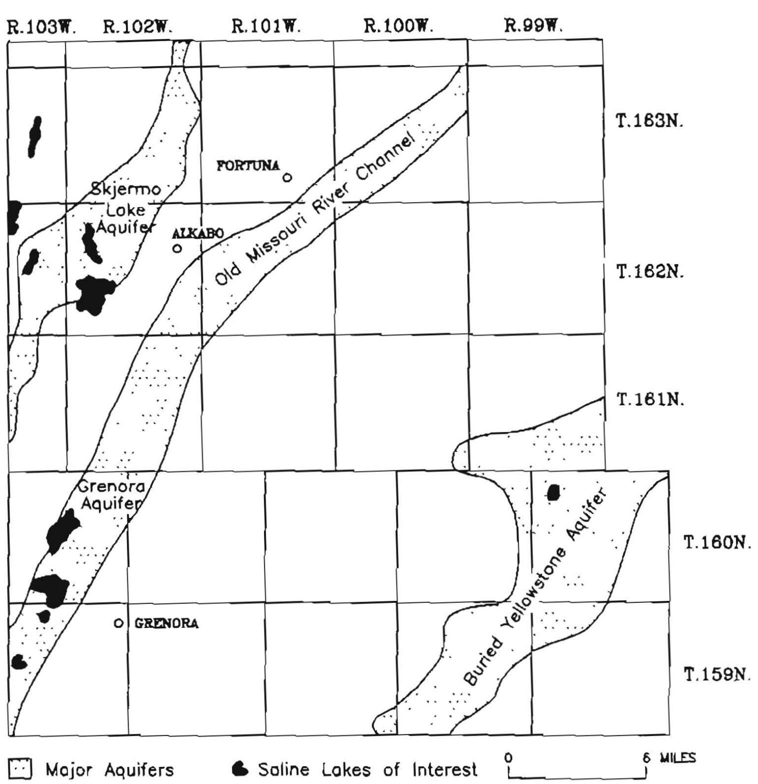

Figure 11 Major glaciofluvial aquifers in the Grenora and Alkabo areas (from Armstrong, 1967, and Wanek, 1996).

deepest of the two is thought to be the interglacial channel of the Missouri River. The drift in this area is underlain by the Bullion Creek Formation (Paleocene). A conspicuous feature east of Miller and North Lakes is the Alkabo end moraine which rises 100 to 250 feet above the surrounding countryside and is composed, in part, of thrust masses. The lakes of interest in this area (Grenora #1 and #2; Stink; Horseshoe; Miller; North; Westby A, B, and C; and McCone) occur within dead-ice moraine and often are associated with collapsed outwash (Clayton et al., 1980). As noted by Hansen (1967) these lake basins generally occur within larger depressions.

Areas of collapsed outwash form aquifers that may be important locally but are generally too thin to support industrial needs. There are three main buried-channel aquifers in Divide and northern Williams counties: Skjermo Lake, Grenora/Missouri River, and Buried Yellowstone aquifers (Figure 11). North, Miller, and Westby A lakes are situated over the Skerjmo Lake Aquifer, a glaciofluvial deposit of sand and gravel, which ranges from less than 40 to over 80 feet thick in this area (Wanek, 1983). The aquifer is generally confined and has a hydraulic conductivity of 400 to 500 feet per day with groundwater flow to the southwest. Water in the aquifer is a calcium bicarbonate type with total dissolved solids ranging from 500 to 1500 milligrams per liter (mg/l). Over the last 18 years, an annual average of 2500 acre-feet of water has been withdrawn from this aquifer for local irrigation (Wanek, 1996). In general, water levels in the aquifer have declined and the TDS has increased since irrigation began, the latter being much more variable across the aquifer. The State Water Commission has denied several irrigation permit applications in this area to prevent further water level declines and aquifer degradation (Wanek, 1991).

Grenora #1 and #2, Stink, and Horseshoe lakes are situated over the Grenora Aquifer (Wanek, 1983). The Grenora Aquifer is the name given to the 400- to 500-foot-thick channel-fill deposits in the buried Missouri River channel in southwest Divide County. The channel fill ranges from sand and gravel to silt and clayey silt. The latter fine-grained sediments often are the most prevalent (Armstrong, 1967). The yields are variable (50-500 gallons per minute) and water quality is often poor. The groundwater in this aquifer system is generally a calcium-magnesium-bicarbonate-type although in some areas sodium and sulfate are dominant (Armstrong, 1967).

Stady E Lake is situated over the Buried Yellowstone Aquifer (Armstrong, 1967). The Buried Yellowstone channel is greater than 600 feet deep in some areas and is filled with sand and gravel, silt, clay, and till. The lithology is quite variable as is the yield (generally 50-500 gallons per minute (gpm) but some areas exceed 500 gpm). Groundwater in this aquifer is generally a calcium-bicarbonate-type but sodium and sulfate are dominant in some places. Total

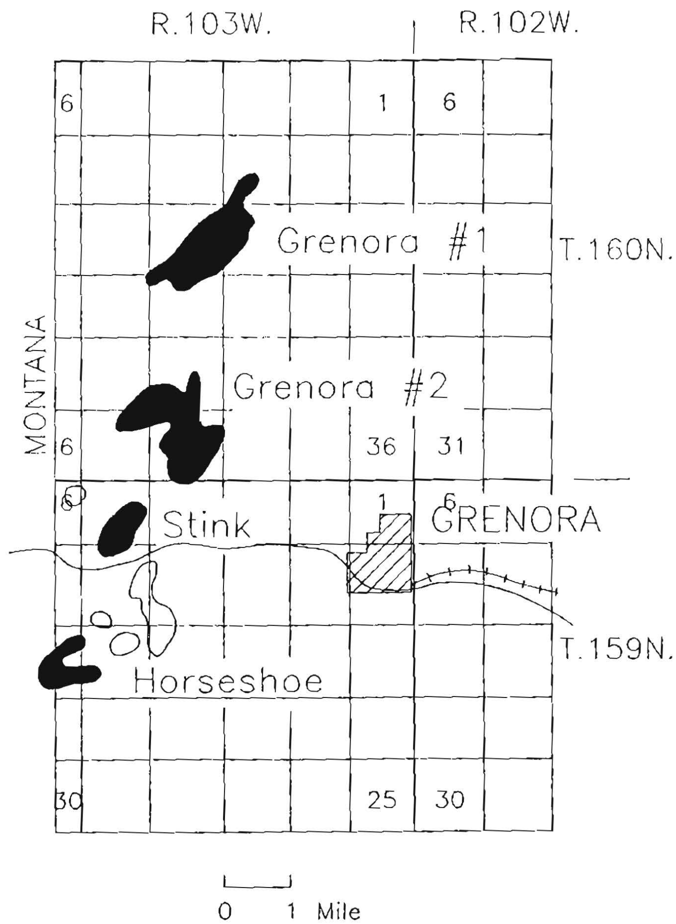

Figure 12. Distribution of the major sodium sulfate deposits in the Grenora group, Divide and Williams counties.

Figure 13. Grenora #1, Divide County, with only a few inches of water. There were 2-3 inches of salt on the lake bottom when this photograph was taken on July 17, 1996. The photograph was taken looking north from the south shore of the lake.

dissolved solids generally range from 1400 to 6500 mg/l (Armstrong, 1967).

Grenora Group

There are at least four lakes in the Grenora area that are underlain by crystal layers of sodium sulfate: Grenora #1, Grenora #2, Stink, and Horseshoe lakes (Figure 12). The lacustrine stratigraphy at Grenora #2 was well documented by the FERA project and by drilling done by the Ozark-Mahoning Company. The U.S. Bureau of Mines drilled three to four holes at Stink and Horseshoe lakes in 1952. The North Dakota Geological Survey drilled four holes at Grenora #1 in 1996 because no detailed subsurface information was available for this site.

Grenora #1

There are two main deposits beneath lakes in the Grenora area. These lakes were referred to as Grenora #1 and Grenora #2 in the FERA reports, names which have been used in subsequent reports on sodium sulfate. Lavine (1935) noted in his report that during dry periods, the intermittent sodium sulfate layer at Grenora #1 was scraped from the lake bottom and transported in wheelbarrows to shore where it was placed in stockpiles of 200 tons and sold to farmers for salt for their cattle. Grenora #1 (referred to as Stink Lake in some early newspaper articles) is the lake where Oscar Quarne and Ernest Jensen discovered the sodium sulfate layer while hunting ducks.

Grenora #1 is located approximately 6 miles northwest of the town of Grenora (Figure 12). The lake extends over an area of 500 acres in portions of sections 10, 15, 16, and 21 (T160N, R103W) in Divide County. Grenora #1 generally contains a foot or so of water during the spring and summer and goes dry in the fall. The lake was completely dry in late September, 1995 and contained only a few inches of water on July 17, 1996 (Figure 13). Large numbers of *Artemia salina* were swimming in the brine and

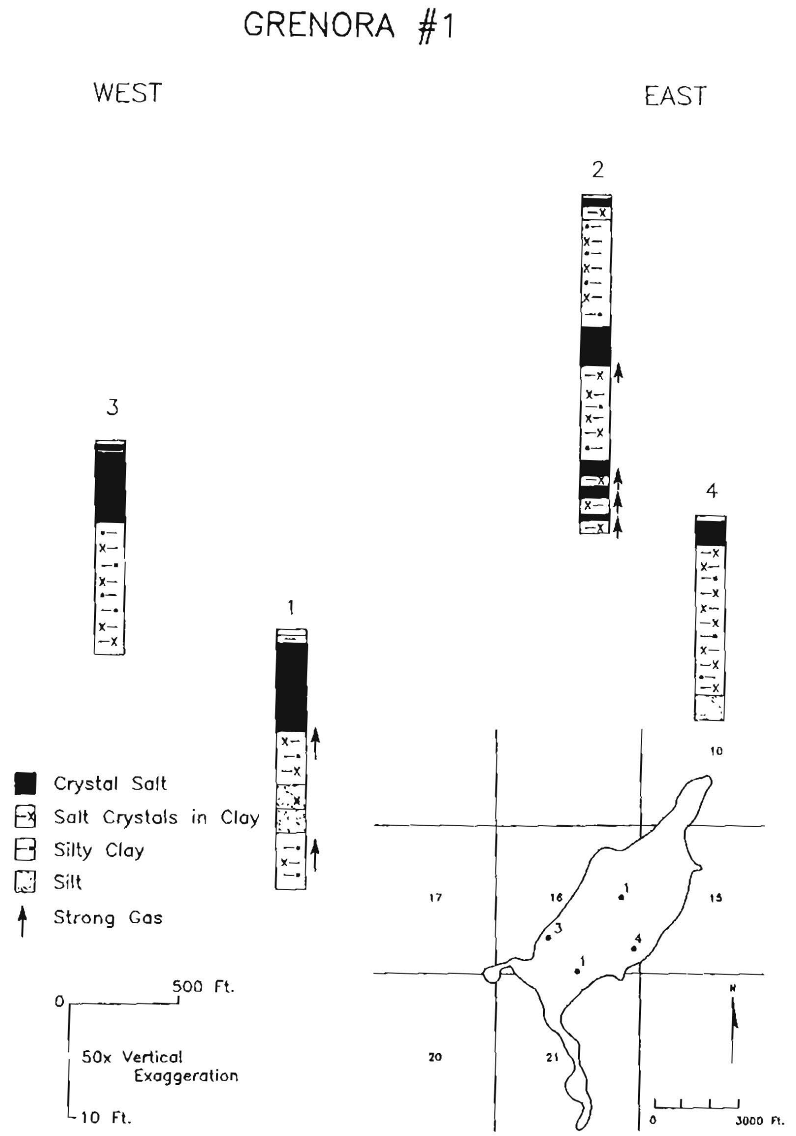

Figure 14. Drill hole lithology at Grenora #1, Divide County.

an equally large number of brine shrimp bodies had been incorporated into the underlying salt layer. The decaying bodies of the brine shrimp that had washed up on shore released a foul odor throughout the entire lake basin. Several springs are present along the southern and western margins of the lake. On January 12, 1996 a large, highly sulfurous spring created a five acre area of standing water along the southwest corner of the lake (nenw section 21). In late February and early March, several additional springs along the southern margin of the lake were outlined by areas of clear, mounded ice.

Under the FERA project, 421 holes were augered in a 346-acre area which covered approximately 85% of the total area of the lake. Drilling sites were established on a 200-foot grid pattern. This project determined that thickness of salt and salt-bearing sediments often varied dramatically from hole to hole, ie., within 200 feet. Lavine (1935 and 1935a) determined that the permanent bed averaged 2.5 feet thick over the area and obtained a maximum thickness of over 30 feet. In general, the holes augered under the FERA project are deepest along the south-southwest portion of the lake, but no stratigraphic patterns can be established based on depths alone.

The Geological Survey augered four holes through the lake in January and March, 1996. The holes ranged in depth from 18 to 30 feet and none of the holes penetrated the base of the lacustrine sediments (Appendix A). The thickness of the permanent crystal bed varied from a few inches to 8 feet (Figure 14). The crystal salt bed appears to be thickest in the southwestern portion of the lake. The permanent bed was underlain by at least 14 feet of lacustrine clays and silts, the last 5 feet of which were often laminated, most likely varved. These organic-rich sediments contained scattered rootlets and small snails. Sodium sulfate crystals were present throughout these sediments. In spite of strong northerly winds (greater than 20 mph), high concentrations of gas forced the abandonment of the holes before the base of lacustrine sediments could be penetrated. A comparison of the total thicknesses of the crystal salt bed and salt-bearing clay in the FERA report with the four holes drilled by this project indicates that most, if not all, of the FERA holes failed to penetrate the base of the salt-bearing section and none likely penetrated the base of the lacustrine section.

Hole no. 2 contained a total of 6 feet of crystalline salt and 24 feet of salt-bearing clay (360 inches). This 360-inch total of salt and salt-mud is much higher than the 54-inch average of the adjacent FERA holes. The same is true of hole no. 4 which contains 20 inches of crystal and 168 inches of salt-bearing mud as compared to the average of 37 inches from the four surrounding FERA holes. This comparison suggests that the 1.75 million short tons of Glauber salt estimated by Lavine (1935) for this lake is low. Binyon (1952) reduced Lavine's estimate to 980,000 short tons based on the assumption that the Lavine's correlations were correct but that the crystal beds only contained 57% Glauber salt.

Based upon information obtained from the four holes drilled by the Geological Survey, an estimated 7.1 million short tons of Glauber salt is present within a 500-acre area of Grenora #1. This estimate was arrived at using an average thickness of 0.28 foot of intermittent salt crystals, 5.18 feet of permanent crystal salt, and 16 feet of salt-bearing mud (Table 1). The tonnage factors and the estimated percentage of Glauber salt were obtained from Binyon (1952). Binyon based his calculations of the average tonnage factors on the chemical analysis of these materials. The estimated percentage of Glauber salt (70% for intermittent crystals, 54% for crystal beds, and 24% for mud and crystals) are averages of all of the percentages determined by Binyon for these materials in the lakes that he studied. Since these numbers are not site specific, the actual percentages will be higher in some areas and lower in others. Since none of the holes penetrated the base of the lacustrine sediments, additional crystal sat beds may be present below the 25-foot level.

Grenora #2

Grenora #2 is located approximately 1.5 miles south of Grenora #1 although channel-shaped portions of both lakes extend to within a quarter mile of each other (Figure 12). Grenora #2 occupies approximately 644 acres in portions of sections 28, 29, 32, and 33 (T160N, R103W) in Divide County and section 4 (T159N, R103W) in Williams County. Grenora #2 generally contains a few feet of water throughout the year (Figure 15). This lake was dry in the fall of 1934 when the FERA study was

TABLE 1

Grenora #1 • 500 Acres

	Average Thickness (feet)	Cubic Feet	Tonnage Factor	Short Tons	Estimated Percent of Glauber Salt	Glauber Salt (short tons)
Brine						
Intermittent Crystals	0.28	6,100,000	22	280,000	70	200,000
Crystal Bed	5.18	113,000,000	22	5,100,000	54	2,800,000
Mud & Crystals	16.00	348,000,000	20	17,000,000	24	4,100,000
TOTAL						7,100,000

Table 1. Estimated amount of Glauber salt at Grenora #1.

undertaken. A thick, intermittent bed of sodium sulfate was visible beneath a few feet of water in October, 1995.

Under the FERA project, 450 holes were augered through the Grenora #2 lake bottom, most drilled on a 200-foot grid. This drilling program determined that the thickness of lacustrine sediments throughout much of the lake ranged from less than 2 feet to over 10 feet. However, in the south-central portion of the lake, a north-south trending 90-acre depression was discovered which contains in excess of 70 feet of lacustrine sediments (Figures 16-17). Lavine (1935) determined that the lacustrine deposits averaged over eleven feet thick in the 461-acre study area. Based on these findings, Lavine estimated the Glauber salt deposit at Grenora #2 to be over 11 million short tons. Binyon (1952) believed that Lavine over-estimated the tonnage, errantly assuming that the Glauber salt content of the permanent crystal bed was approximately 90% while Binyon assumed it to be closer to 50%. Without any basic data on the site, Binyon estimated there are 5.5 million short tons of Glauber salt in this deposit.

A few years after the FERA reports identified Grenora #2 as the largest deposit of sodium sulfate known in the state, the site was purchased by Ozark-Mahoning Mining out of Tulsa, Oklahoma. In 1937, as the company drilled wells in search of a water supply to be used in processing, the company was informed by the North Dakota Attorney General's office that the state of North Dakota maintained ownership of the lake bottom and therefore any minerals derived from it. Ozark-Mahoning worked out a lease agreement with the state and then in 1938 began a lawsuit to quiet its title (Grossman, 1949). In 1948, judgment was rendered for the company and the state appealed the decision, which was upheld by the court (Carvell, 1988). In 1961, after 24 years of inactivity at the site, two settling ponds were constructed on the west end of the lake and talk resumed in the local newspapers that a $500,000 processing plant would be built near Grenora. No salt was ever processed from the site. Local landowner Dave Jensen recalls that the summer of 1961 did not get hot enough to raise the lake temperatures to the desirable point and the company, disappointed over the unpredictability of our seasons, left the state.

Figure 15. Grenora #2, Divide County, with a foot or two of water. The photograph was taken looking east along the southwest corner of the lake in September, 1995.

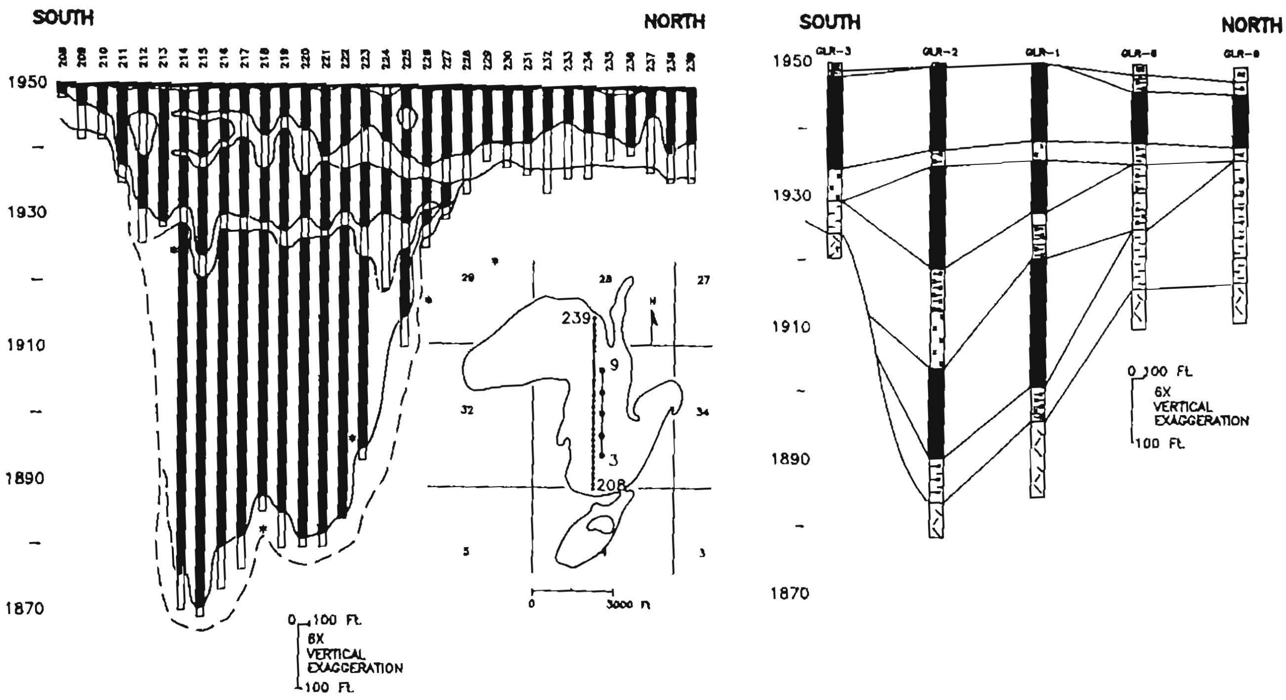

Figure 16. North-south geologic cross sections of Grenora #2, Divide County. Basic data for the section on the left is from FERA fieldbook "Deposit 2". Data for the section on the right is from McIlveen (1977).

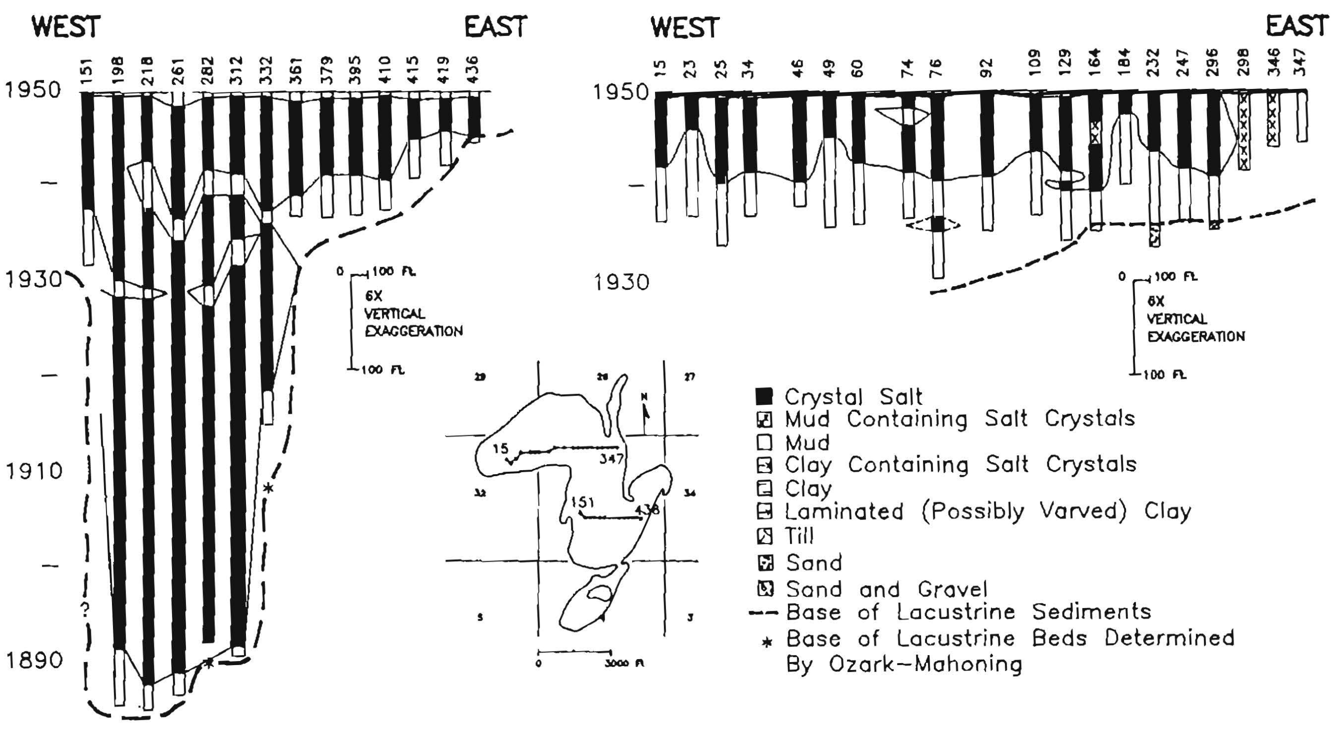

Figure 17. East-west geologic cross sections of Grenora #2, Divide County. Basic data is from FERA fieldbook "Deposit 2".

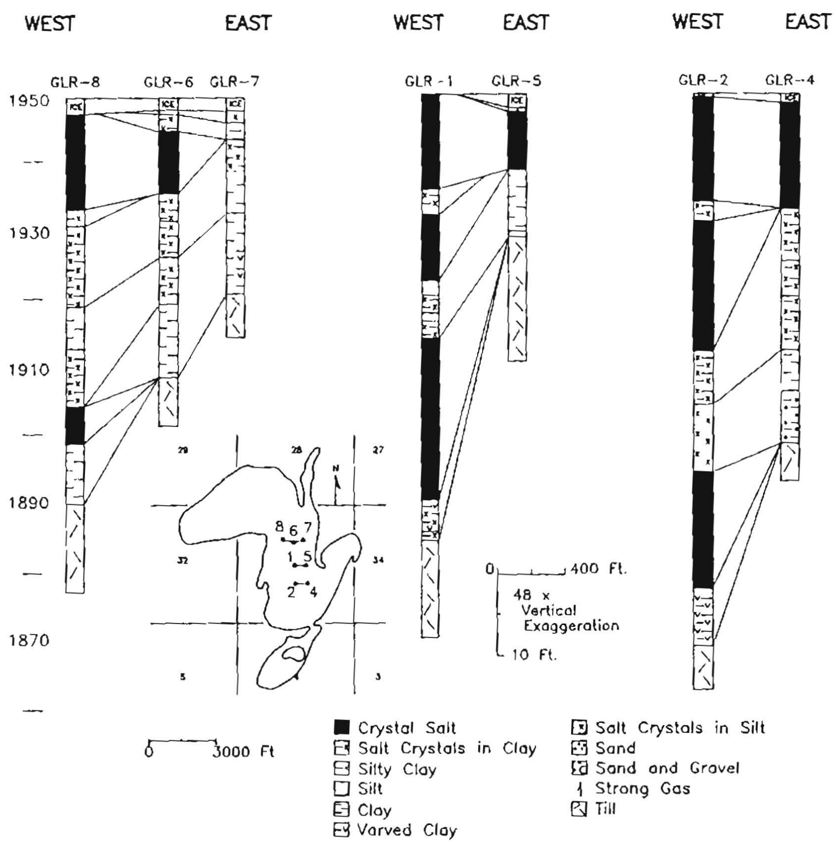

Figure 18. East-west geologic cross sections of Grenora #2, Divide County. Basic data obtained from McIlveen (1977).

In January and February of 1977, Ozark-Mahoning drilled nine holes through the lacustrine sediments at this lake (McIlveen, 1977). This program confirmed the presence of a northwest-southeast trending 40-foot-deep depression in the glacial deposits beneath this lake, which was subsequently filled with lacustrine deposits. The lacustrine deposits range in thickness from 25 to 67 feet and are underlain by till (Figures 16-18). The cumulative thickness of crystal salt in the nine holes ranged from 0 in well no. 7 near the northeast end of the lake to 42.5 feet of salt in the south-central part. A 20-foot-thick salt bed was the thickest crystal salt layer encountered by Ozark-Mahoning (hole no. 1). The Ozark-Mahoning holes were spaced from 350 to 500 feet apart on an east-west line and 880 feet apart along a north-south line. Even with relatively closely spaced holes, it is difficult to correlate these beds with a high degree of confidence.

Ozark-Mahoning's drilling program was undertaken to determine the accuracy of sodium sulfate reserve estimates for the lake made by the FERA (Lavine, 1935) and the U.S. Bureau of Mines (Binyon, 1952). According to McIlveen and Cheek (1994) this project confirmed the accuracy of the Bureau of Mines estimate of 5.5 million short tons of Glauber salt. Ozark-Mahoning's drilling program also confirmed the information gathered by the FERA project that the thickness of the lacustrine deposits varied from 20 to a maximum of 70 feet in a depression along the southern end of the lake. In general, there is good agreement between the FERA and Ozark-Mahoning lithologic logs. However, this comparison suggests that the FERA workers may have reported high salt-bearing muds and clays as crystal salt, overestimating the crystal salt content by an average of 33%.

Stratigraphic correlation of both the FERA and Ozark-Mahoning data led to an estimate of 6.4 million short tons of Glauber salt over an area of 644 acres at Grenora #2. This estimate was determined by splitting the site into three general areas (north, central, and south) and averaging the thicknesses for intermittent salt, permanent crystal salt, and salt-bearing muds and clays for each of the three areas (Table 2). The central area contains the most precise estimate due to the detailed Ozark-Mahoning information while the other two areas were calculated based on the less reliable data from the FERA drilling program.

TABLE 2

Grenora # • Central - 77 Acres

	Average Thickness (feet)	Cubic Feet	Tonnage Factor	Short Tons	Estimated Percent of Glauber Salt	Glauber Salt (short tons)
Brine	1.50	5,040,000	32	160,000	9	14,000
Crystal Bed	16.10	54,100,000	22	2,500,000	54	1,300,000
Mud & Crystals	11.00	37,000,000	20	1,800,000	24	440,000
TOTAL						1,800,000

TABLE 2

Grenora #2 • Southern - 221 Acres

	Average Thickness (feet)	Cubic Feet	Tonnage Factor	Short Tons	Estimated Percent of Glauber Salt	Glauber Salt (short tons)
Brine	1.50	14,000,000	32	450,000	9	40,000
Crystal Bed	3.00	29,000,000	22	1,300,000	54	710,000
Mud & Crystals	2.00	19,000,000	20	960,000	24	230,000
TOTAL						980,000

TABLE 2

Grenora #2 • Northern - 346 Acres

	Average Thickness (feet)	Cubic Feet	Tonnage Factor	Short Tons	Estimated Percent of Glauber Salt	Glauber Salt (short tons)
Brine	1.50	23,000,000	32	700,000	9	60,000
Crystal Bed	8.00	120,000,000	22	5,500,000	54	3,000,000
Mud & Crystals	3.00	45,000,000	20	2,300,000	24	500,000
TOTAL						3,600,000

Table 2. Estimated amount of Glauber salt at Grenora #2.

Stink Lake

Stink Lake is located just to the southwest of Grenora #2 and is bounded on the south by U.S Highway 50 (Figure 12). It occupies approximately 153 acres in the central and south-central portions of section 5 and a small area in the northwest quarter of section 8 (T159N, R103W) in Williams County (Figure 19). The lake normally contains only a foot or two of water and generally goes dry by the end of August.

The U.S. Bureau of Mines drilled four holes through the lake bottom in the early 1950s (Binyon, 1952). The holes ranged in depth from 12 to 16 feet and apparently did not penetrate the base of the lacustrine sediments (Figure 20). A permanent crystal salt bed, ranging in thickness from 8 to 11 feet, was encountered within 6 inches of the surface. In the deepest hole (hole no. 1), an additional 4 feet of salt was present beneath the initial salt layer. Until the total thickness of lacustrine sediments is determined at this site, any estimate of salt reserves beneath this lake should be regarded as a minimum value.

Binyon (1952) estimated there are 1.2 million short tons of Glauber salt available beneath Stink Lake, based upon an area of 87 acres, and a 10.5-foot-thick permanent bed. Binyon based his calculations on only sixty percent of the total area of the lake. As is true of all the deposits evaluated by the Bureau of Mines, the percentage of Glauber salt in an individual layer (ie., crust, mud, permanent salt bed, etc.) was determined for this site by averaging the chemical concentrations of site-specific samples as determined by laboratory analysis. If the two upper crystal beds extend throughout Stink Lake, the sodium sulfate reserves at this site should be closer to 2.2 million short tons (Table 3).

Horseshoe Lake

Horseshoe Lake is a U-shaped lake that occupies approximately 109 acres in the central and southern portions of section 18 (T159N, R103W) in Williams County and a small part of section 24 (T33N, R58E) in Montana (Figure 12). In recent years, the lake has not gone dry and contained an average of 1.5 feet of water on

Figure 19. Stink Lake, Williams County, commonly goes completely dry by fall. Only a few isolated pools of water remained when this photograph was taken looking northwest from the southeast corner of the lake in September, 1995.

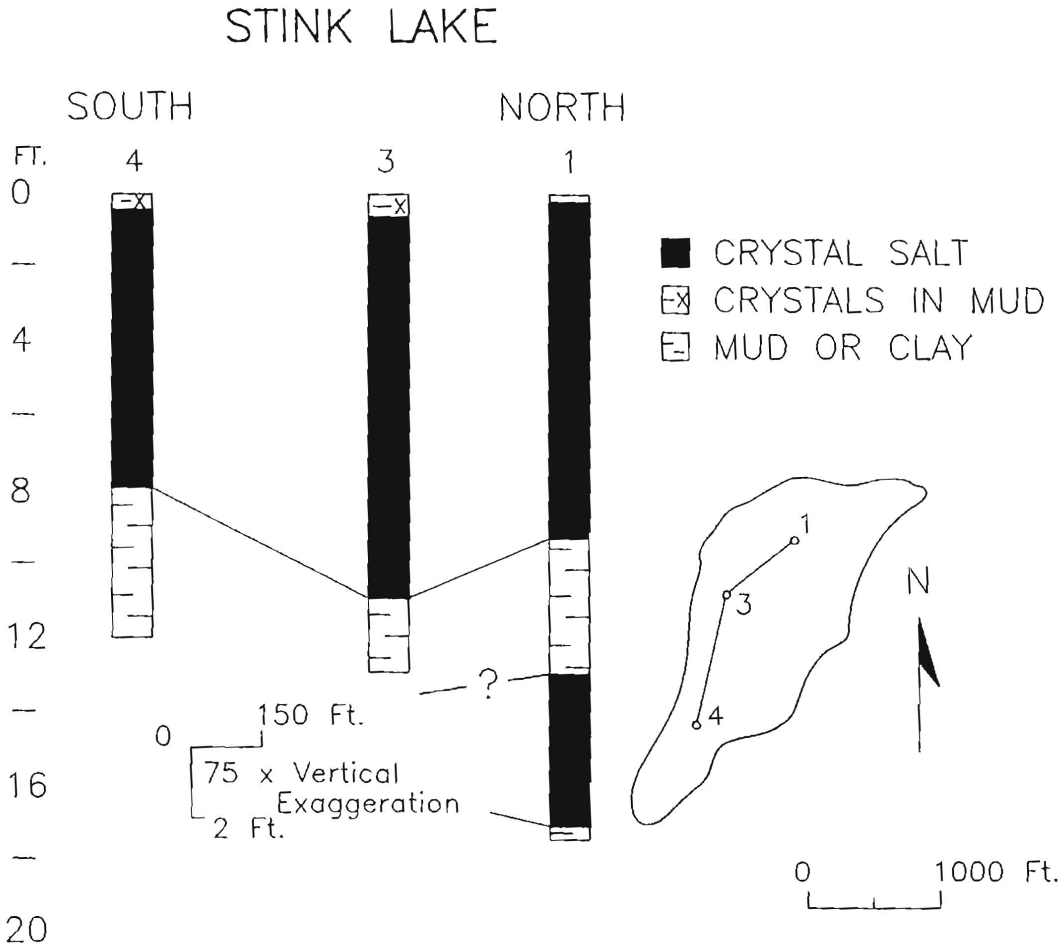

Figure 20. North-south geologic cross section of Stink Lake, Williams County. Basic data obtained from Binyon (1952).

TABLE 3

Stink Lake • 153 Acres

	Average Thickness (feet)	Cubic Feet	Tonnage Factor	Short Tons	Estimated Percent of Glauber Salt	Glauber Salt (short tons)
Mud & Crystals	0.39	2,600,000	20	130,000	11	14,000
Crystal Bed	10.46	69,700,000	22	3,200,000	66.3	2,100,000
Crystals & Mud	0.52	3,500,000	20	170,000	32.4	56,000
TOTAL						2,200,000

Table 3. Estimated amount of Glauber salt at Stink Lake. Modified from Binyon (1952).

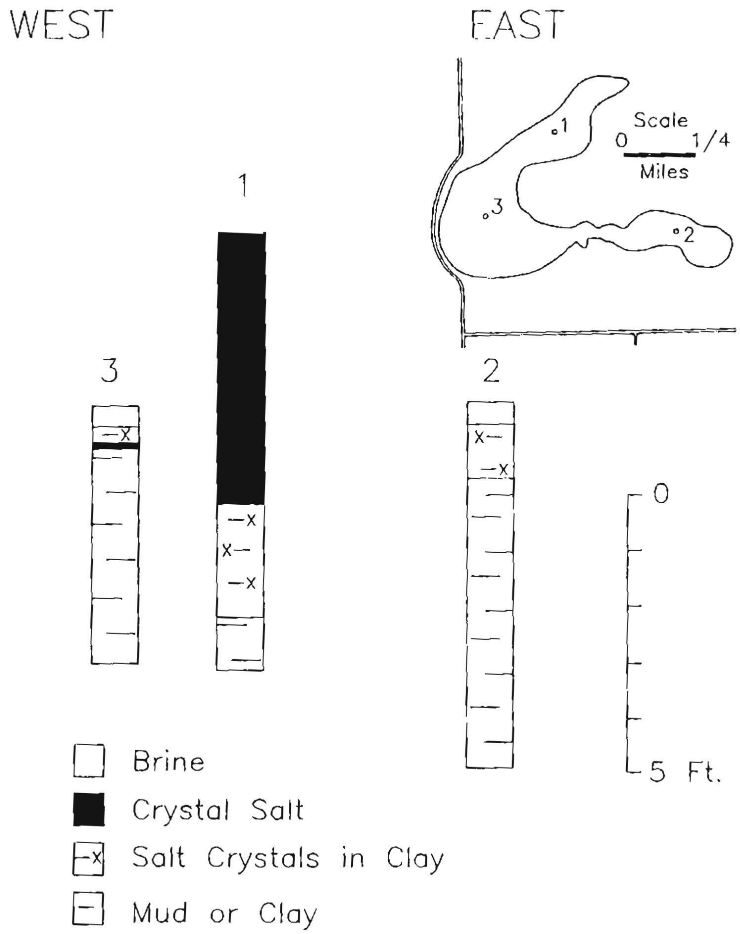

Figure 21. Drill hole lithology at Horseshoe Lake, Williams County. Basic data obtained from Binyon (1952).

TABLE 4

Horseshoe Lake • 109 Acres

	Average Thickness (feet)	Cubic Feet	Tonnage Factor	Short Tons	Estimated Percent of Glauber Salt	Glauber Salt (short tons)
Crust	0.34	1,600,000	32	50,000	8.2	4,000
Mud & Crystals	0.42	2,000,000	20	100,000	5.9	5,900
Crystals & Mud	1.37	6,500,000	20	330,000	15.9	52,000
TOTAL						62,000

Table 4. Estimated amount of Glauber salt at Horseshoe Lake. Modified from Binyon (1952).

July 17, 1996. The lake commonly is colored green to dark green due to high concentrations of algae.

The U.S. Bureau of Mines drilled three holes through the bottom of Horseshoe Lake in the early 1950s (Binyon, 1952). None of the holes penetrated the base of the lacustrine sediments and only one hole (hole no. 1) encountered a crystal salt bed (Figure 21). Additional drilling is needed to determine both the areal extent of the crystal salt bed and the total thickness and character of lacustrine sediments beneath this lake.

Horseshoe Lake is unique in that it contains the highest concentrations of bicarbonate (37,700 mg/l) and alkalinity (59,400 mg/l of calcium carbonate) of any of 40 or so surrounding lakes that have been sampled and analyzed by Reiten (1991) and Donovan (1992) (Appendix B). Bicarbonate concentrations in the five other lakes sampled during the fall of 1995 ranged from 1,100 to 2,600 mg/l. Conversely, Horseshoe Lake contained the lowest concentrations of sulfate (44,500 mg/l), half the concentration of many of the other lakes.

Binyon (1952) estimated that the Horseshoe Lake basin contains approximately 87,000 short tons of Glauber salt. This estimate was based upon an average thickness of 1.4 feet of crystal salt over an area of 154 acres. Binyon's estimate likely is too high due to an over-estimate of the size of this basin. Recalculating the estimate based on an area of 109 acres results in an estimated resource of 62,000 short tons of Glauber salt (Table 4).

Stady E

Stady E occupies approximately 130 acres in the southern portion of section 5 and the northern portion of section 8 (T160N, R99W) in Divide County (Figure 12). The lake is situated 5 miles east of U.S. Highway 85 and 8 miles north of Alamo. Stady E is approximately 20 miles east of the lakes in the Grenora group but is included in this section.

The U.S. Bureau of Mines augered four holes on this lake, ranging in depth from 7 to 21 feet, in the fall of 1949 (Binyon, 1952). The permanent crystal salt bed ranged in thickness from 1 to 18 feet and demonstrates how variable the crystal bed can be over a relatively small distance (Figure 22). The base of the lacustrine sediments does not appear to have been penetrated at this site. However, it is likely that there was a depression along the eastern portion of the lake immediately following deglaciation that was caused by either a glacier overriding a channel or the melting of an ice block.

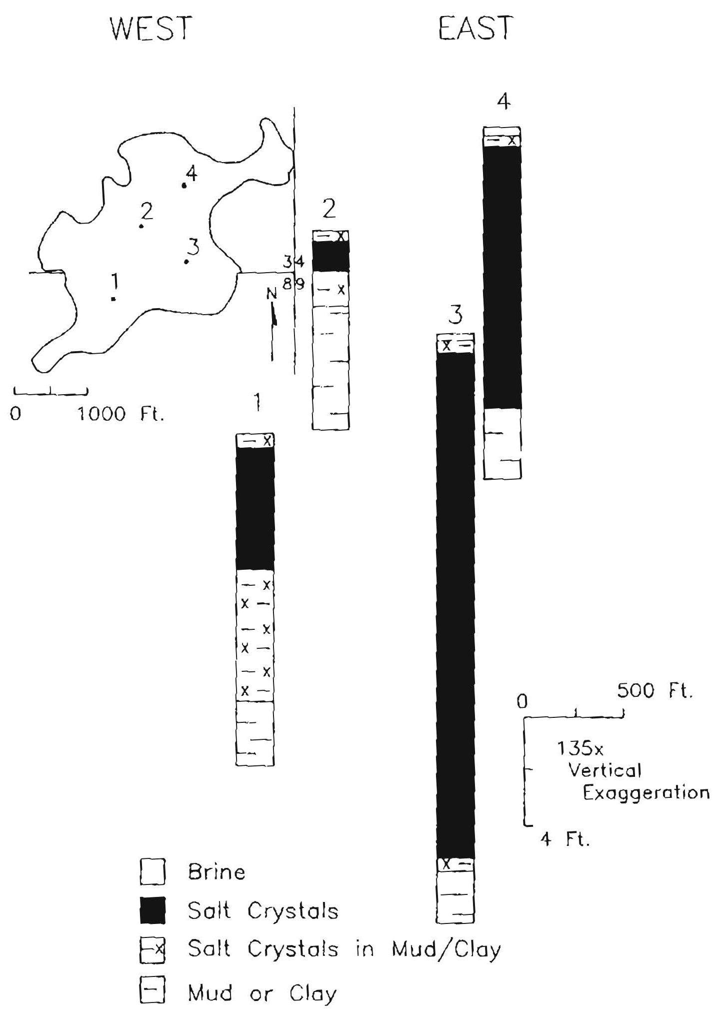

Figure 22. Drill hole lithology at Stady E, Divide County. Basic data obtained from Binyon (1952).

TABLE 5 Stady E • 132 Acres						
	Average Thickness (feet)	Cubic Feet	Tonnage Factor	Short Tons	Estimated Percent of Glauber Salt	Glauber Salt (short tons)
Crust	0.10	576,000	32	18,000	14.8	2,700
Mud & Crystals	0.44	2,520,000	20	126,000	17.7	23,000
Crystals Bed	9.66	55,660,000	22	2,530,000	70.1	1,770,000
Mud & Crystals (Below)	1.59	9,160,000	20	458,000	10.4	48,000
TOTAL						1,800,000

Table 5. Estimated amount of Glauber salt at Stady E. Modified from Binyon (1952).

Additional drilling is needed at this site to adequately determine the thickness of the lacustrine sediments and the salt resource.

Binyon estimated there are approximately 1.8 million short tons of Glauber salt in the Stady E deposit (Table 5). This estimate was based primarily on an average salt bed thickness of 9.7 feet, which is 1.5 feet more than the actual average thickness from the four holes. Binyon likely weighted the average based on an assumption that hole no. 3 was not located in the deepest part of the depression or that this feature extended for some distance either side of this hole. Additional drilling is needed to further refine the estimated reserves of Glauber salt at this site but will likely not substantially change this estimate.

Alkabo Group

There are six lakes (Miller, North, Westby A, Westby B, Westby C, and McCone) included within the Alkabo Group in Divide County (Figure 23). At least two well-documented holes have been drilled at each of these lakes.

Miller Lake

Miller Lake occupies approximately 600 acres in portions of sections 19-21, 29, and 30 (T162N, R102W) in Divide County (Figure 23). The lake is situated within a northeast-southwest trending depression draped by collapsed fluvial sediments. East of the lake is a series of glacial thrust ridges. In general, the lake commonly contains one to three feet of water throughout the year. The lake was only a few inches deep in the fall of 1934 when the FERA project was undertaken. On July 16, 1996 the lake contained between 1 and 1.5 feet of brine (Figure 24).

A total of 408 holes were augered in a 300-acre area of Miller Lake under the FERA project. This project determined that there is a 90-acre, north-south trending depression within which the lacustrine sediments reach a maximum thickness of 50 feet (Figure 25). This depression is similar in character to the lacustrine-filled depression in Grenora #2. Based upon the FERA drilling project, Lavine (1935) estimated 5 million short tons of Glauber salt are present in the lacustrine sediments beneath this lake. Lavine (1935a) noted that "the mineral bed of Miller Lake is much cleaner than any other North Dakota deposit."

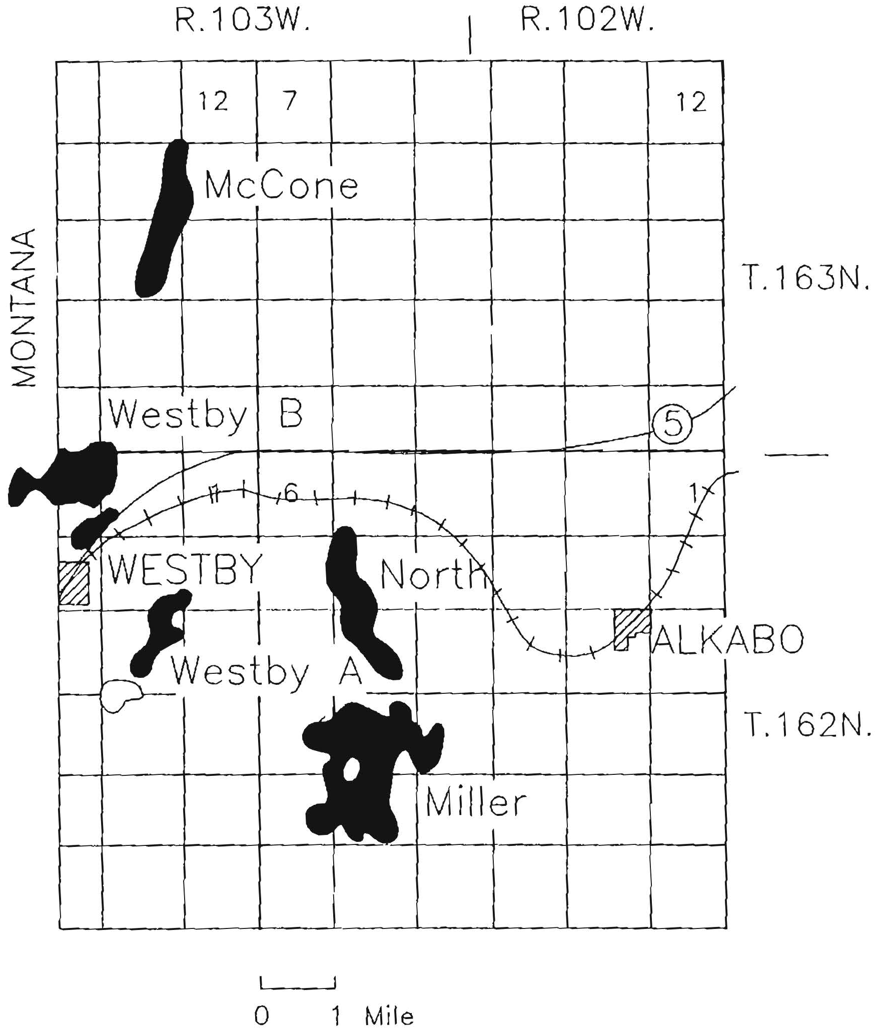

Figure 23. Distribution of the major sodium sulfate deposits in the Alkabo group, Divide County.

Binyon (1952) did not do any drilling at Miller Lake and did not have any detailed information about the lake's stratigraphy available to him. Binyon reduced the estimated salt reserves at this site to 2.75 million short tons based upon the assumption that the permanent crystal salt bed only contained 57% Glauber salt.

The North Dakota Geological Survey drilled 5 holes on Miller Lake during January, February, and March, 1996 (Appendix A). The lacustrine sediments in these holes ranged in thickness from 15 to 49 feet (Figure 26). The thickest lacustrine section (hole no. 1) matched well with Lavine's (1935) lacustrine isopach map. At this locality, there were eleven sodium sulfate crystal beds or layers with a combined total of 14 feet of crystal. Most of the beds are approximately one foot thick with the thickest being 5 feet. The sulfate layers are bounded by lacustrine clays which also contain thin layers or random crystals of sodium sulfate. In addition, individual selenite crystals are present throughout portions of the core. The lacustrine clays contain scattered plant material (generally rootlets) and are generally finely laminated, containing thin, darkly colored organic-rich layers and layers of green algae (Figure 27). Occasionally bioturbated zones were noted in the core (Figure 27). Cumulative crystal salt totals of 10 and 11 feet were present in hole nos. 3 and 5. In the latter hole, the drilling had to be discontinued after several failed attempts to penetrate an extremely well-indurated layer of Glauber salt. Although hole no. 1 matched well with Lavine's isopach map, the other three holes did not. These holes contain 12 to 27 feet of salt-bearing sediments, yet plot within Lavine's 2-foot contour (Figure 25). Therefore, although Lavine appears to have accurately depicted the

Figure 24. Miller Lake, Divide County, commonly contains a couple feet of water throughout the year. Photograph taken looking east from the western edge of the lake during the summer of 1996.

area of thickest lacustrine sediments, the salt-bearing sediments outside of this depression are much thicker than he has suggested. The limited drilling done by the Survey suggests that the thickest accumulations of lacustrine sediments occur along the northeast and southwest portions of the lake (Figure 26).

Gas (hydrogen sulfide and methane) was encountered in the lacustrine clays of hole nos. 1 and 2. The highest concentrations were observed immediately below the base of the crystal salt beds, at depths of 20 feet or more below the surface. Gas bubbled continuously in hole no. 1 from a depth of 24 feet on, at times with sufficient vigor to splatter mud out of the borehole. Hole no. 2 had to be discontinued before the base of the lacustrine sediments was reached due to the gas (Figure 8).

On July 16, 1996 the lake contained between 1 and 1.5 feet of brine. The entire lake bottom was covered with 4 to 6 inches of Glauber salt crystals. The base of this layer consisted of one to two inches of very indurated crystals which may have formed the previous year. This layer was overlain by 3 to 4 inches of loose crystals which likely had formed in recent weeks. This upper layer readily went into solution after a one-to two-inch rain occurred in the area on July 17. This rainfall event also created a two- to three-inch layer of relatively fresh water which floated on the surface of the brine. This layer was quite evident due to the contrasting rates of speed and direction of floating bodies of *Artemia salina*. On July 16 another interesting phenomenon was visible due to the crystal clear nature of the water. Numerous gas bubbles, at the approximate rate

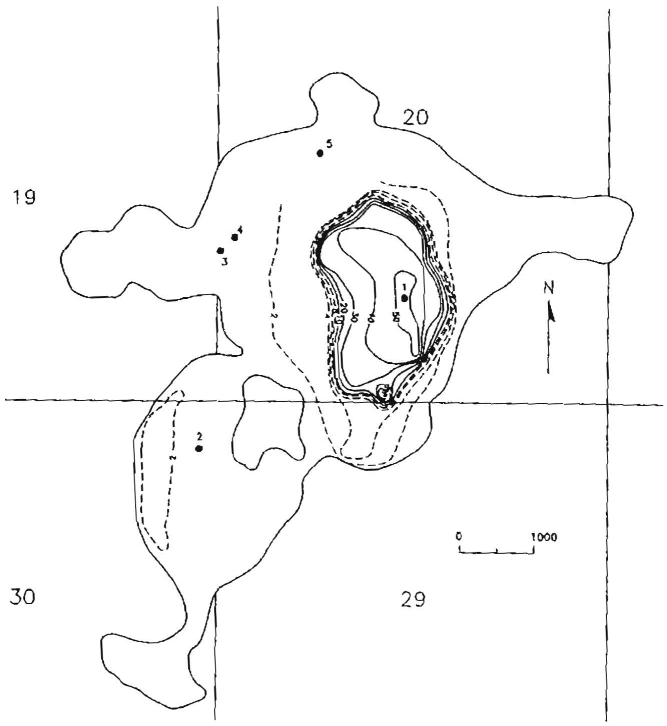

Figure 25. Isopach map of crystal salt and salt-bearing muds and clays at Miller Lake, Divide County (from Lavine, 1935). The five holes depicted were drilled by the NDGS in 1996.

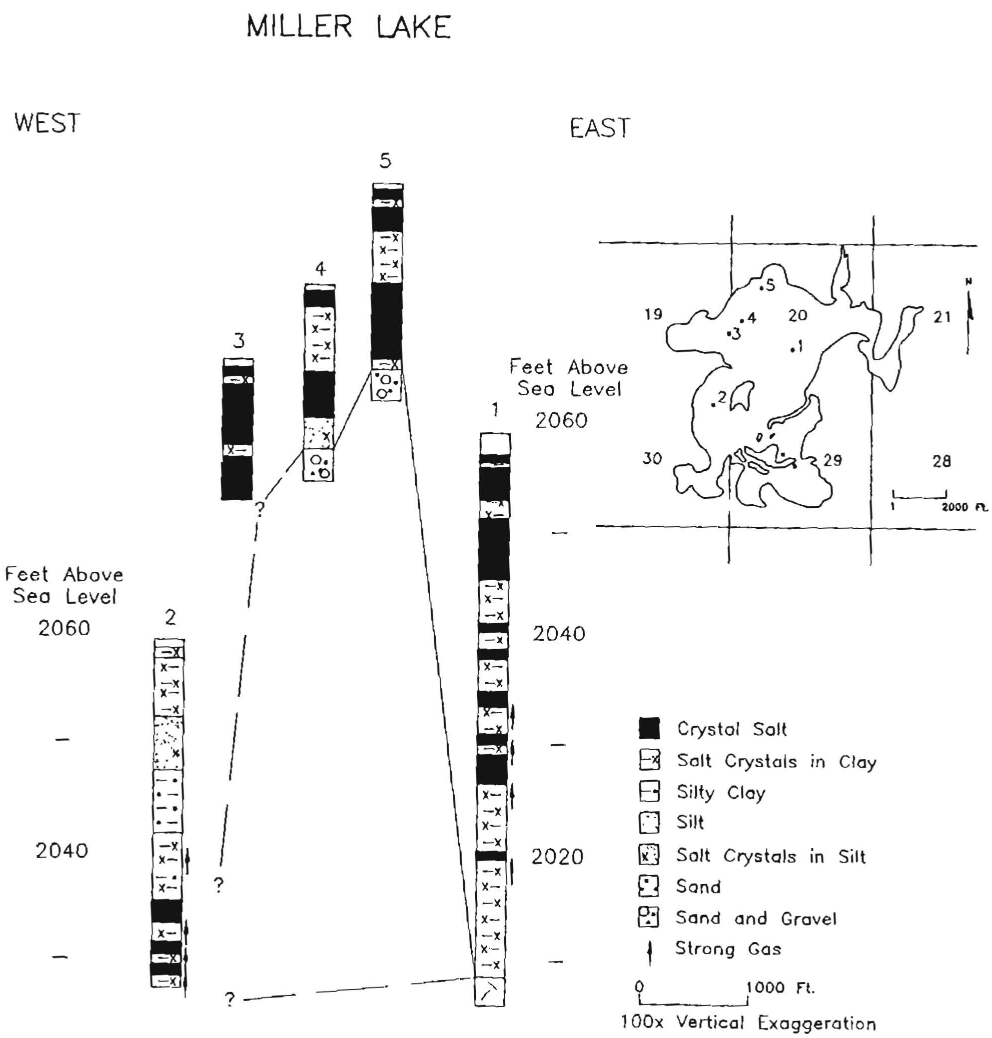

Figure 26. Geologic fence diagram of the lacustrine sediments at Miller Lake, Divide County.

of one every few seconds, emanated from numerous pipes or vents that extended down through the layers of slush and crystal salt and exposed the underlying black, organic mud (Figure 28). The vents were generally spaced approximately 10 feet apart but in some areas there was one every foot or two. It was also evident that some of the least active vents had been crystallized over. *Artemia salina* were found to be extremely abundant throughout the lake and appeared to congregate along these vents (Figure 29). It was noted that the Glauber salt at Miller Lake, as with many of the brine lakes in this study, often takes on a reddish hue due to the high concentration of the red-colored brine shrimp that are incorporated into the intermittent salt layers. *Artemia salina* are reportedly being harvested in parts of Saskatchewan for fish food. The Chaplin Brine Shrimp Company harvested approximately

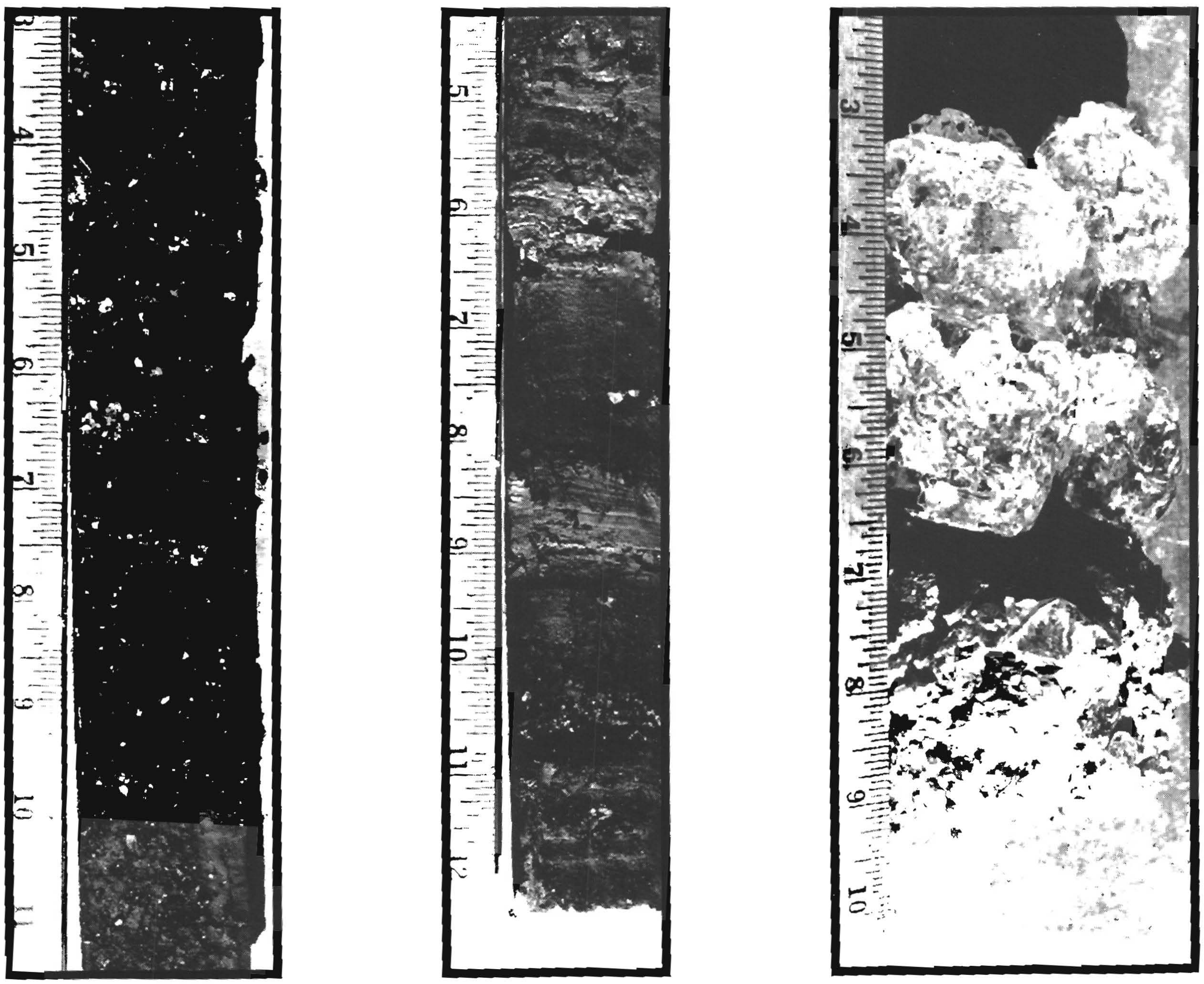

Figure 27. Selected (1¾ and 2½ inch) sediment cores from Miller Lake, Divide County. *Left to right:* a) Numerous small mirabilite crystals in an organic-rich clay from a depth of 16.2 to 16.9 feet in hole no. 2; b) laminated, possibly varved, silt and clay with scattered mirabilite crystals from a depth of 19.4 to 20 feet in hole no. 2; and c) mirabilite crystals and mud from a depth of 22 to 22.8 feet in hole no. 1.

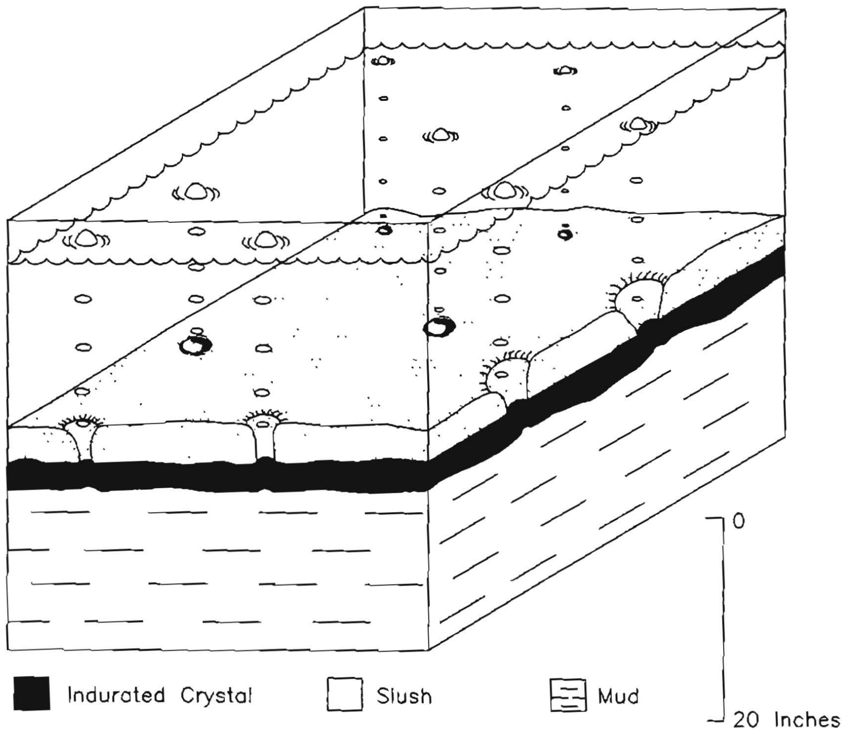

Figure 28. Diagram of gas bubbling to the surface at Miller Lake, Divide County.

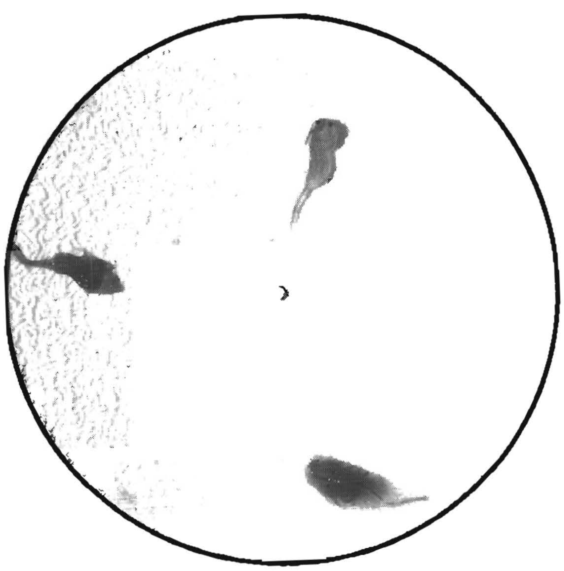

Figure 29. Four specimens (two clustered at the bottom) of *Artemia salina* from Miller Lake, Divide County. Depicted at twice their normal size (2X).

100,000 lbs. of brine shrimp from Chaplin Lake, Saskatchewan in the 1970s.

Binyon (1952) speculated that Lavine's (1935) estimate of 5 million short tons of Glauber salt for this lake was too high and revised the estimate to 2.75 million short tons based on his assumption that the percentage of Glauber salt in the lacustrine sediments at this lake is lower than the value Lavine used. Based on the five NDGS holes, an estimated 13 million short tons of Glauber salt is present at Miller Lake. This estimate was obtained by taking an average of one foot of brine, 0.6 feet of intermittent crystals, 11.8 feet of permanent crystal salt, and 15.4 feet of salt-bearing mud over a 600 acre area (Table 6).

North Lake

North Lake is located in portions of sections 5, 7, 8, and 17 (T162N, R102W) (Figure 23). The lake is oriented along a northwest-southeast axis and is bounded on the east by hummocky topography and is two miles west of a north-south trending glacial thrust ridge. North Lake contained a foot of water during the summers of 1995 and 1996 before going dry late in the fall of the year (Figure 30).

The FERA group drilled only 50 holes at this locality because the project was winding down and very little salt-bearing sediments were encountered. A series of closely spaced holes was drilled along a north-south line through the middle of the Lake which according to Skene (1934a), contained "no salt whatsoever". Additional drilling did determine that a 50-foot-wide ring of salt existed around the exterior of the lake. This ring of salt was very broken but averaged 8 feet in depth and reportedly reached a maximum depth of 80 feet (Lavine, 1935; Lavine and Feinstein, 1935).

Near the center of section 17 (T162N, R102W), the Sodium Corporation of America constructed an earthen dam which transformed the southeastern limb of the lake into a settling pond for sodium sulfate production. The Geological Survey drilled eight holes along an east-west line in the reservoir and seven holes along an east-west line in North Lake (Appendix A). Lacustrine sediments in the reservoir ranged in thickness from 2 to 9 feet and averaged 6 feet (Figure 31). A crystal salt bed is present at or very near the surface in the 36-acre reservoir ranging in thickness from 1.6 to 6.5 feet with an average thickness of 4.5 feet. Salt-bearing mud averaged 1.4 feet thick across the reservoir area. Glauber salt in the reservoir was estimated at

TABLE 6

Miller Lake • 600 Acres

	Average Thickness (feet)	Cubic Feet	Tonnage Factor	Short Tons	Estimated Percent of Glauber Salt	Glauber Salt (short tons)
Brine	1.00	26,000,000	32	820,000	9	74,000
Intermittent Crystals	0.60	16,000,000	22	710,000	70	500,000
Crystal Bed	11.80	308,000,000	22	14,000,000	54	7,600,000
Mud & Crystals	15.40	402,000,000	20	20,000,000	24	4,800,000
TOTAL						13,000,000

Table 6. Estimated amount of Glauber salt at Miller Lake.

Figure 30. The dried surface of North Lake, Divide County. Photograph taken looking north across the Sodium Corporation of America's reservoir in September, 1995.

200,000 tons. Most of this crystal salt appears to have been deposited during the time that the Sodium Corporation of America operated this site. Several holes were drilled along the edge of the lake where Lavine (1935) indicated a ring of salt was present but no indication was found that a salt-filled depression rings the lake. The Survey drilling program indicated the thickest accumulation of lacustrine sediments was near the center of the lake, not the perimeter (Figure 31). The lacustrine sediments beneath North Lake were underlain by both till and outwash sand and gravel.

The Miller and North Lake site was developed by George Krem, a Chicago businessman (president of Holland America Company of Chicago), under the name Sodium Corporation of America. Work began in 1948 with construction of a dam across the southern end of North Lake. The dam created a settling pond into which water was pumped through a pipeline system from Miller Lake (Figure 32). Approximately one quarter of a mile of 30-inch pipe from the Ft Peck Dam project was used at Miller Lake. In the late summer when lake water had reached its maximum temperature, water was pumped from Miller Lake into the settling pond. In the fall the temperatures cooled and the salt precipitated and the wastewater was drained back into Miller Lake. Salt in the settling pond was scraped into a pile in January when the ground was sufficiently frozen to support the weight of vehicles.

The September and October, 1960 records of Gillferd Rust, a longtime employee of George Krem's, detail hourly readings of the air, lake, and reservoir temperatures along with Baume' gravity readings of the brine. These records demonstrate the importance of timing to the success of the operation. This was especially true with the draining of the settling pond because if it was done too late, unwanted impurities settled out into the salt.

It was anticipated that mining would continue at this locality for 40 years and plans were to establish a processing plant at Westby, Montana. Shortly thereafter, the plans changed and it was determined that the plant would be located near Alkabo, North Dakota. Initially it was projected that the project would require a permanent work force of 50 people, but because the processing plant was never built, only about a half a dozen were employed. George Krem very much wanted to build a plant at Alkabo and at one point had raised the needed investment capital but conditions would have required him to relinquish sole control over the project, something that he could not bring himself to do. Krem, an entrepreneur, had several other mineral ventures, a chemical plant in Chicago, a magnesium mine in California, and a sulfur mill in Utah (Gillferd Rust, per. comm., 1995).

Because Glauber salt is approximately half water, it is desirable to dry it prior to

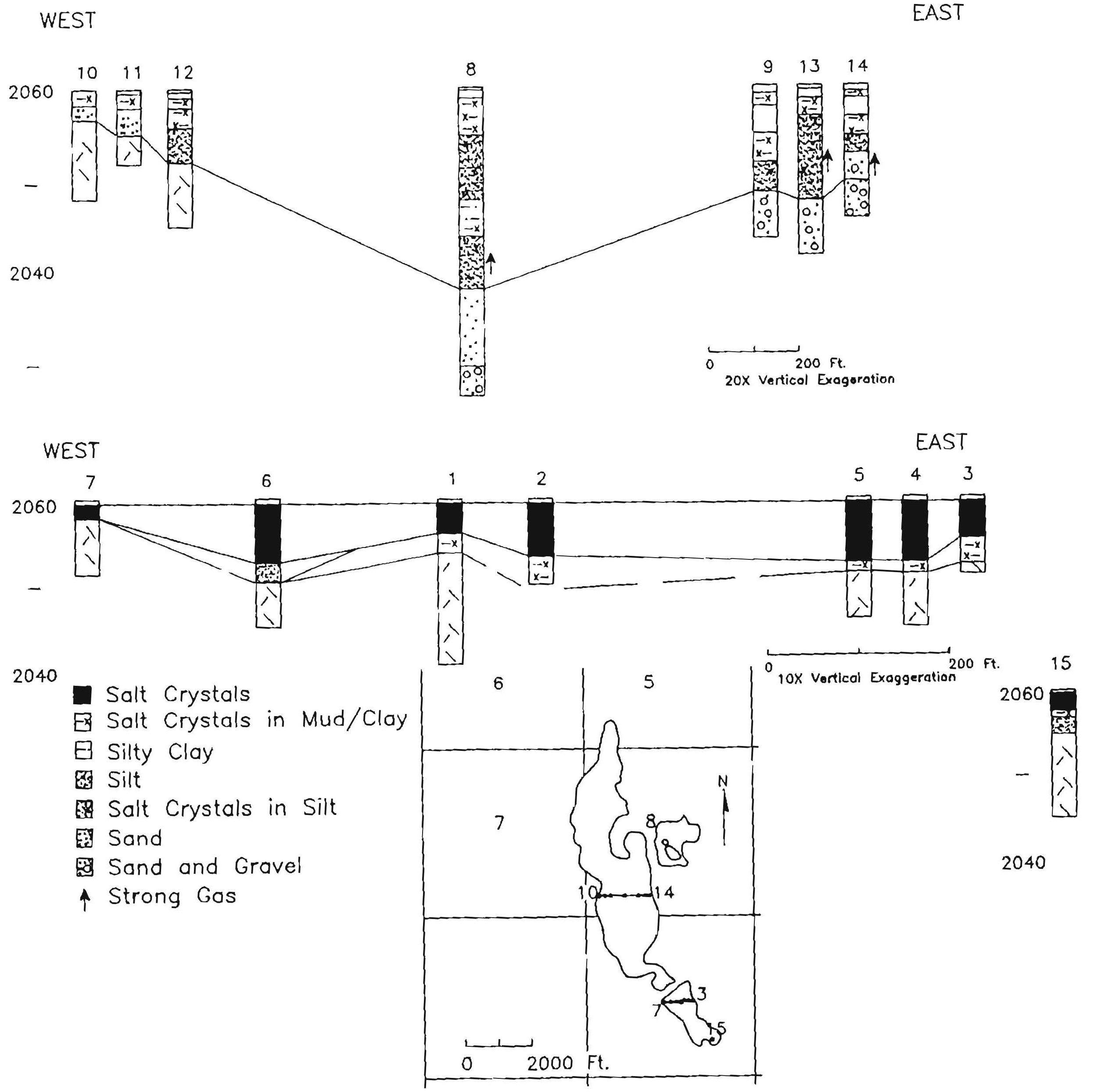

Figure 31. Geologic cross sections of North Lake, Divide County.

Figure 32. Gillferd Rust, one of the original employees of the Sodium Corporation of America. Mr. Rust stands before a diesel engine that was used to pump brine from Miller Lake, Divide County, into the company's settling pond. The photograph was taken looking south along the Miller Lake drainage channel in March, 1996.

shipping to cut costs. A dryer, fueled by coal mined south of Westby, Montana was used to dry the salt prior to shipping on the Soo line. Unfortunately, the operation was unable to remove a sufficient amount of water and the coal soot created a contamination problem for the salt. In the early 1950s, a railroad spur was built to within a mile of the site and several boxcar loads were shipped east in an attempt to interest industry in the product. In 1951, records indicate that 996 tons of Glauber salt was shipped out of state from this site (Budge, 1954). In the mid 1950s, several carloads of Glauber salt were also sent to Iowa. Unfortunately, the salt recrystallized in the boxcars and had to be blasted out with dynamite (Gillferd Rust, per. comm., 1995)

Due to lack of markets and shipping costs, the site was abandoned in 1960. For at least two years prior to its abandonment (1954-1955) the site had not operated. A stockpile of 10,000 tons of Glauber salt left at the site eventually eroded. Ten years prior to the abandonment of this site, George Krem (1950) listed high and rising freight costs along with an unfavorable tariff situation with Canada as two of the major obstacles to overcome in establishing a successful sodium sulfate processing plant.

Lavine and Feinstein (1935) estimated there are one million short tons of Glauber salt at this site. Binyon (1952) reduced this estimate to 500,000 on an assumption that they had overestimated the percentage of Glauber salt. The Survey drilling program determined lacustrine sediments range in thickness from 5 to 22 feet and average just over 10 feet in North Lake proper. The seven holes averaged 0.36 foot of intermittent crystal, 0.56 foot of permanent crystal, and 10.2 feet of salt-bearing strata. Based on these data, an estimated 1.8 million short tons of Glauber salt is present in North Lake (Table 7).

TABLE 7						
North Lake Proper • 248 Acres						
	Average Thickness (feet)	Cubic Feet	Tonnage Factor	Short Tons	Estimated Percent of Glauber Salt	Glauber Salt (short tons)
Intermittent Crystals	0.30	3,900,000	22	180,000	70	120,000
Crystal Bed	0.56	6,100,000	22	280,000	54	150,000
Mud & Crystals	10.20	110,000,000	20	5,500,000	24	1,300,000
North Lake Reservoir • 36 Acres						
Crystal Bed	4.50	7,000,000	22	320,000	54	170,000
Mud & Crystals	1.40	2,200,000	20	110,000	24	26,000
TOTAL						1,800,000

Table 7. Estimated amount of Glauber salt at North Lake.

Westby A

Westby A or Freund Lake is primarily located in section 14 although it extends slightly into sections 11 and 23 (T162N, R103W) (Figure 23). It occupies a small closed basin that trends north-southeast and may have at one time been a channel prior to its being overridden by a glacier. Westby A contained approximately one foot of water throughout most of the summer of 1995 before going completely dry in the fall. On July 16, 1996 the lake contained less than 6 inches of water and had a thin layer (< 2 inches) of salt.

This lake was investigated by the FERA project but detailed findings were not reported (Lavine, 1935). Lavine did note that the north end of the lake contained the largest amount of salt estimating the strata contained 70% crystals to a depth of 20 feet. In contrast, Binyon (1952) augered three holes across the lake and reported finding no permanent crystal salt along the north end of the lake but 6 to 9 feet of salt in the central and southern portions.

The North Dakota Geological Survey cored three holes in this lake in January and February, 1996 (Appendix A). A thin (2-inch) intermittent bed of salt crystals was present at the surface, but no permanent bed of crystal salt was encountered during the drilling program (Figure 33). The intermittent bed was underlain by 11 to 14 feet of salt-bearing silt and clay. The upper part of the lacustrine deposits in hole no. 1 are dominated by faintly bedded silt. The silt is underlain by 6 feet of organic-rich silt and clay (Figure 34). Several thin (one to two inch thick) beds of sodium sulfate were encountered in the clay within this interval. These salt layers were occasionally green due to algae incorporated into the salt when it precipitated from the lake. In addition, several large (greater than one inch) selenite crystals are present near the base of the laminated (varved) lacustrine sediments (Figure 35). The lamina were distorted by pressure exerted by the growing selenite crystals. A piece of wood (identified as poplar by Catherine Yansa, University of Wisconsin) was encountered at the base of the lacustrine units in hole no. 1. The lacustrine deposits are underlain by 5 feet of sand which is underlain by at least 10 feet of sand and gravel. The upper sand grades laterally into silt.

The permanent crystal bed previously identified by Ed Tullis (Binyon, 1952) was not encountered during the Survey drilling program, suggesting that these beds may be fairly localized (Figure 33). Additional drilling adjacent to Bureau of Mines hole nos. 2 and 3 is needed to answer this question.

Lavine (1935) did not give an estimate but Binyon (1952) estimated 903,500 short tons of Glauber salt is present in Westby A. Based on an average of 0.15 feet of intermittent crystal, 3 feet of permanent crystal, and 8.1 feet of salt-bearing sediments, an estimated 900,000 short tons of Glauber salt occur in an area of 118 acres at this site (Table 8). This amount compares favorably with Binyon's estimate. Although these estimates are close, Binyon based his determination on an area exactly twice as large as that used here.

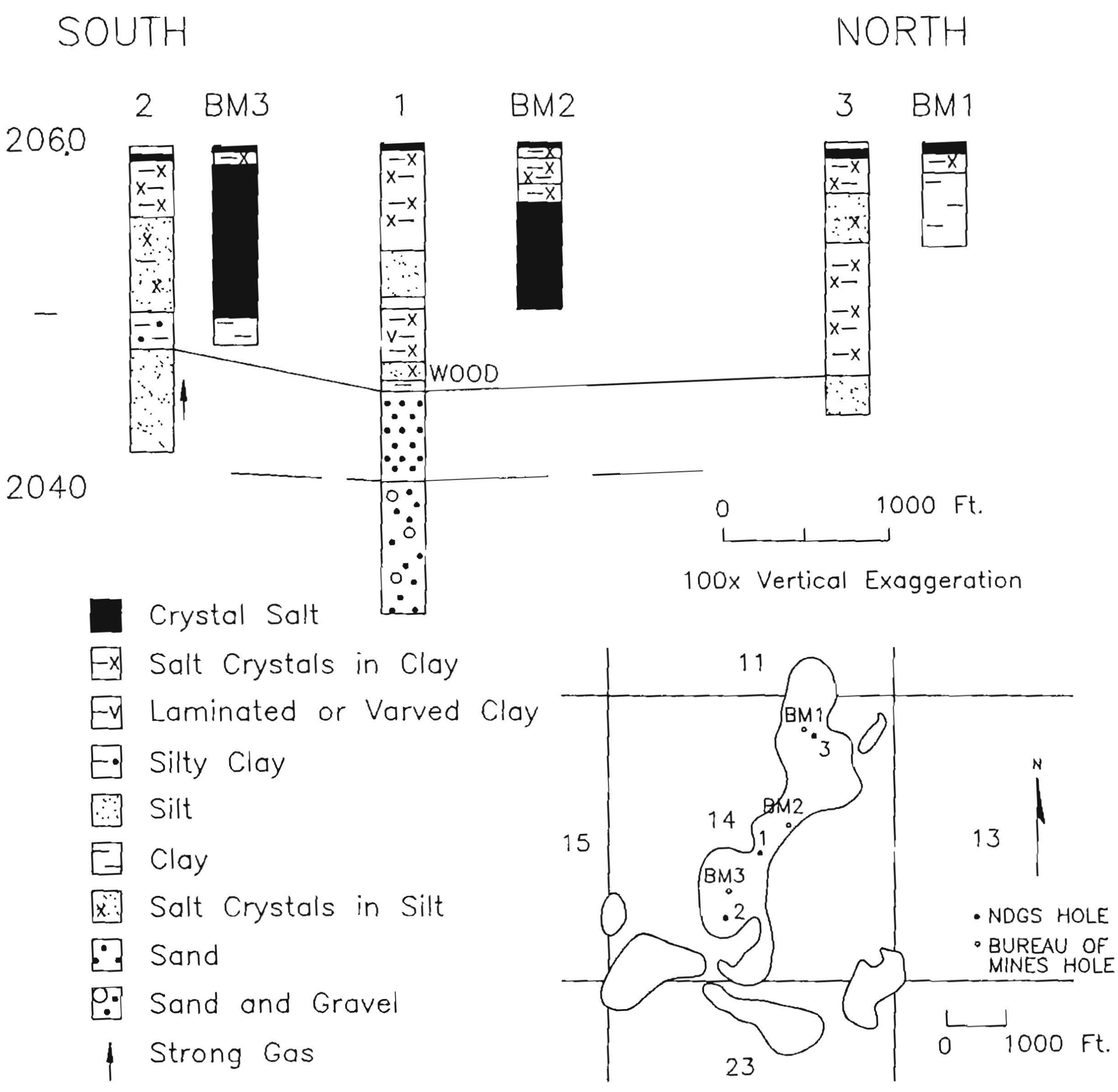

Figure 33. Geologic cross section across Westby A, Divide County. Data for BM holes was obtained from Binyon (1952).

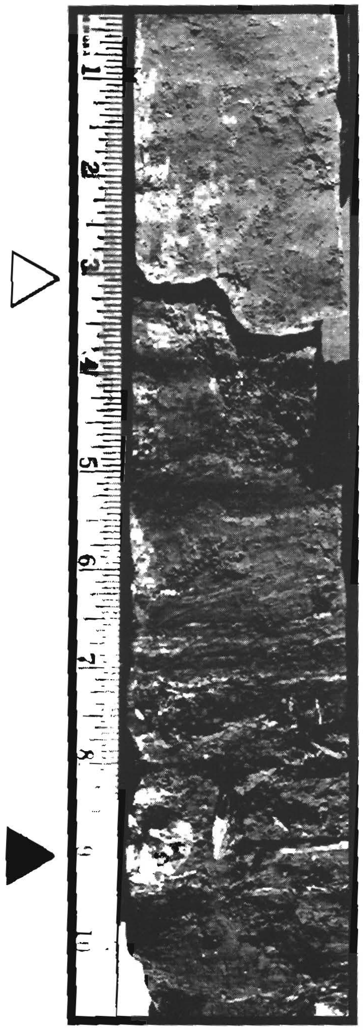

Figure 34 Laminated, possibly varved, silts and clays from sediment core at Westby A, Divide County. The upper portion of the core appears to have been bioturbated (open arrow) The growth of selenite crystals has disturbed the laminae near the base of the core (solid arrow). The selected interval is from a depth of 11 to 11.9 feet in hole no. 1.

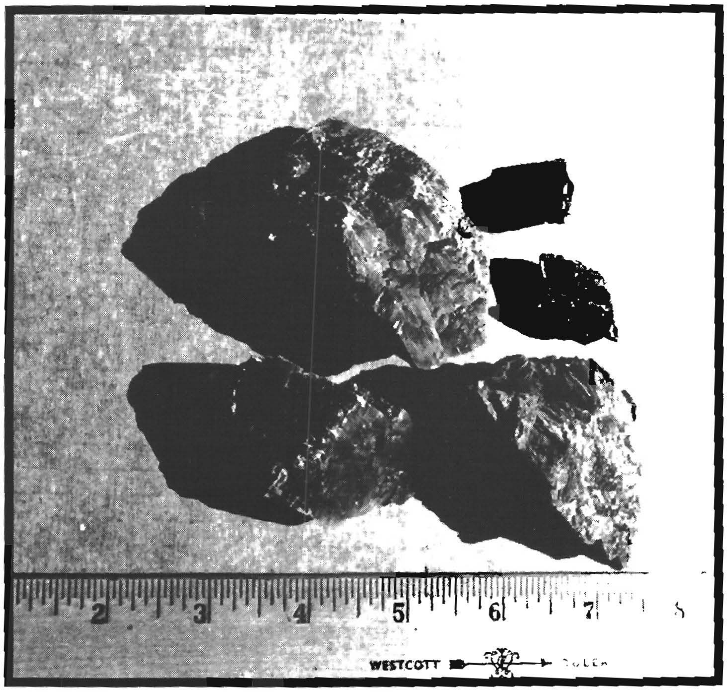

Figure 35 Selenite crystals (calcium sulfate) from sediment cores at Westby A, Divide County Crystals range in size from and eighth of an inch to over three inches and were obtained from a depth of 13 to 14 feet (hole no 1).

TABLE 8

Westby A • 118 Acres

	Average Thickness (feet)	Cubic Feet	Tonnage Factor	Short Tons	Estimated Percent of Glauber Salt	Glauber Salt (short tons)
Intermittent Crystals	0.15	770,000	22	35,000	70	24,000
Crystal Bed	3.00	15,000,000	22	700,000	54	380,000
Mud & Crystals	8.10	42,000,000	20	2,100,000	24	500,000
TOTAL						900,000

Table 8 Estimated amount of Glauber salt at Westby A

Westby B (Round Lake)

Westby B (Round Lake) occupies approximately 403 acres in the north half of section 3 (T162N, R103W) in North Dakota and the east half of section 12 (T36N, R58E) in Montana (Figure 23). The lake is located one mile north of the town of Westby, Montana. Westby B generally contains a foot of water during the spring and summer, going dry by early fall. This lake was completely dry in September, 1995 and contained less than a foot on July 17, 1996.

In the early 1950s, the U.S. Bureau of Mines drilled six holes in Westby B, four in the North Dakota portion of the lake and two on the Montana side. The holes ranged in depth from 7 to 19 feet. None penetrated the base of the lacustrine sediments, the three deepest holes were halted in crystal salt (Figure 36). The crystal bed was generally within a foot of the surface and was at least 20 feet thick. Additional drilling is needed to determine the thickness of the upper crystal salt bed as well as the total thickness and character of the lacustrine sediments beneath this lake.

Binyon (1952) assumed an average crust thickness of just over 1 foot and an average crystal bed thickness of 9 feet over an area of 386 acres in his Glauber salt estimate of 3.8

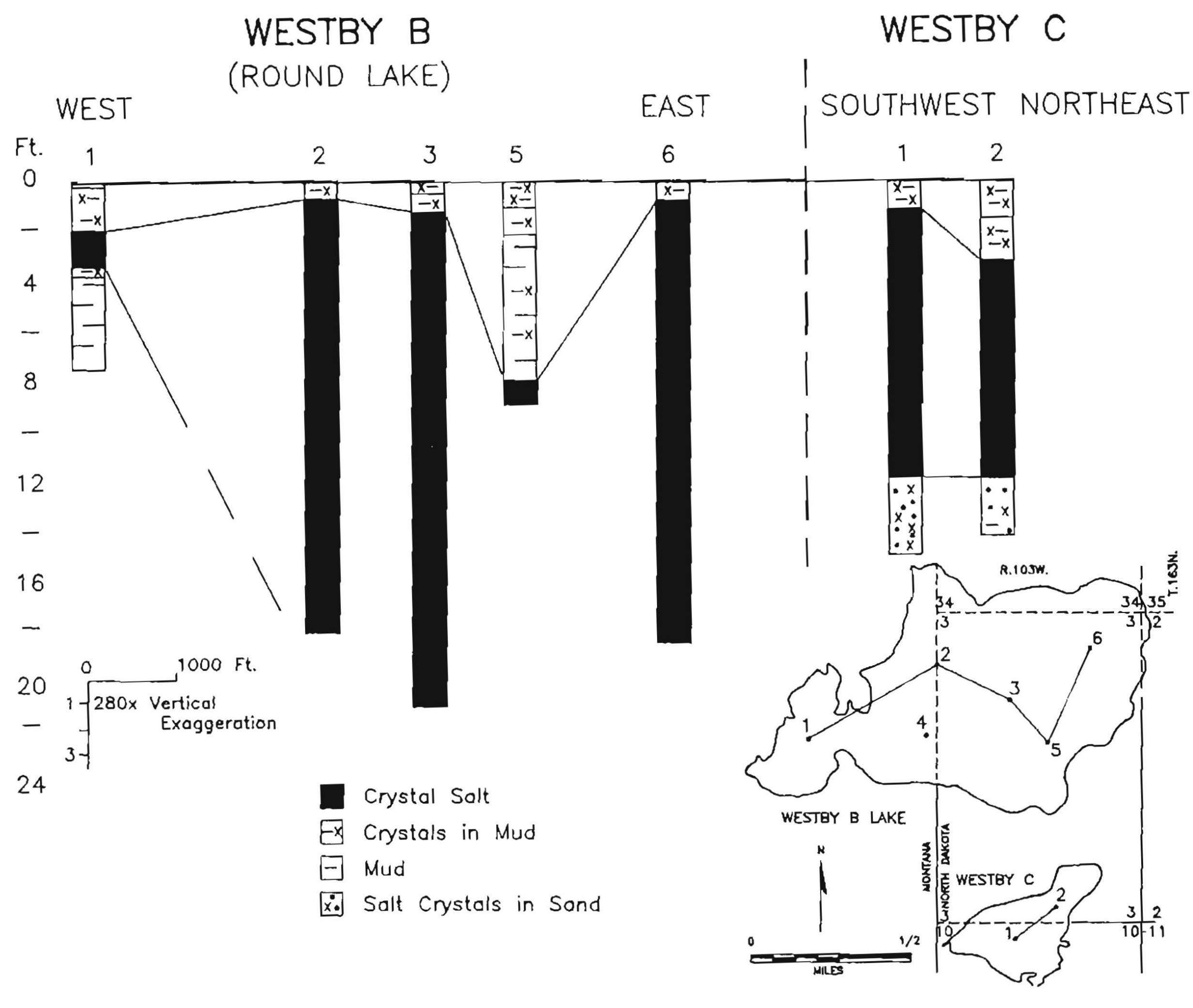

Figure 36. Geologic cross sections of Westby B and C, Divide County. Basic data from Binyon (1952).

million short tons (Table 9). Binyon determined from the chemical analysis of the crystalline bed that it contained 54% Glauber salt. This estimate should be viewed as a minimum value since the base of the crystalline salt bed was not penetrated by any of the holes.

Westby C

Westby C is a small, 58-acre lake that occupies the southern portion of section 3 and the northern part of section 10 (T162N, R103W) (Figure 23). The lake is situated half way between the town of Westby and Westby B (Round Lake). Westby C commonly contains a foot or so of water in the spring and summer and goes dry in the fall. Westby C was completely dry in September, 1995.

The U.S. Bureau of Mines drilled two holes in this lake. Both holes penetrated the base of the lacustrine sediments at 12 feet (Figure 36). A 9- to 10.5-foot-thick bed of crystal salt was encountered in both holes within three feet of the surface.

Binyon (1952) estimated that 390,000 short tons of Glauber salt are available in the lacustrine sediments beneath Westby C. He based this estimate, in part, on an average crystal salt bed thickness of 4.9 feet, half of the actual average thickness of the bed in the two holes. Since the two holes were drilled near the center of the lake, Binyon used this reduced amount to compensate for any thinning that might occur along the margin of the lake. If the bed does not thin as rapidly as Binyon assumed, the actual amount of Glauber salt at this site may be closer to 660,000 short tons (Table 10).

TABLE 9

Westby B • 386 Acres

	Average Thickness (feet)	Cubic Feet	Tonnage Factor	Short Tons	Estimated Percent of Glauber Salt	Glauber Salt (short tons)
Crust	1.16	19,000,000	20	950,000	14.4	140,000
Crystal Bed	9.08	149,000,000	22	6,750,000	54.5	3,700,00
TOTAL						3,800,000

Table 9. Estimated amount of Glauber salt at Westby B. Modified from Binyon (1952).

TABLE 10

Westby C • 57 Acres

	Average Thickness (feet)	Cubic Feet	Tonnage Factor	Short Tons	Estimated Percent of Glauber Salt	Glauber Salt (short tons)
Crust	3.85	9,600,000	20	500,000	24.2	120,000
Crystal Bed	9.80	24,000,000	22	1,100,000	49.0	540,000
TOTAL						660,000

Table 10. Estimated amount of Glauber salt at Westby C. Modified from Binyon (1952).

McCone Lake

McCone Lake occupies approximately 250 acres in the eastern halves of sections 14 and 23 (T163N, R103W) (Figure 23). The lake generally contains a foot or so of water during the spring and summer but goes dry in the fall. The lake was dry, with the exception of a few small pools of water by mid-October, 1995.

Holes were drilled at this lake under the FERA project, but no data were ever presented in the subsequent reports and the field notes for this lake are missing. Lavine and Feinstein (1935) reported a maximum thickness of 20 feet of crystal bed with an average thickness of 10 feet across the lake. The U.S. Bureau of Mines did not drill at this lake.

The North Dakota Geological Survey cored two holes in this lake in January and February, 1996 (Appendix A). A third hole was planned for the north end of the lake but permission to drill could not be obtained from the landowner. The central hole (hole no. 1) encountered 6 feet of permanent crystal salt but the southern hole did not encounter any crystal bed (Figure 37). The lacustrine sediments ranged in thickness from 10 feet in hole no. 1 to 22 feet in hole no. 2. Except for the upper two feet of hole no. 2, the sediments at this site contained no visible salt crystals.

Lavine and Feinstein (1935) estimated that 3 million short tons of Glauber salt occur at McCone Lake. Two or three additional holes are needed to more accurately determine the

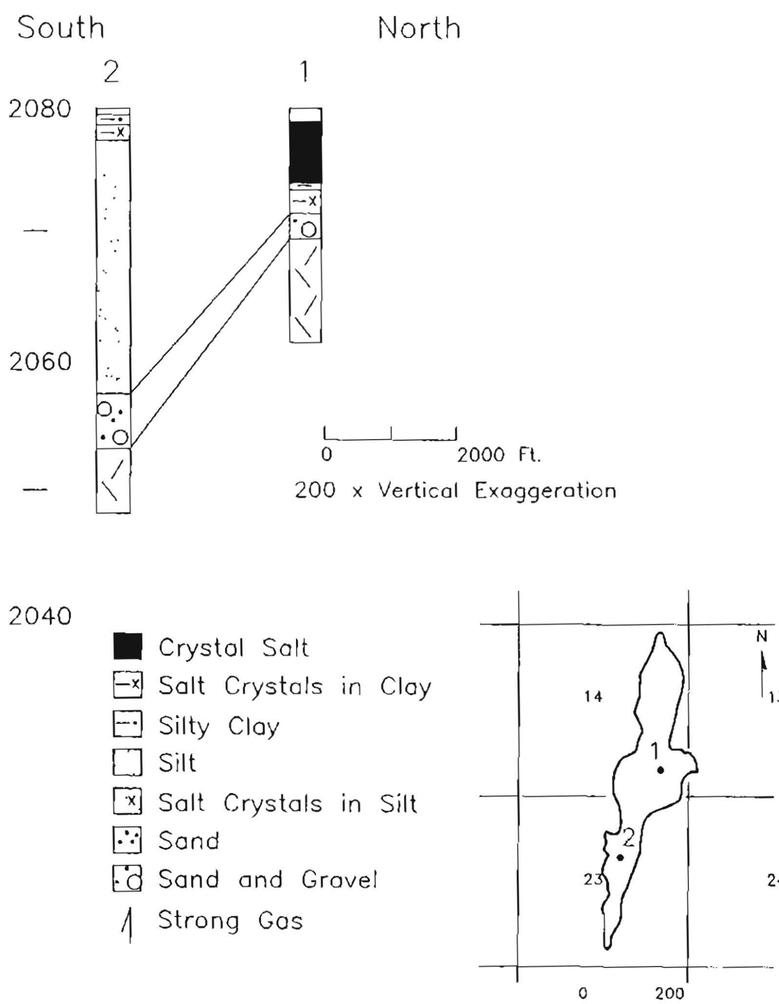

Figure 37 Geologic cross section of McCone Lake, Divide County.

character of the lacustrine sediments and the sodium sulfate reserves at this site. An estimated 750,000 short tons of Glauber salt are present within 223 acres of McCone Lake. This estimate was based on an average thicknesses of 0.14 foot of brine, 2.25 feet of permanent crystal bed, and 1.5 feet of salt-bearing mud (Table 11). This estimate is half of the 1.5 million short tons estimated by Binyon (1952). Binyon's estimate was based on the 10-foot average crystal thickness reported by Lavine and Feinstein (1935).

Geology and Geohydrology of the Stanley Area

At least four lakes in the Stanley area are underlain by crystal layers of sodium sulfate: White, Stanley A, Stanley #1, and Stanley #2 (Figure 38). Over 450 holes were hand-augered under the FERA project at these four lakes. The U.S. Bureau of Mines augered a total of 18 holes at White and Stanley A lakes.

Stanley Group

North-central Mountrail County is covered by glacial deposits that range in thickness from less than 50 feet to over 200 feet (Clayton, 1972). The cover in this area is primarily till, consisting of pebbly to sandy clay, but collapsed outwash and ice-walled lake plain sediments are also present (Figure 39). This area of Mountrail County is underlain by sediments derived during separate glacial events including the Dead Man (?), Napoleon (?), and Lostwood drifts (Clayton, 1972). The Lostwood drift is present at the surface throughout this area. All of the lakes of interest in this area (White, Stanley #1, Stanley #2, and Stanley A) are located either wholly or partly in outwash sediments. At least three buried glacial channels are present in this area (Figure 40). White Lake is situated over a 350-foot-deep northwest-southeast trending buried channel (Armstrong, 1971). A 150-to 300-foot-thick buried channel underlies portions of Stanley #1 and Stanley A lakes. The glacial deposits in this area overlie the Sentinel Butte and Bullion Creek formations (Paleocene).

TABLE 11

McCone Lake • 223 Acres

	Average Thickness (feet)	Cubic Feet	Tonnage Factor	Short Tons	Estimated Percent of Glauber Salt	Glauber Salt (short tons)
Intermittent Crystals	0.14	1,300,000	22	60,000	70	42,000
Crystal Bed	2.25	21,900,000	22	995,000	54	537,000
Mud & Crystals	1.50	14,600,000	20	730,000	24	175,000
TOTAL						750,000

Table 11. Estimated amount of Glauber salt at McCone Lake.

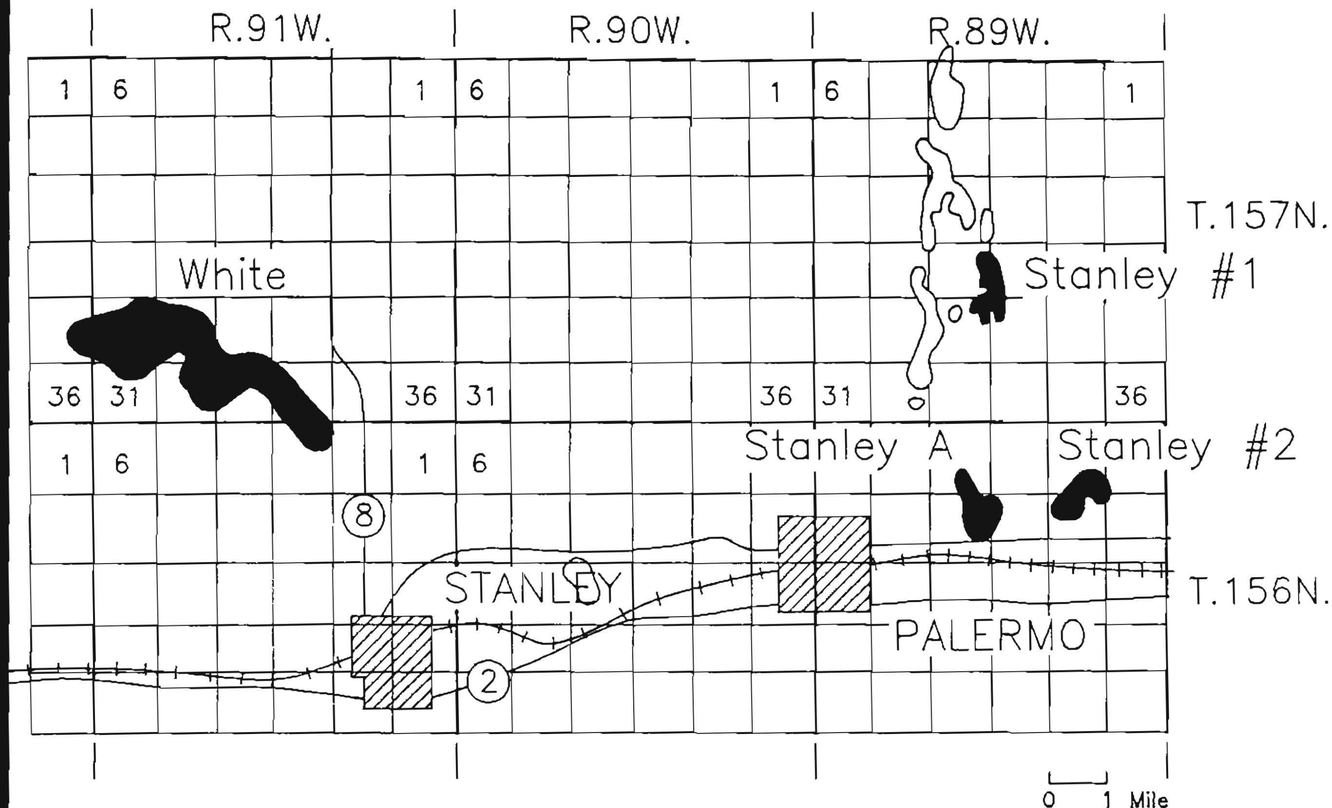

Figure 38. Distribution of the major sodium sulfate deposits in the Stanley group, Mountrail County.

The buried channels previously mentioned are part of the Shell Creek Aquifer system, an important aquifer in this area. The buried channel beneath White Lake is referred to as the White Lake Branch of the Shell Creek Aquifer (Figure 40). The White Lake Branch consists primarily of saturated till which contains 12 to 40-foot-thick sand and gravel lenses. These lenses are generally isolated. The buried channel beneath Stanley #1 and Stanley A is the Central Branch of the Shell Creek Aquifer (Figure 40). The Central Branch Aquifer also contains lenses of sand and gravel in till, but these lenses are much thicker (up to 130 feet thick) and appear to be more continuous than those in the White Lake Branch (Armstrong, 1971). Armstrong doubts that pumping rates of over 100 gpm could be maintained in the White Lake Branch for more than a few weeks. Rates of over 100 gpm are likely obtainable in the Central Branch of this aquifer. Groundwater in the White Lake Branch is generally a sodium sulfate type with TDS ranging from 1,100 to 2,300 ppm. Groundwater in the Central Branch is generally a sodium sulfate type with TDS around 1700 ppm (Armstrong, 1971).

White Lake

White Lake occupies approximately 2,650 acres in portions of sections 27-35 (T157N, R91W), sections 5 and 6 (T156N, R91W), and section 25 (T157N, R92W) (Figure 38). A field notebook from the FERA project

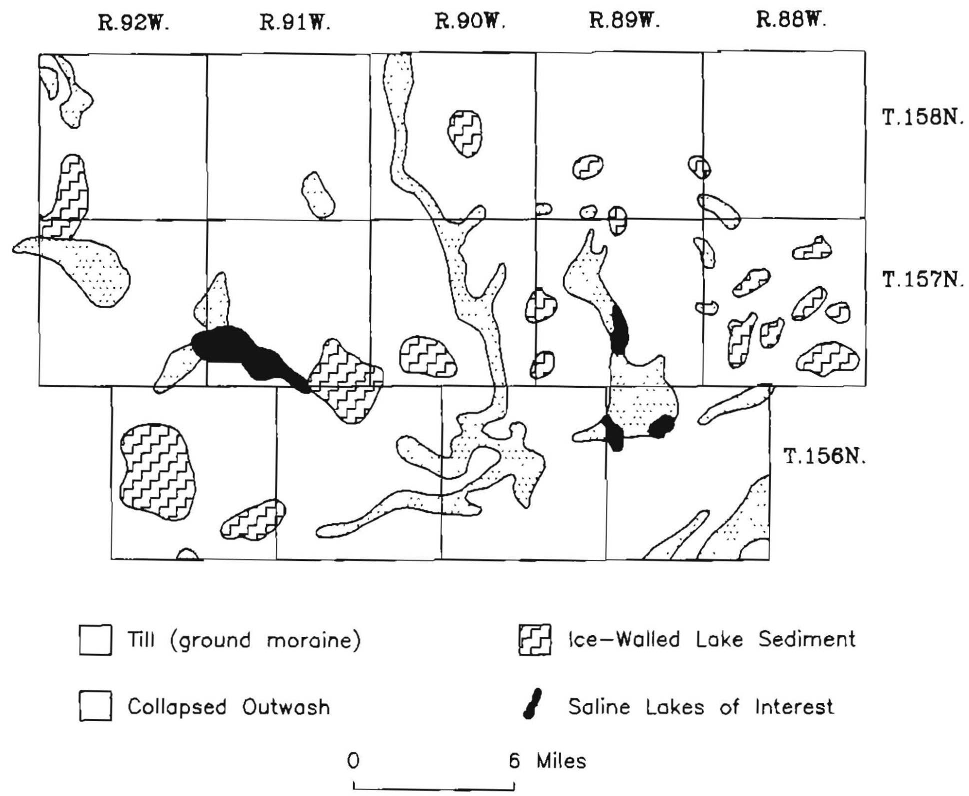

Figure 39 Geologic map of north-central Mountrail County (from Clayton et al., 1980).

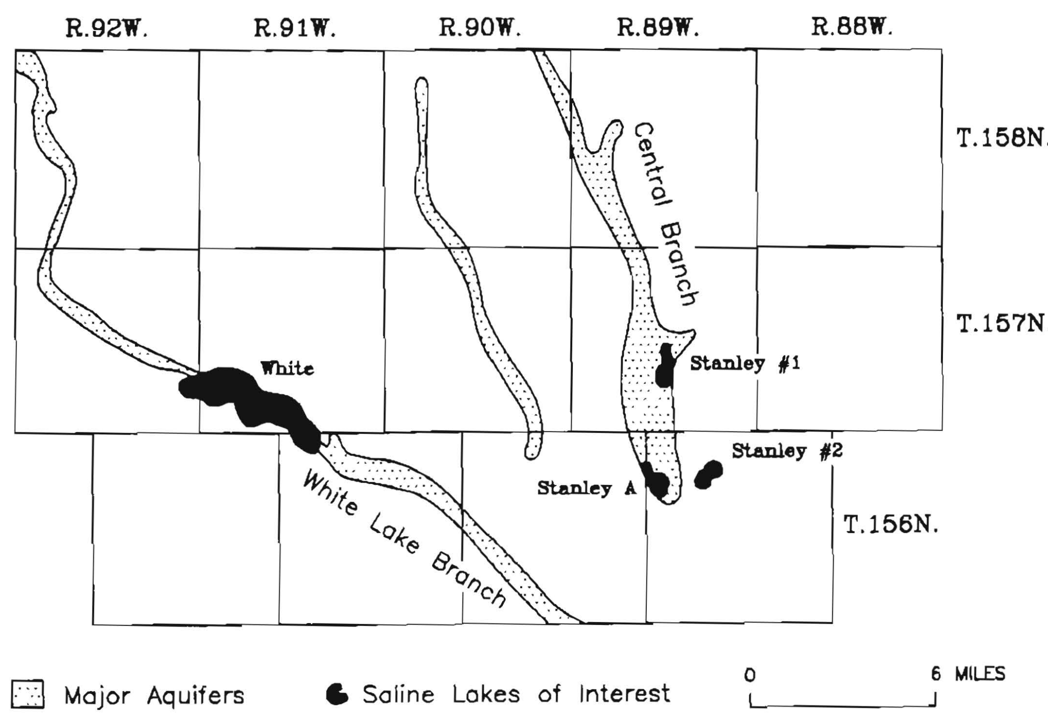

Figure 40. The major glaciofluvial aquifers in north-central Mountrail County (from Armstrong, 1971).

Figure 41. White Lake, Mountrail County, commonly contains three or four feet of water in the fall. The photograph was taken looking north across the middle of the lake in September, 1995.

(Special Collections, UND) indicates that White Lake was dry in July, 1934). Grossman (1949), reported that the lake had a maximum depth of 10 to 12 feet in the late 1940s (Figure 41). However, the U.S. Bureau of Mines did not measure water depths in excess of 4 feet in the fall of 1949 (Binyon, 1952). A water sample obtained from the lake in late September, 1995 contained total dissolved solids of 112,000 mg/l and high concentrations of sulfate (86,500 mg/l) (Appendix B). A sample obtained by Grossman (1949) in early September, 1948 contained slightly less concentrated water (TDS of 94,000 ppm and sulfate of 59,000).

The FERA workers augered 73 holes in White Lake. Field notes (FERA field notebook "A") indicate the western portion of the lake generally contained less than 6 inches of crystal salt, the east, 6 to 12 inches, and the central part of the lake contained 12 to 18 inches. Based on these data, Grossman (1949a) estimated that 2.5 million short tons of Glauber salt is present at this site.

The U.S. Bureau of Mines augered ten holes across the lake basin (Figure 42). Most of the augering took place from a homemade barge/ platform in one to four feet of water. Most of the holes were an average of 10 feet deep but one reached 18 feet. None of the holes apparently penetrated the base of the lacustrine sediments. An intermittent bed of crystals, ranging from 8 to 12 inches in thickness, was found to extend throughout the lake (Figure 42). Binyon noted that the crystal layer was underlain by a 0.5-to 3-foot layer of slush (a combination of brine, crystals, and mud) which in turn was underlain by mud (or clay). Only the top foot or two of mud contained crystals.

Using the average thicknesses presented in Table 12, Binyon (1952) estimated a total of 4.6 million short tons of Glauber salt was present

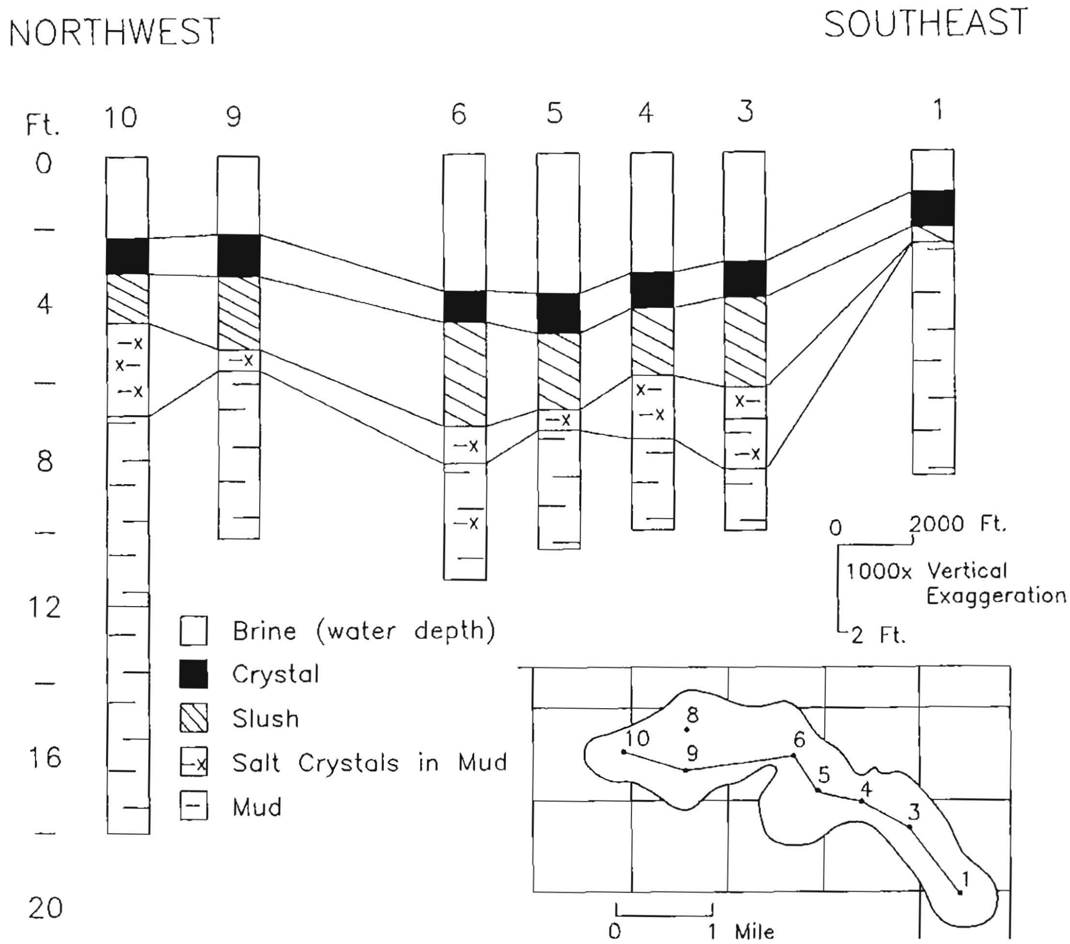

Figure 42. Geologic cross section of White Lake, Mountrail County. Basic data obtained from Binyon (1952).

in the brine and lacustrine sediments at this site. The tonnage would increase if additional salt layers are present in the lacustrine sediments below the depths penetrated by the Bureau of Mines holes.

In 1961, the Belle Fourche Bentonite Products Company of Belle Fourche, South Dakota constructed a settling pond for Glauber salt adjacent to White Lake (southern edge of section 30 and north-central part of section 31, T157N, R91W). The site operated by pumping approximately 50 million gallons of lake water into the 20-acre settling pond and then pumping the wastewater out after the salt precipitated. The resulting Glauber salt was then bulldozed into a large pile along the east edge of the settling pond (Figure 43).

The company had planned to erect a processing building west of Stanley to prepare the salt for shipping, but the plant was never built. A large pile containing approximately 120,000 cubic yards of sodium sulfate has remained at the site for nearly 35 years. The surface of the pile has dehydrated, forming a resistant crust much like a snowbank, and runoff has channeled at least three large caverns through the pile. Strong winds routinely disperse the white salt over the countryside.

Figure 43. Belle Fourche Bentonite Products Company's stockpile of sodium sulfate at White Lake, Mountrail County. The photograph was taken looking east across the company's settling pond in the summer of 1995.

TABLE 12

White Lake • 2,647 Acres

	Average Thickness (feet)	Cubic Feet	Tonnage Factor	Short Tons	Estimated Percent of Glauber Salt	Glauber Salt (short tons)
Brine	1.16	125,000,000	32	3,900,000	10.1	390,000
Intermittent Crystals	0.88	94,000,000	25	3,760,000	62.8	2,360,000
Mud & Crystals	2.51	270,000,000	20	13,490,000	13.8	1,860,000
TOTAL						4,600,000

Table 12. Estimated amount of Glauber salt at White Lake. Modified from Binyon (1952).

Stanley A

Stanley A is located 2.5 miles east of Palermo and occupies approximately 282 acres in sections 6 and 7 (T156N, R89W) and section 1 (T156N, R90W) (Figure 38). The lake generally contains a foot or so of water in the spring and summer and goes dry in the fall (Figure 44). Stanley A was dry, except for a few scattered pools near springs in September, 1995 and contained only a few inches of brine in late August, 1996. As noted by Grossman (1949), a large spring is present along the west edge of the lake (nwswnw section 7). This spring was flowing steadily in early March, 1996, following two successive weeks of subzero temperatures (Figure 6). Grossman analyzed a water sample from this in September, 1948 and found it to be a sodium sulfate-bicarbonate type with a TDS of 1,961 ppm, 8 ppm of chloride, 636 ppm of sulfate, 353 ppm sodium, and an alkalinity of 880 ppm.

FERA field notebook "A" indicates that Stanley A was briefly probed and then dismissed when it was determined that it "contains Na_2SO_4 but deposit is not extensive." The U.S. Bureau of Mines drilled eight shallow holes across this lake basin in 1949 (Binyon, 1952). The holes ranged in depth from 4 to 14 feet and apparently did not penetrate the base of the lacustrine sediments. In October, 1949, a thin (less than 3 inches), intermittent crystal bed was present throughout the lake and was overlain by an inch or two of water. A 1.5-to 7-foot-thick permanent crystal salt bed was present throughout the lake with the thickest occurrences along the southern and western edges (Figure 45). There is at least 7 feet of mud, containing various concentrations of salt crystals, beneath the permanent salt layer.

Binyon (1952) estimated there are 2.1 million short tons of Glauber salt in the Stanley A deposit (Table 13). He made this determination after obtaining the average thicknesses and salt content of the lithologies at this site. Most of the Bureau of Mines holes were halted after encountering clay that did not contain appreciable amounts of salt crystals. However, the base of the lacustrine sediments must be penetrated before it can be reliably ascertained that there are not additional salt layers beneath this site. Additional deeper holes were scheduled to be drilled by the Geological Survey in February and March, 1996 but were postponed to the following winter due to an abnormally deep snow cover that made access to the lake impossible.

TABLE 13

Stanley A • 316 Acres

	Average Thickness (feet)	Cubic Feet	Tonnage Factor	Short Tons	Estimated Percent of Glauber Salt	Glauber Salt (short tons)
Brine	0.10	1,300,000	32	42,000	8.1	3,500
Crust	0.14	1,900,000	32	58,000	67.6	39,500
Mud & Crystals	0.60	8,200,000	20	410,000	40.1	164,000
Crystal Bed	3.60	49,500,000	22	2,300,000	58.0	1,300,000
Mud & Crystals	2.96	40,000,000	20	2,000,000	30.5	610,000
TOTAL						2,100,000

Table 13. Estimated amount of Glauber salt at Stanley A. Modified from Binyon (1952).

Figure 44 The dried surface of Stanley A, Mountrail County. A tire, bottle, wood, and rocks are imbedded in the soft mud and salt of the lake bottom. The photograph was taken looking northwest from the south shore in August, 1996.

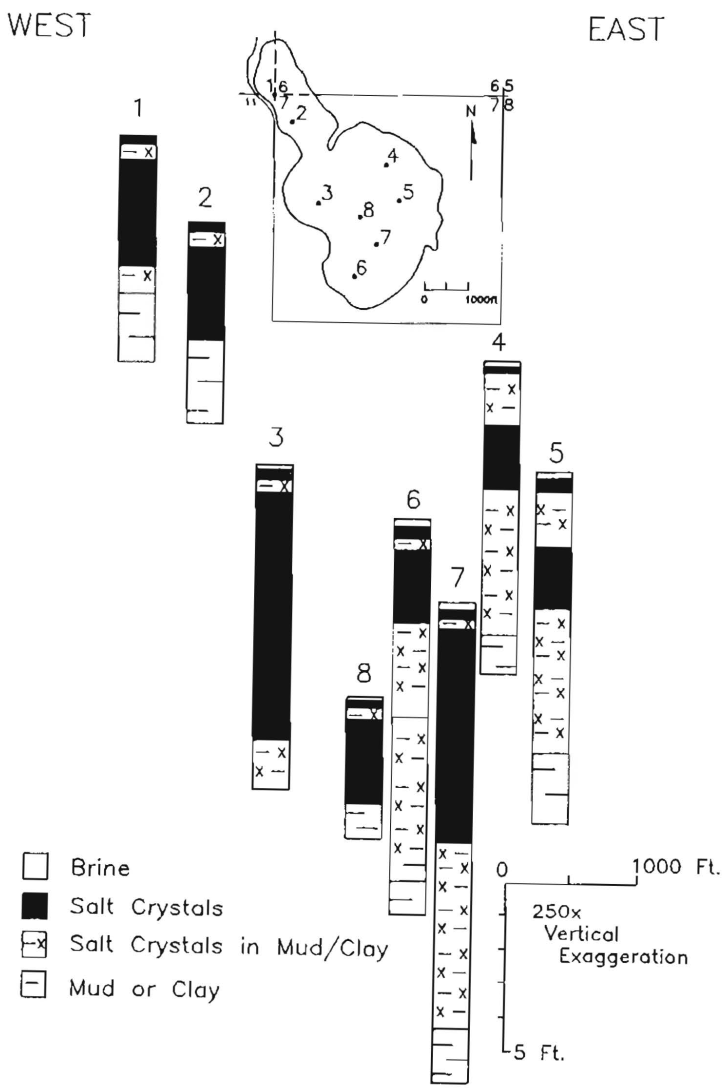

Figure 45 Drill hole lithology at Stanley A, Mountrail County. Basic data obtained from Binyon (1952).

Stanley #1

Stanley #1 occupies 250 acres in portions of sections 21, 22, 27, and 28 (T157N, R89W) in Mountrail County (Figure 38). According to the FERA report, this lake was dry in the fall of 1934. In more recent years it has commonly contained a foot or two of water throughout the year. Lavine (1935) noted the presence of several small springs around the margin of the lake and a large spring at the southern end.

According to FERA notebook "B", 210 holes were augered at Stanley #1. However, Lavine (1935) reported only 130 holes were augered at the site. These holes were spaced 200 feet apart and covered all but the southern end of the lake. The missing 70 holes may have been drilled in the southern portion of the lake and probably omitted from the map because they contained less than a foot of crystal salt. The notebook lists the thicknesses for "crystal" and "mud" that were encountered in each hole. The notebook indicates that the lacustrine sediments at this site are at least 14 feet thick. The crystal bed is present at or very near the surface and ranges in thickness from only a few inches to over 14 feet. The thickest salt accumulations occur near the center of the lake (Figure 46).

Lavine estimated that approximately 1 million short tons of Glauber salt occur in the lacustrine sediments at this site based on an

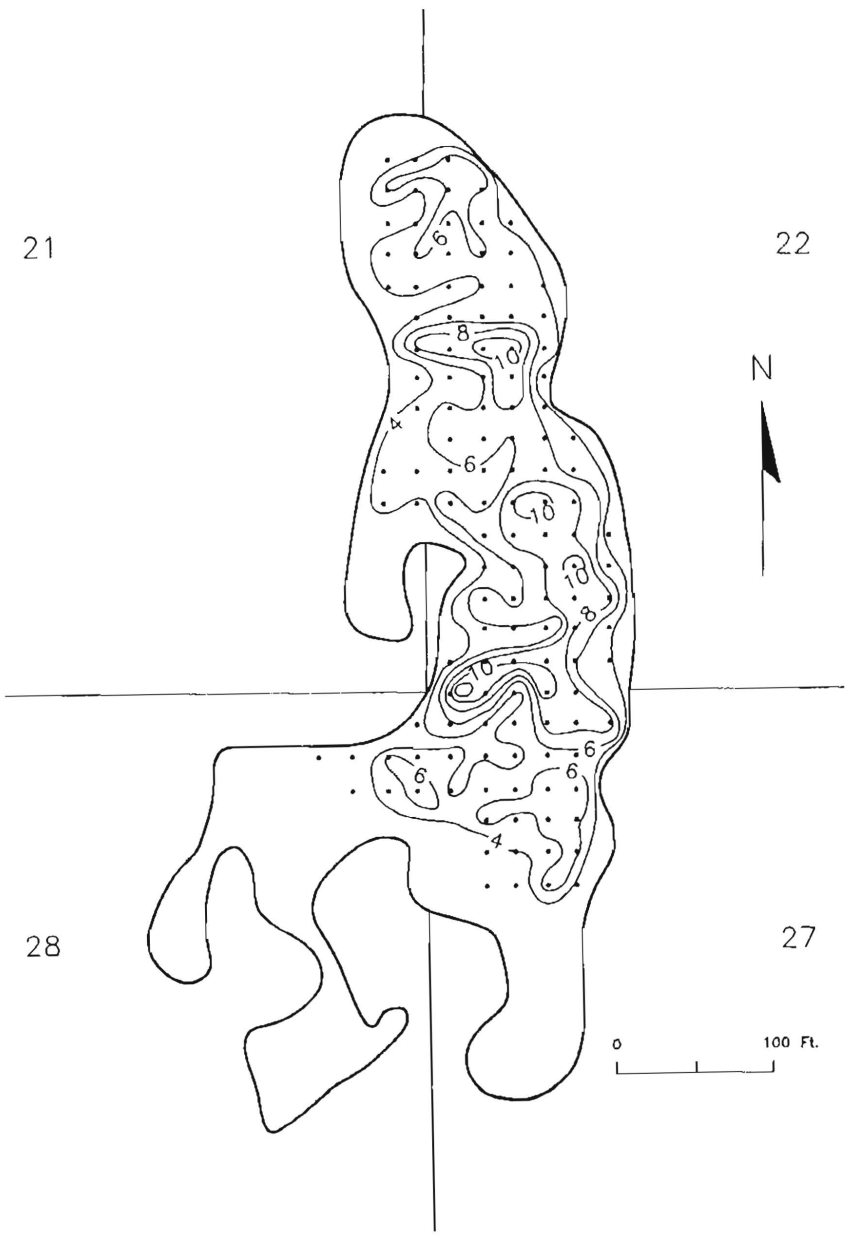

Figure 46. Isopach map of crystal salt at Stanley #1, Mountrail County. Basic data obtained from FERA notebook "B".

TABLE 14						
Stanley #1 • 124 Acres						
	Average Thickness (feet)	**Cubic Feet**	**Tonnage Factor**	**Short Tons**	**Estimated Percent of Glauber Salt**	**Glauber Salt (short tons)**
Crystal Bed	5.00	27,000,000	22	1,200,000	54	660,000
Mud & Crystals	2.00	11,000,000	20	540,000	24	130,000
TOTAL						800,000

Table 14. Estimated amount of Glauber salt at Stanley #1.

average salt thickness of 5.7 feet. Lavine (1935, 1935a) noted that this site contained a higher percentage of carbonate and bicarbonate (10% of soluble material) than the other deposits that they tested. Binyon (1952) revised the estimate of Glauber salt at this site to 570,000 short tons based upon the assumption that the crystal bed at this site is only 57% Glauber salt. Based on the data in the FERA notebook, a 124-acre area of the site contains approximately 800,000 short tons of Glauber salt (Table 14).

Several holes were scheduled to be drilled at Stanley #1 by the North Dakota Geological Survey in February and March, 1996, but thick snow accumulations in the lake basin made access impossible without snow removal equipment. The local landowner warned of the presence of numerous springs along the margins of the lake.

Stanley #2

Stanley #2 is located one mile east of Stanley A and occupies approximately 230 acres in portions of sections 4,5,8, and 9 (T156N, R89W) in Mountrail County (Figure 38). The lake was dry in the fall of 1934 when the FERA project took place. However, in the last few years it has generally contained a foot or two of water throughout the year (Figure 47). Stanley #2 contained the lowest concentration of TDS (93,400 mg/l) of any of the seven lakes sampled in September, 1995 (Appendix B). The lake also contained a high number of the zooplankton *Artemia salina*.

Aproximately 165 holes were hand-augered at 200-foot spacings throughout the lake under the FERA project. FERA notebook "B" lists thicknesses of "crystal" and "mud" for the holes augered in this lake. There are at least two crystal salt beds at this site. The upper salt bed is at or very near the surface and the second is 6 feet below. The presence of a second salt bed is reported from only one hole (hole no. 153) which lists: "one foot of crystal, 6 feet of mud, and 3 feet of crystal." The upper salt bed reaches a maximum thickness of over 5 feet near the southern and central portions of the lake (Figure 48). None of the holes appear to have penetrated the base of the lacustrine sediments.

Lavine (1935) estimated that approximately 600,000 short tons of Glauber salt occur in the upper crystal salt bed at this site. He noted that this bed was relatively free of mud but did contain lenses of silt. A total of 26 samples of this salt bed were chemically analyzed under this project. The U.S. Bureau of Mines did not drill at this site but reduced the estimated amount of Glauber salt to 342,000 short tons based on the assumption that the crystal bed was only

Figure 47. Mirabilite and thenardite have crystallized along the shore of Stanley #2, Mountrail County. The dark staining in the salt is from the bodies of *Artemia salina*. The photograph was taken looking northeast in September, 1995.

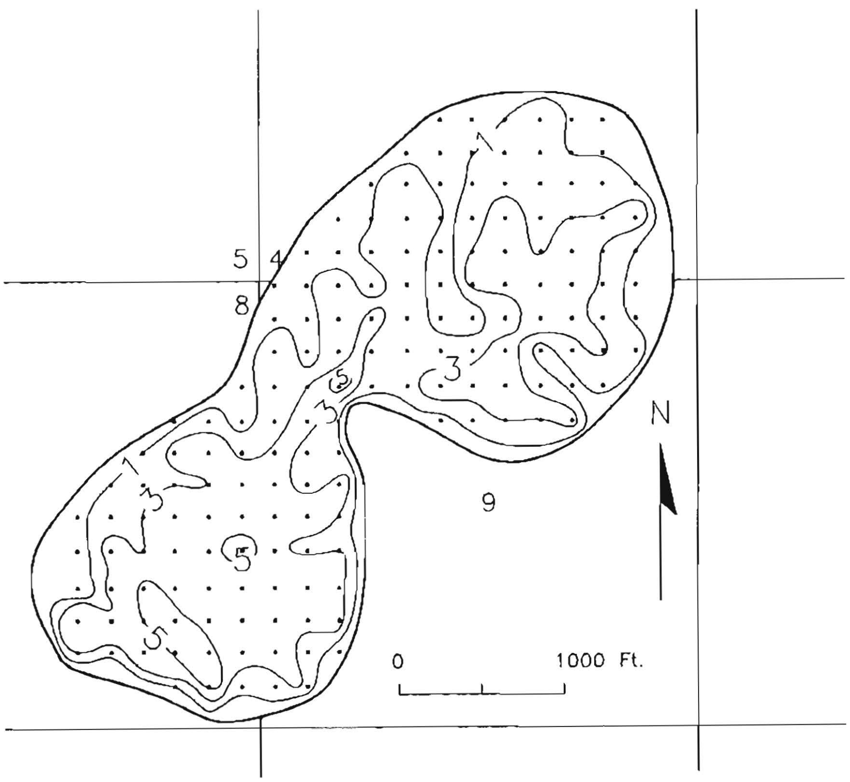

Figure 48. Isopach map of upper salt bed at Stanley #2, Mountrail County. Basic data obtained from FERA notebook"B".

57% Glauber salt. Based on the drill hole information in the FERA notebook, this site contains approximately 780,000 short tons of Glauber salt (Table 15). If the lower crystal bed extends throughout the lake or if additional crystal beds or crystal-bearing clay exist below the second salt bed, the actual reserves of Glauber salt at this site may be much higher.

As first noted by Lavine (1935), these brines are very temperature-sensitive and can precipitate large volumes of salt overnight. This rapid crystallization is quite obvious in the late summer and fall when waterfowl occasionally become encrusted with salt. On two separate occasions (September, 1995 and August, 1996), I encountered waterfowl that were unable to fly due to a heavy coating of salt on their feathers (Figure 49). Local residents have observed ducks swimming in a circular pattern in these lakes in an attempt to keep the lake from entirely crystallizing, just as they instinctively do when a lake begins to freeze over.

The Geological Survey had planned to drill several holes at Stanley #2 during February and March, 1996 to more adequately determine the lithology and the reserves of sodium sulfate. Deep snow accumulations prevented access onto the ice.

Figure 49. A salt-encrusted Ross' goose at Stanley #2, Mountrail County. The photograph was taken in October, 1995.

TABLE 15

Stanley #2 • 230 Acres

	Average Thickness (feet)	Cubic Feet	Tonnage Factor	Short Tons	Estimated Percent of Glauber Salt	Glauber Salt (short tons)
Brine	1.50	15,000,000	32	470,000	9	40,000
Crystal Bed	2.50	25,000,000	22	1,100,000	54	620,000
Mud & Crystals	1.00	10,000,000	20	500,000	24	120,000
TOTAL						780,000

Table 15. Estimated amount of Glauber salt at Stanley #2.

Geologic History of Sulfate Deposits

There is general consensus among workers who have studied the saline lakes in this area of North America that the sodium sulfate deposits began forming at the time that the glaciers began receding, approximately 12,000 years ago (Cole, 1926; Witkind, 1952; Rueffel, 1968 and 1976). Tomkins (1954) determined this is a sufficient amount of time by calculating that 3 million short tons of sodium sulfate would accumulate in a closed basin receiving 100 gpm of spring water with a sodium sulfate concentration of 1,000 ppm over a period of 12,000 years. It was noted early on that these salt deposits occurred in basins that have no drainage outlets (Cole, 1926; Lavine, 1935; Tomkins, 1948). The numerous springs that surround these lakes characteristically contain high concentrations of total dissolved solids. However, Cole (1926) obtained relatively fresh water from a pipe he had inserted down through a brine spring in Saskatchewan suggesting that at least some of these brine springs are obtaining their high ionc concentrations as they flow through salt layers in the lacustrine deposits.

The early workers also noticed that these deposits often were present in stream valleys that had been overridden and partly filled with glacial sediments. Last and Slezak (1987) determined that the sodium sulfate deposits occur in three general types of settings in this area: channel or riverine basins, sinkhole basins or kettles, and broad, flat depressions. A northwest-trending line of these lake or playa deposits extends from northwestern North Dakota through northeastern Montana and the southern part of the Canadian Provinces of Saskatchewan and Alberta, representing one of the principal belts of sodium sulfate deposits in the world (McIlveen and Cheek, 1994).

Several theories have been offered concerning the origin of these salt deposits. One initially proposed by Cole (1926) and later expanded on by Grossman (1968) pointed to the dissolution of deeply buried Paleozoic evaporites. However, Last and Slezak (1987) argued that the chemistry of the playa brines and the Paleozoic brines are not compatible. They believed that shallow groundwater is more compatible and appears to be the source for the major ions for these saline lakes. This compatibility is not readily apparent from a cursory comparison of their chemical concentrations (Lavine, 1935, Grossman, 1949; Binyon, 1952; Armstrong, 1965; Donovan; 1992). This is why Grossman (1968) believed the relative purity of these salt deposits argued against their being formed primarily from spring water which contains other salts. These differing interpretations as to origin may be the result of an open or partially open hydrologic system in many of these basins that provides for some degree of groundwater throughflow (Sloan, 1970; Wanek, 1983; Wood and Sanford, 1990; Reiten, 1991). The degree of flow through likely has an impact on the types and amounts of evaporative minerals that form in a given basin. Wanek (1983) noted that the lakes in this area can be grouped into two categories, those with less than 5000 mg/l TDS, which are likely interconnected with aquifers and have a flow-through system, and those greater than 19,000 mg/l TDS, which are largely spring-fed and do not have flow-through systems, the latter acting as evaporative concentration basins. This was confirmed by Reiten (1991) in a study of surface water chemistry in the northeastern corner of Montana. Reiten noted that the TDS of lakes is largely dependent on the flux of groundwater moving out of an individual lake, ie., if the flux is restricted, the TDS increases as a result of evaporation. Donovan (1994) determined through mass budget calculations that about 80 percent of the solute inflow to a playa basin in northeastern Montana was lost to brine outflow and wind erosion. Donovan (1992) and Donovan and Rose (1994) noted that the chemical character of evaporative lakes in this area was largely dependent on the position at which the lake intercepted the groundwater flow system. Most of the lakes in this area are thought to be influenced by shallow groundwater systems. However, Donovan and Rose concluded that some of the deeper depressions might intercept deeper flow paths.

At the time these lakes began to form, presumably immediately following active glaciation, there was a significant amount of relief on the floors of some of the small basins or partially sediment-plugged channels (50 to 80 feet at Miller Lake and Grenora #2). These depressions likely formed when huge blocks of ice were deposited in preglacial valleys and then overridden with glacial material. When the blocks of ice melted, kettles formed in the partially filled channels. Over thousands of years, the deeper portions of the basins were filled with lacustrine sediments, often containing beds of Glauber salt. As a result of this sedimentation, these lake bottoms are relatively flat with no visible evidence to indicate the significant variability in the thickness of the underlying lacustrine sediments. The relief on the base of the lacustrine deposits can be determined only by drilling or perhaps by geophysical means such as shallow seismic, ground-penetrating radar, or electrical resistivity soundings.

Geochemistry, Paleontology, and Paleoclimate Studies

Detailed studies of the geochemistry, mineralogy, and paleontology of the lacustrine sediments are beyond the scope of this project. In recent years, a number of scientists have been studying the lacustrine stratigraphy beneath shallow lakes in southwestern Canada as a means of interpreting Holocene climatic changes (Last, 1984, 1989a, 1989b, 1990; Vance et al, 1992). Last (1991) noted that, due to the closed nature of the basins, the sediments in these lakes should be sensitive indicators of paleoclimatic changes. However, the lacustrine strata have undergone several post-depositional changes, mineral diagenesis, salt dissolution, and mud diapirism, that can significantly alter this stratigraphy, making paleoenvironmental reconstruction difficult (Last, 1990; 1991). The difficulty encountered in tracing salt beds in closely spaced drill holes at Grenora #2 likely is the result of localized sedimentation patterns and postdepositional salt solution.

In recent years several inquiries have been made by research groups interested in obtaining sediment cores of lacustrine strata in the state. At least one study by a group of scientists from Penn State, the University of Minnesota, and West Virginia University is currently underway at a small lake in southern Divide County. Interest has reportedly been expressed by individuals within the grain futures market for research that will identify Holocene climatic cycles that may be used to predict future weather patterns. In addition, the utilities industry has also expressed interest in the Holocene climatic record relative to the predictions of global warming (Jon Reiten, per. comm., 1996)

Portions of the cores and cuttings from the North Dakota Geological Survey project are being made available to other scientists for both micropaleontology, macropaleontology, and geochemistry. Catherine Yansa, a doctoral candidate at the University of Wisconsin, is analyzing core from several lakes for macroflora and palynomorphs. Wood obtained at the base of the lacustrine deposits in Westby A, tentatively identified as poplar, is scheduled to undergo dating by the Carbon-14 method. Pollen grains of *Salsola kali* (Russian thistle), a weed that was introduced into this area in the late 1800s, will enable an additional age to be established near the top of the lacustrine sequence (Vance et al., 1992). Geochemical analysis of lacustrine strata for these paleoclimatic studies will be of interest to the sodium sulfate industry.

Sodium Sulfate Industry

Currently nine sodium sulfate plants are operating in North America; five in Saskatchewan, one in Mexico, and one in each of the following states; Texas, California, and Utah (McIlveen and Cheek, 1994). Saskatchewan has had a long history of sodium sulfate production, beginning in 1919 at Muskiki Lake (Tomkins, 1954). Saskatchewan's reserves of sodium sulfate have been estimated at over 58 million metric tons (Rueffel, 1976). Over the past 75 years, more than twenty companies have mined sodium sulfate from ten sites in the province (Saskatchewan Energy and Mines, 1994). The closest site to North Dakota operated at Sybouts, or Alkali Lake, near Gladmar, Saskatchewan. This site operated just across the border from Plentywood, Montana from 1941 to the mid 1980s and produced a total of 850,000 metric tons of salt. Most of the Glauber salt in Saskatchewan has been produced by pumping brine into crystallization ponds, although dredging and underground solution mining have also been employed. Traditionally, the brine is pumped into the crystallization ponds when it has reached its highest temperature and the water is pumped out after it has cooled and deposited the salt. After the ground freezes, the salt in the reservoir is scraped into a pile and transported to the plant for processing. A drawback of the crystallization method is its reliance on favorable weather conditions. Although the dredging method overcomes reliance on weather, this system requires additional cleaning and filtering to remove the mixture of sand, mud, algae and brine shrimp that are often intermixed with the permanent salt bed. Many of the plants use a combination of dryers and evaporators to process the salt. Multiple-effect evaporators, centrifuges, and kilns can also be used. The finished product is then crushed and screened to assure a uniform size of product before it is shipped to market. Facilities must take precautions during storage to ensure that the anhydrous salt cake is protected against moisture (Rueffel, 1968).

Historically, a fluctuating market has caused problems for the industry (Figure 50). Saskatchewan's annual production in 1995 of 313,737 metric tons was far below the 547,000 metric tons produced in 1982 and follows a general decline in production that began in 1982 (Paul Guliov, per comm, 1996). This decline directly reflects the sharp decline in consumption by the pulp and paper industry (Morel-a-I'Hussier, 1992). In 1995, sodium sulfate listed for an average of $81.52 a metric ton (Canadian currency-based on the average price for food-grade and nonfood-grade salt). This was close to the average price over the last five years but was substantially below the high of $98.12/metric ton paid in 1984 (Saskatchewan Energy and Mines, 1995).

Unpredictability in the natural sodium sulfate market stems from a decline in reliance of the kraft paper industry upon sodium sulfate and the large amount of sodium sulfate produced as a byproduct in U.S. manufacturing. The U.S. Bureau of Mines estimated that world production of sodium sulfate in the early 1990s was approximately 51% natural and 49% byproduct. However, at the present time, sodium sulfate processors are experiencing an increased demand from the detergent industry. Sodium sulfate is used as a bulking agent in detergent. An average box of detergent in North America contains between 20 and 25 percent sodium sulfate. Although it is claimed to improved detergent efficiency, sodium sulfate is essentially inert (Morel-a-I'Hussier, 1992). One Saskatchewan plant manager noted that the plants he knew had sold all of the product they could make this year and likely would again next year. But given the volatile market over the last 15 years, he could not predict the market 5 years from now. One of the factors apparently driving the market are women in third world countries switching from bar soap to powdered detergent to wash their clothes (Paul Guliov, per. comm., 1996). If the current demand continues, a processing plant in northwestern North Dakota may be viable.

A recent development in southern Saskatchewan may hold promise for the development of the state's sodium sulfate resources. Ormiston Mining at Ormiston, Saskatchewan is in the process of converting their sodium sulfate processing plant, built in 1929, to sodium bicarbonate. This procedure requires the addition of carbon dioxide and anhydrous ammonia to sodium sulfate and results in the formation of sodium bicarbonate and ammonium sulfate. The ammonium sulfate is currently marketed as fertilizer. Both carbon dioxide and anhydrous ammonia are scheduled to be marketable byproducts of the Dakota Gasification Plant at Beulah. A pipeline has been proposed to transport carbon dioxide from the Beulah plant to Weyburn, Saskatchewan. If a sodium bicarbonate plant is built in the northwestern part of the state it may be feasible to obtain carbon dioxide from this pipeline. The gasification plant is currently investigating the feasibility of producing food-grade carbon dioxide.

In recent years, sodium bicarbonate (baking soda) has seen a marked increase in its use in products such as tooth paste and laundry detergent. In addition to the increased demand for food-grade sodium bicarbonate, Airborne Technologies of Calgary, Alberta (Ormiston's parent company) has been marketing a sulfur scrubbing system that utilizes sodium bicarbonate instead of lime. This system is claimed to be as good as, if not superior to, lime scrubbers and operates at a fraction of the cost. Six coal-fired generating stations operate in North Dakota. These could potentially switch to a sodium bicarbonate scrubbing system. These plants currently consume over 100,000 tons of lime a year. Airborne Technologies system would require only a fraction of this amount for sodium bicarbonate because much of it is renewed during their process. Still, these plants represent a potential market for this technology and for the utilization of one of the state's natural resources. In addition to this market, Ormiston is investigating using crystals of sodium bicarbonate for sandblasting.

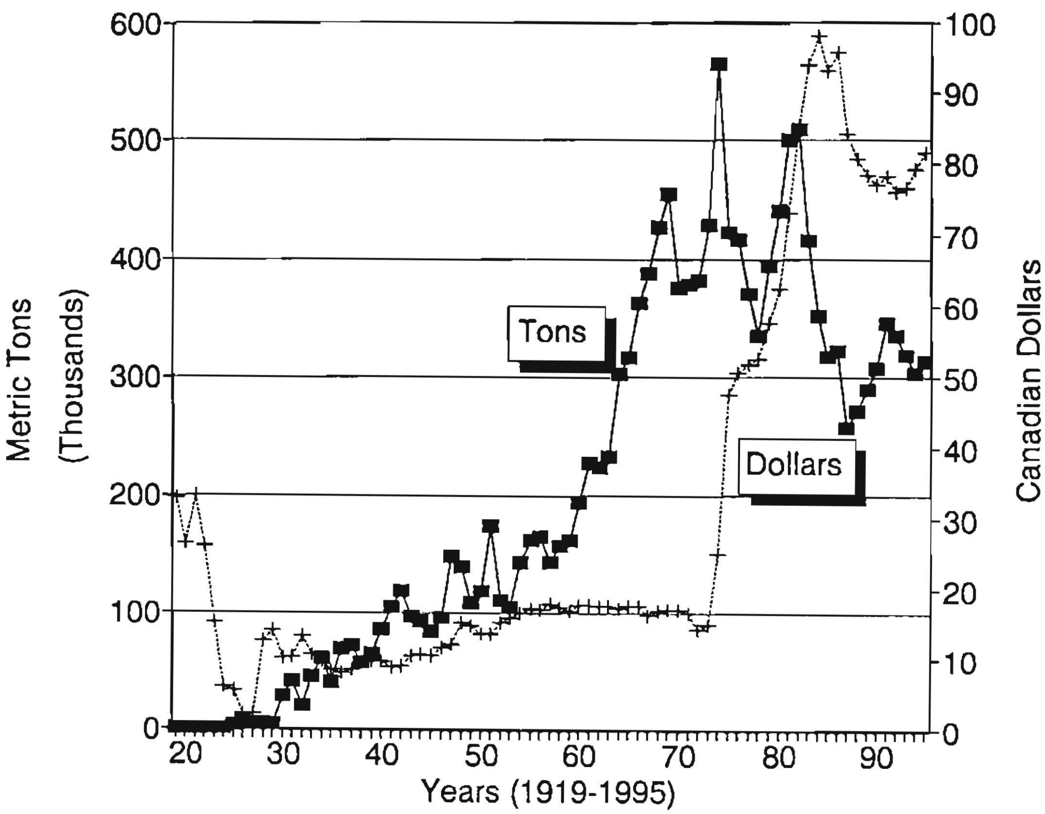

Figure 50. Historical summary of sodium sulfate production and price in Saskatchewan.

Conclusions

Several requirements must be met before a sodium sulfate processing plant can be established. Tomkins (1954) determined that a site must have a reserve of at least 500,000 metric tons of sodium sulfate to justify the establishment of a processing plant. He also suggested that the lake water must contain 12% or more sodium sulfate to make for an economic brine operation. All but one of the fifteen lakes discussed in this report (Horseshoe) meet these criteria with Miller, Grenora #1, Grenora #2, and Westby B appearing to be the most promising (Figure 51). The subsurface information from this study, combined with that of the previous studies, has resulted in a revised estimate of 46.3 million short tons of Glauber salt in these 15 lakes (Table 16). This compares to previous estimates of 21 million short tons (Lavine, 1934) and 26.5 million short tons (Binyon, 1952). The FERA estimate included only 6 of these 15 lakes and Binyon's estimate included 14 (all but North Lake). The large discrepancy between Binyon's and the North Dakota Geological Survey's estimate is largely the result of more accurate subsurface data for six of the lakes.

The most advantageous situation for the harvesting of sodium sulfate results from the presence of thick layers of salt at the surface. These readily go into solution when fresh water is added to the basin. The thick layers of mud and clay between the layers of crystal salt and the lake bottom may hamper the uptake of sodium sulfate as mining progresses. Layers of salt or salt-laden mud are at or near the surface in all of the lakes that were studied. As development progressed at these lakes, gravel-filled trenches or cased holes, constructed to intersect deeper salt layers, could increase the salinity of the brine.

A reliable source of fresh water is an important component of any processing plant. Water is needed to wash impurities from the salt during processing and may be used to increase the level of the lake during periods of drought. In the 1960s, a plant at Ingebrigt, Saskatchewan required 1500 gallons per minute of fresh water (Rueffel, 1968). At this site, a fresh-water reservoir was constructed so that water could be supplied to the lake whenever it was needed. All of the lakes studied, with the exception of Westby B and C, McCone, and Stanley #2, are believed to be situated over major buried channel aquifers. The quantity and quality of the water available from these aquifers are highly variable, but in most cases several wells near the vicinity of the plant may be able to supply the water needs. A unique problem is posed at Miller Lake because the State Water Commission has declined to issue new irrigation permits for the Skjermo Lake Aquifer for several years. Another potential source of water may be the proposed northwest water pipeline system. Initial plans by the State Water Commission

TABLE 16

LAKE	FERA	USBM	NDGS
Grenora #1	1.75	0.98	7.1
Grenora #2	11.1	5.5	6.4
Stink	--	1.2	2.2
Horseshoe	--	0.09	0.06
Stady E	--	1.8	1.8
Miller	5.0	2.75	13.0
North	1.0	0.5	1.8
Westby A	--	0.9	0.9
Westby B	--	3.8	3.8
Westby C	--	0.39	0.66
McCone	--	1.5	0.75
White	2.5*	4.6	4.6
Stanley A	--	2.1	2.1
Stanley #1	1.0	0.57	0.8
Stanley #2	0.6	0.34	0.78

* *Estimate made by Grossman, 1949*

Table 16. Estimated sodium sulfate resources (in millions of short tons) at selected lakes in northwestern North Dakota.

called for water to be piped to the communities of Fortuna and Grenora, within close proximity of the lakes in the Grenora and Alkabo groups. Recently, the scope of this project was reduced due to funding problems. Current plans call for the pipeline to run only as far northwest as the town of Noonan. The presence of a salt-processing plant in this part of the state might change the economics and make extension of the pipeline into this area more feasible.

The recent production of sodium bicarbonate from sodium sulfate deposits is an example of how changing technologies and markets can make the development of natural resources that have been known for years suddenly economically viable. This illustrates why it is very important to carefully analyze these resources so that the needed scientific information is available when opportunities such as this arise. This study, along with the previous studies of the State Geological Survey and the U.S. Bureau of Mines make it possible for industry to quickly evaluate these deposits under ever-changing economic conditions.

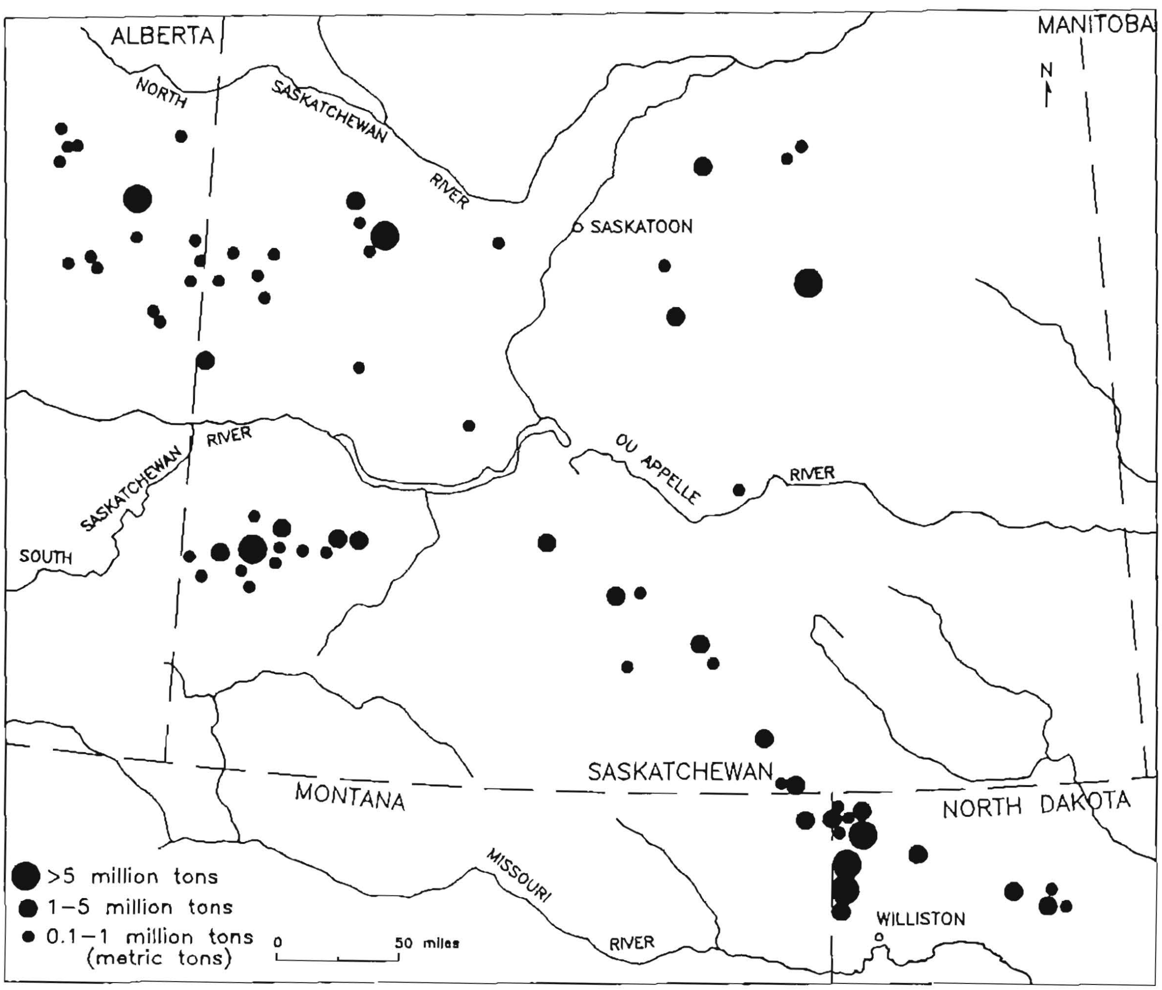

Figure 51. Major sodium sulfate deposits of southern Canada and the northern United States (modified from Last and Slezak, 1987).

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Appendices

APPENDIX A - Geologic Logs of North Dakota Geological Survey Holes

Grenora #1
Hole 1
T160N R103W section 16, 500 fnl 2904 fwl.
Elevation: 1962 Landowner: State of North Dakota

Feet	
0-1	*Clay,* dark gray/black, organic rich, silty, slight H_2S.
1-9	*Sodium Sulfate Crystals,* clear, approximately 10% silt and clay, salt and pepper appearance,moderate H_2S.
9-14	*Clay,* dark gray/brown, silty, organic rich, strong H_2S,saturated, small sodium sulfate crystals throughout deposit.
14-16	*Silt,* light gray, clayey, sodium sulfate crystals.
16-18	*Silt,* medium gray, clayey, clay lenses.
18-23	*Silt and Clay,* dark brown, laminated, possibly varved, sand lenses, sodium sulfate crystals, extremely high H_2S and methane.

Grenora #1
Hole 2
T160N R103W section 16, 2640 fnl 750 fel.
Elevation: 1962 Landowner: State of North Dakota

Feet	
0-0.25	Ice.
0.25-0.6	*Crystal bed.*
0.6-2	*Clay,* black, very organic, crystals.
2-12	*Clay,* dark gray to green, silty, crystals, strong H_2S.
12-15	*Crystal bed,* strong gas blow beneath this bed.
15-24	*Clay,* brown to dark gray/green, silty laminae or lenses, green silt lenses, contains both individual crystals and white layers of salt.
24-25	*Crystal bed.*
25-26	*Clay,* dark brown, silty, crystals, strong gas.
26-27	*Crystal bed.*
27-28.5	*Clay,* dark brown, silty, crystals, strong gas.
28.5-29	*Crystal bed.*
29-30	*Clay,* dark brown, silty, crystals, very strong gas.

Drilling halted due to health risks posed by gas.

Grenora #1

Hole 3

T160N R103W section 16, 1200 fsl 1900 fwl.

Elevation: 1962 Landowner: State of North Dakota

Feet	
0-0.25	Ice.
0.25-0.5	*Crystal bed.*
0.5-0.9	*Clay,* black, silty, crystals.
0.9-7	*Crystal bed.*
7-19	*Clay and silt,* gray/brown to brown to green, laminated, contains roots, insect fragments, crystals, moderate H_2S.

Grenora #1

Hole 4

T160N R103W section 16, 800 fsl 200 fel.

Elevation: 1962 Landowner: State of North Dakota

Feet	
0-0.25	Ice.
0.25-0.6	*Crystal bed.*
0.6-0.9	*Mud,* black, crystals, H_2S.
0.9-2	*Crystal bed.*
2-16	*Clay,* dark gray to dark brown, silty, silt lenses, crystals, moderate H_2S.
16-18	*Silt,* gray, clayey, crystals.

Miller Lake

Hole 1

T162N R102W section 20, 1300 fsl 3000 fel.

Elevation: 2058 Landowner: Elwin Hazlitt

Feet	
	Drilled through 2 feet of ice.
0-0.5	*Crystal bed,* clear, small crystals.
0.5-1	*Clay,* dark brown/black, sodium sulfate crystals, possibly gypsum crystals, H_2S.
1-1.3	*Crystal bed,* clear, contains approximately 10% black organic debris.
1.3-2.5	*Clay,* dark gray to black, approximately 50% crystals, H_2S.
2.5-4.25	*Crystal bed,* clear, contain black organic debris.
4.25-6	*Clay,* gray, silty, contains random sodium sulfate crystals.
6-11	*Crystal bed,* clear, contains approximately 10% black organic debris.
11-11.2	*Crystal bed,* clear, very hard, may contain gypsum.
11.2-15.5	*Clay,* medium gray, contains sodium sulfate crystals.
15.5-16	*Crystal bed,* clear, contains clay lenses.
16-18	*Clay,* medium gray, contains large sodium sulfate crystals.
18-19	*Crystal bed,* clear.
19-22	*Clay,* medium gray, contains large sodium sulfate crystals.
22-23.5	*Crystal bed,* clear.

23.5-26	*Clay,* medium gray, contains large sodium sulfate crystals, very strong H_2S/methane.
26-27	*Crystal bed,* clear.
27-28	*Clay,* medium gray, contains large sodium sulfate crystals, very strong H_2S/methane, very large volumes of gas bubbling out of the hole from 27 feet on.
28-29	*Crystal bed,* clear.
29-31	*Clay,* medium gray, contains large sodium sulfate crystals, very strong H_2S/methane.
31-32	*Crystal bed,* clear.
32-37	*Clay,* medium gray, contains large sodium sulfate crystals, very strong H_2S/methane.
37--38	*Crystal bed,* clear.
38-41	*Clay,* medium gray, contains large sodium sulfate crystals, very strong H_2S/methane.
41-49	*Clay,* dark brown to black, contains sodium sulfate crystals, extremely high H_2S/methane.
49-54	*Till,* gray, pebbly.

Miller Lake

Hole 2

T162N R102W section 30, 1000 fnl 600 fel.

Elevation: 2058 Landowner: Claire Bjorgen

Feet	
0-0.5	Ice.
0.5-1.5	*Mud,* black, 50% crystals.
1.5-7	*Clay,* light gray/brown to black, silty, crystals.
7-12	*Silt,* light gray, crystals.
12-18	*Clay,* yellow/gray/green to gray, silt laminae.
18-24	*Clay,* dark green to black, silty, highly organic, contains crystals, strong gas.
24-26	*Crystal bed.*
26-28	*Clay,* black, silty, crystals, strong gas.
28-29	*Crystal bed.*
29-30	*Clay,* dark green to black, silty, crystals, gas.
30-31	*Crystal bed.*
31-32	*Clay,* dark green to black, silty, crystals, strong gas.

Drilling discontinued due to high gas concentrations.

Miller Lake

Hole 3

T162N R102W section 19, 1900 fsl 100 fel.

Elevation: 2058 Landowner: Claire Bjorgen

Feet	
0-0.8	Ice.
0.8-1.5	*Crystal bed,* 20% mud.
1.5-2.5	*Clay,* dark gray to black, organic rich, 40% crystals.
2.5-8	*Crystal bed.*
8-9	*Clay,* black to dark gray, silty, crystals.
9-13	*Crystal bed,* last two feet extremely hard--had to discontinue drilling after wearing out three bits.

Miller Lake
Hole 4
T162N R102W section 20, 1900 fsl 300 fwl.
Elevation: 2058 Landowner: Claire Bjorgen

Feet	
0-.0.3	Ice.
0.3-1.5	*Crystal bed.*
1.5-8	*Clay,* gray, silty, crystals, moderate H_2S.
8-12	*Crystal bed.*
12-15	*Silt,* brown to dark brown, sandy, crystals.
15-18	*Sand and gravel,* dark brown, medium sized.

Miller Lake
Hole 5
T162N R102W section 20, 1700 fnl 1100 fwl.
Elevation: 2058 Landowner: Elwin Hazlitt

Feet	
0-0.3	Ice.
0.3-1	*Crystal bed.*
1-2	*Clay,* brown, silty, crystals, some H_2S.
2-4	*Crystal bed.*
4-9	*Clay,* gray, silty, crystals, H_2S.
9-16	*Crystal bed.*
16-17	*Clay,* dark brown, silty, crystals.
17-20	*Sand and gravel,* brown, medium sized.

North Lake Reservoir
Hole 1
T162N R102W section 17, 2500 fsl 2600 fel.
Elevation: 2059 Landowner: Gillferd Rust

Feet	
0-0.5	Ice.
0.5-4	*Sodium sulfate crystal layer,* clear, contains black organic debris (10%), water at 4 feet, moderate H_2S.
4-6	*Clay,* gray to brown, contains thin (< 2 inches) sodium sulfate lenses.
6-18	*Till,* gray, pebbly, FeO stained, occasional sodium sulfate or gypsum crystal.

North Lake Reservoir
Hole 2
T162N R102W section 17, 2500 fsl 2700 fel.
Elevation: 2059 Landowner: Gillferd Rust

Feet	
0-0.25	Ice.
0.25-1.5	*Crystal bed,* white to clear.
1.5-4	*Crystal bed,* gray to black, mud stringers.
4-4.2	*Crystal bed,* clear to white, well indurated.
4.2-6	*Crystal bed,* dark gray to black, moderate H_2S.
6-9	*Clay,* brown, crystal lenses.

North Lake Reservoir
Hole 3
T162N R102W section 17, 2500 fsl 1900 fel.
Elevation: 2059 Landowner: Gillferd Rust

Feet	
0-0.2	Ice.
0.2-0.4	*Crystal bed,* some mud.
0.4-4	*Crystal bed,* contains silt and clay lenses.
4-7	*Clay,* dark gray to black, organic rich, silty, crystals.
7-8	*Till,* gray to tan, pebbles, FeO stained.

North Lake Reservoir
Hole 4
T162N R102W section 17, 2500 fsl 1942 fel.
Elevation: 2059 Landowner: Gillferd Rust

Feet	
0-0.2	Ice.
0.2-7	*Crystal bed,* black from 2 to 6 inches, clear to white remainder of bed.
7-8	*Clay,* dark gray to black, silty, organic rich, crystals.
8-14	*Till,* light brown to tan, sandy, pebbles.

North Lake Reservoir
Hole 5
T162N R102W section 17, 2500 fsl 1992 fel.
Elevation: 2059 Landowner: Gillferd Rust

Feet	
0-0.2	Ice.
0.2-7	*Crystal bed,* varies from dark to white, white zone from 4 to 5 feet.
7-8	*Clay,* black, silty, organic rich, crystals.
8-13	*Till,* brown to tan, sandy, pebbly, FeO stained.

North Lake Reservoir

Hole 6

T162N R102W section 17, 2500 fsl 2804 fel.

Elevation: 2059 Landowner: Gillferd Rust

Feet	
0-0.2	Ice.
0.2-7	*Crystal bed,* very clean zone from 4 to 5 feet.
7-9	*Silt,* dark gray to black, crystals, saturated, moderate H_2S.
9-14	*Till,* medium brown to tan, sandy, pebbles.

North Lake Reservoir

Hole 7

T162N R102W section 17, 2500 fsl 3004 fel.

Elevation: 2059 Landowner: Gillferd Rust

Feet	
0-0.2 .	Ice.
0.2-2	*Crystal bed.*
2-8	*Till,* brown, pebbles.

North Lake Reservoir

Hole 15

T162N R102W section 17, 1300 fsl 1900 fel.

Elevation: 2059 Landowner: Gillferd Rust

Feet	
0-0.2	Ice.
0.2-2	*Crystal bed.*
2-3	*Clay,* dark gray to black, crystals.
3-5	*Silt,* gray to brown, laminated.
5-14	*Till,* tan to light brown, pebbles.

North Lake

Hole 8

T162N R102W section 8, 600 fsl 1200 fwl.

Elevation: 2059 Landowner: Eugene Herman

Feet	
0-0.2	Ice.
0.2-0.8	*Crystal bed.*
0.8-5	*Clay,* dark gray to black, silty, crystals, slight to moderate H_2S.
5-12	*Silt,* light to medium gray, clayey, crystals.
12-16	*Clay,* dark brown, silty, organic rich, some gas.
16-22	*Silt,* dark brown, clayey, organic rich, crystals (?), high concentrations of H_2S.
22-30	*Sand,* dark brown, fine to medium grained, silty.
30-34	*Sand and gravel,* medium brown to reddish brown, medium to coarse grained sand, small to medium pebbles.

North Lake

Hole 9

T162N R102W section 8, 600 fsl 500 fwl.

Elevation: 2059 Landowner: Eugene Herman

Feet	
0-0.5	*Crystal bed.*
0.5-2	*Clay,* dark gray-black, silty, crystals, H_2S.
2-5	*Crystal bed.*
5-8	*Clay,* dark brown, silty, crystals.
8-11	*Silt,* dark brown, clayey, crystals.
11-16	*Sand and gravel,* medium brown, fine to coarse grained sand, small pebbles.

North Lake

Hole 10

T162N R102W section 8, 600 fsl 2100 fwl.

Elevation: 2059 Landowner: Eugene Herman

Feet	
0-1.5	*Clay,* dark gray, silty, crystals.
1.5-3	*Sand,* light gray/brown, medium grained,clayey.
3-12	*Till,* light brown, sandy, pebbles.

North Lake

Hole 11

T162N R102W section 8, 600 fsl 2000 fwl.

Elevation: 2059 Landowner: Eugene Herman

Feet	
0-0.2	Ice.
0.2-2	*Clay,* dark gray to black, silty, crystals.
2-5	*Sand,* gray, very fine to fine grained, clayey.
5-8	*Till,* gray, sandy, pebbles.

North Lake

Hole 12

T162N R102W section 8, 600 fsl 1870 fwl.

Elevation: 2059 Landowner: Eugene Herman

Feet	
0-0.2	Ice.
0.2-0.5	*Crystal bed.*
0.5-2	*Clay,* dark gray to black, silty, crystals, some H_2S.
2-4	*Clay,* dark to medium gray, silty, crystals.
4-8	*Silt,* gray to gray/green, clayey, occasional coarse sand grain, moderate H_2S.
8-15	*Till,* medium brown, sandy, small pebbles.

North Lake

Hole 13

T162N R102W section 8, 600 fsl 400 fwl.

Elevation: 2059 Landowner: Eugene Herman

Feet	
0-0.2	Ice.
0.2-1	*Crystal bed.*
1-3	*Clay,* gray, silty, 30% crystals.
3-12	*Silt,* gray to green, clayey, crystals, moderate to strong H_2S.
12-18	*Sand and gravel,* brown, medium pebbles.

North Lake

Hole 14

T162N R102W section 8, 600 fsl 355 fwl.

Elevation: 2059 Landowner: Eugene Herman

Feet	
0-0.2	Ice.
0.2-1	*Mud,* dark gray, silty, crystals.
1-3	*Crystal bed.*
3-5	*Clay,* medium gray, silty, crystals.
5-7	*Silt,* medium brown, sandy.
7-10	*Sand,* medium to dark brown, some pebbles, high H_2S.
10-14	*Sand and gravel,* medium to dark brown.

Westby A

Hole 1

T162N R103W section 14, 2400 fsl 2500 fel.

Elevation: 2058 Landowner: James Nordhagen

Feet	
0-6	*Clay,* dark gray, silty, organic rich, medium to large sodium sulfate crystals scattered throughout this unit, moderate H_2S.
6-9	*Silt,* light to medium gray, clayey, small random sodium sulfate crystals.
9-9.5	*Clay,* gray/brown to brown, mottled, silty.
9.5-13	*Clay,* gray to gray/brown and brown to dark brown, laminated possibly varved, one to two inch thick sodium sulfate crystal beds adjacent to organic rich beds at 12.5 and 13 feet.
13-14	*Silt,* dark gray/green to black, clayey, large sodium sulfate crystals.
14-14.5	*Clay,* dark brown, organic rich, contains a piece of wood.
14.5-20	*Sand,* dark brown to black, fine to coarse grained, poorly sorted, saturated, slight H_2S.
20-28	*Sand,* medium brown, medium to coarse grained, occasional pebbles.

Westby A
Hole 2
T162N R103W section 14, 1200 fsl 2200 fwl.
Elevation: 2058 Landowner: Harlow Freund

Feet	
0-0.5	Ice.
0.5-4	*Clay,* dark gray, crystals, moderate H_2S.
4-10	*Silt,* gray, clayey, crystals.
10-12	*Clay and silt,* laminated, gray silt, gray/brown clay.
12-18	*Silt,* light gray, clayey, moderate to strong H_2S.

Westby A
Hole 3
T162N R103W section 14, 700 fnl 1400 fel.
Elevation: 2058 Landowner: Brian Elm

Feet	
0-0.3	Ice.
0.3-0.4	*Crystal bed.*
0.4-3	*Clay,* dark gray, silty, crystals.
3-6	*Silt,* light gray/green, dark gray, clay beds, laminated, crystals.
6-14	*Clay and silt,* dark gray/green to dark brown laminated, selenite and glauber crystals, very thin, salt layers-some stained green.
14-16	*Silt,* dark gray/brown, clayey.

McCone Lake
Hole 1
T163N R103W section 14, 600 fnl 900 fel.
Elevation: 2078 Landowner: Irving Wittmayer

Feet	
0-1	*Gravel* with clay lenses.
1-5.5	*Sodium sulfate crystal layer,* clear with some organic debris, salt and pepper appearance.
5.5-6	*Clay,* black, organic rich.
6-8	*Clay,* gray/green, silty, contains random sodium sulfate crystals.
8-10	*Gravel,* black, sandy, silty, may contain sodium sulfate crystals.
10-18	*Till,* gray, pebbly.

North Lake

Hole 13

T162N R102W section 8, 600 fsl 400 fwl.

Elevation: 2059 Landowner: Eugene Herman

Feet	
0-0.2	Ice.
0.2-1	*Crystal bed.*
1-3	*Clay,* gray, silty, 30% crystals.
3-12	*Silt,* gray to green, clayey, crystals, moderate to strong H_2S.
12-18	*Sand and gravel,* brown, medium pebbles.

North Lake

Hole 14

T162N R102W section 8, 600 fsl 355 fwl.

Elevation: 2059 Landowner: Eugene Herman

Feet	
0-0.2	Ice.
0.2-1	*Mud,* dark gray, silty, crystals.
1-3	*Crystal bed.*
3-5	*Clay,* medium gray, silty, crystals.
5-7	*Silt,* medium brown, sandy.
7-10	*Sand,* medium to dark brown, some pebbles, high H_2S.
10-14	*Sand and gravel,* medium to dark brown.

Westby A

Hole 1

T162N R103W section 14, 2400 fsl 2500 fel.

Elevation: 2058 Landowner: James Nordhagen

Feet	
0-6	*Clay,* dark gray, silty, organic rich, medium to large sodium sulfate crystals scattered throughout this unit, moderate H_2S.
6-9	*Silt,* light to medium gray, clayey, small random sodium sulfate crystals.
9-9.5	*Clay,* gray/brown to brown, mottled, silty.
9.5-13	*Clay,* gray to gray/brown and brown to dark brown, laminated possibly varved, one to two inch thick sodium sulfate crystal beds adjacent to organic rich beds at 12.5 and 13 feet.
13-14	*Silt,* dark gray/green to black, clayey, large sodium sulfate crystals.
14-14.5	*Clay,* dark brown, organic rich, contains a piece of wood.
14.5-20	*Sand,* dark brown to black, fine to coarse grained, poorly sorted, saturated, slight H_2S.
20-28	*Sand,* medium brown, medium to coarse grained, occasional pebbles.

Westby A

Hole 2

T162N R103W section 14, 1200 fsl 2200 fwl.

Elevation: 2058 Landowner: Harlow Freund

Feet	
0-0.5	Ice.
0.5-4	*Clay,* dark gray, crystals, moderate H_2S.
4-10	*Silt,* gray, clayey, crystals.
10-12	*Clay and silt,* laminated, gray silt, gray/brown clay.
12-18	*Silt,* light gray, clayey, moderate to strong H_2S.

Westby A

Hole 3

T162N R103W section 14, 700 fnl 1400 fel.

Elevation: 2058 Landowner: Brian Elm

Feet	
0-0.3	Ice.
0.3-0.4	*Crystal bed.*
0.4-3	*Clay,* dark gray, silty, crystals.
3-6	*Silt,* light gray/green, dark gray, clay beds, laminated, crystals.
6-14	*Clay and silt,* dark gray/green to dark brown laminated, selenite and glauber crystals, very thin, salt layers-some stained green.
14-16	*Silt,* dark gray/brown, clayey.

McCone Lake

Hole 1

T163N R103W section 14, 600 fnl 900 fel.

Elevation: 2078 Landowner: Irving Wittmayer

Feet	
0-1	*Gravel* with clay lenses.
1-5.5	*Sodium sulfate crystal layer,* clear with some organic debris, salt and pepper appearance.
5.5-6	*Clay,* black, organic rich.
6-8	*Clay,* gray/green, silty, contains random sodium sulfate crystals.
8-10	*Gravel,* black, sandy, silty, may contain sodium sulfate crystals.
10-18	*Till,* gray, pebbly.

APPENDIX B - Chemistry of Water Samples from Selected Lakes in Northwestern North Dakota

		Miller	Grenora 1	Grenora 2	Horseshoe	White	Stanley 2
		162	160	160	159	157	156
		102	103	103	103	91	89
		30	15	33	18	31	8
		9/21/95	9/21/95	9/21/95	9/21/95	9/21/95	9/21/95
Sodium (Na)	mg/L	27700	34100	26600	40100	22700	35000
Magnesium (Mg)	mg/L	9170	25600	5030	56.9	170	61.9
Silica (SiO_2)	mg/L	2.70	10.3	18.8	224	113	100
Potassium (K)	mg/L	1940	4180	1150	376	251	340
Calcium (Ca)	mg/L	218	885	316	30.3	81.7	23.7
Manganese (Mn)	mg/L	0.189	1.17	0.200	0.126	0.582	0.176
Iron (Fe)	mg/L	0.147	0.563	1.61	3.41	18.5	0.597
Chloride	mg/L	6100	12500	7430	4600	576	910
Fluoride (F)	mg/L	0.71	0.83	0.52	6.93	---	1.12
pH		8.62	8.13	8.60	9.59	9.10	9.02
Carbonate (CO3)	mg/L	496	<1	243	17100	694	328
Bicarbonate (HCO3)	mg/L	2110	2380	1110	37700	2580	1650
Hydroxide (OH)	mg/L	<1	<1	<1	<1	<1	<1
Alkalinity ($CaCO_3$)(Total)	mg/L	2550	1950	1310	59400	3270	1900
Conductivity	umhos/cm	74200	85700	70000	82000	69700	60400
Sulfate as (SO_4)	mg/L	123000	163000	89200	44500	86500	55900
Nitrate + Nitrite (N)	mg/L	0.08	0.09	0.05	0.12	0.05	0.06
Hardness Total (as $CaCO_3$)	mg/L	38300	108000	21500	310	904	314
Hardness (Total)	gr/gal.	2240	6280	1260	18	53	18
Turbidity	NTU	80.0	210	185	195	27.0	32.0
Cation Sum	me/L	2023	3749	1617	1759	1012	1537
Anion Sum	me/L	2786	3787	2094	2245	1884	1228
Difference	me/L	-762.8	-37.59	-476.6	-485.4	-872.3	308.5
Percent Difference	%	-15.9	-0.50	-12.8	-12.1	-30.1	11.2
Percent Sodium	%	59.5	39.5	-71.5	99.1	97.6	99.0
Sodium Adsorption Ratio		61.6	45.2	78.9	990	328	859
Dissolved Solids (TDS)	mg/L	170000	241000	131000	125000	112000	93400