ANALYSIS OF RECENT AND HISTORICAL SALT-CRUST THICKNESS MEASUREMENTS AND ASSESSMENT OF THEIR RELATIONSHIP TO THE SALT LAYDOWN PROJECT, BONNEVILLE SALT FLATS, TOOELE COUNTY, UTAH

by

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Editor's Note: Appendices for this paper appear in a separate file on this CD.

ABSTRACT

The Bureau of Land Management (BLM) conducted a bore-hole drilling program on the Bonneville Salt Flats in October 2003 to obtain current salt-crust thickness measurements for comparison with 1988 thickness measurements previously made by BLM. A total of 69 bore holes were drilled, and two different measurement methods were compared in 55 of the 69 bore holes (BLM mud auger and Utah State Department of Highways UDOT pole). Differences in accuracy and precision between the two methods were analyzed, and we determined that the mud-auger method produced more reliable measurements. Salt-crust volumes were computed from 1988 and 2003 thickness measurements and their respective salt-crust boundaries to see if measurable changes could be observed.

We concluded from our analysis of the 1988 and 2003 measurements and their respective calculated volumes that 1) salt-crust volumes determined by the 2003 mud auger measurements were 7% larger than those determined by the 2003 UDOT pole measurements, 2) there was virtually no difference between salt-crust volumes determined by the 1988 and 2003 pole measurements, and 3) the Laydown Project produced no measurable change in salt crust thickness, but did help maintain the ion mass balance in the shallow-brine aquifer, which contributes to maintenance of the existing salt-crust volume.

INTRODUCTION

The Bonneville Salt Flats (BSF) is located in the western part of the Great Salt Lake Desert of northwestern Utah. The BSF is part of a large playa that occupies one of several enclosed sub-basins that comprise the Great Salt Lake Desert (figure 1). These sub-basins include the Bonneville Salt Flats, Pilot Valley, and the Newfoundland Basin (White 2002, 2004; Kohler and White, 2004). The BSF is roughly divided into a north and south half by the east-west trending Interstate Highway 80 (I-80) and the adjacent Western Pacific Railroad right-of-way (Western Pacific, now Union Pacific, Railroad right-of-way is parallel to, and 1,400 feet south of I-80). The north half includes the sites of the historic circular race track and 10- to 12-mile long International Track, and is dominated by public land managed by the U.S. Bureau of Land Management (BLM). The south half of the BSF is mainly private and dominated by commercial potash production. The twin cities of Wendover, UT and Wendover, NV are adjacent to I-80 and about 4 miles west of the BSF's western margin.

The BSF is the site of automobile land-speed records, unusual geology, stark contrasts, and unique scenery. Consequently, it has become famous as an area of national and international interest. However, perceived depletion of the salt crust encompassing the historic racetrack areas of the BSF has become a growing concern to the public and land managers for at least 26 years (McMillan, 1974; Lines, 1979). This concern is based on changes in salt-crust area and volume reported between 1960 and 1988 that were measured north of the Western Pacific Railroad and I-80 (McMillan, 1974; Lines, 1979; Brooks, 1991). Since 1988, BLM has monitored salt-crust thickness at specified Salt Flats monitoring-well locations to document any further measurable changes in salt-crust thickness (White, 2002, 2004).

Purpose and Scope

The purpose of this paper is to 1) summarize similarities and differences between 1988 and 2003 salt-crust thickness measurements taken at the same surveyed locations on the BSF salt-crust surface, and 2) evaluate the

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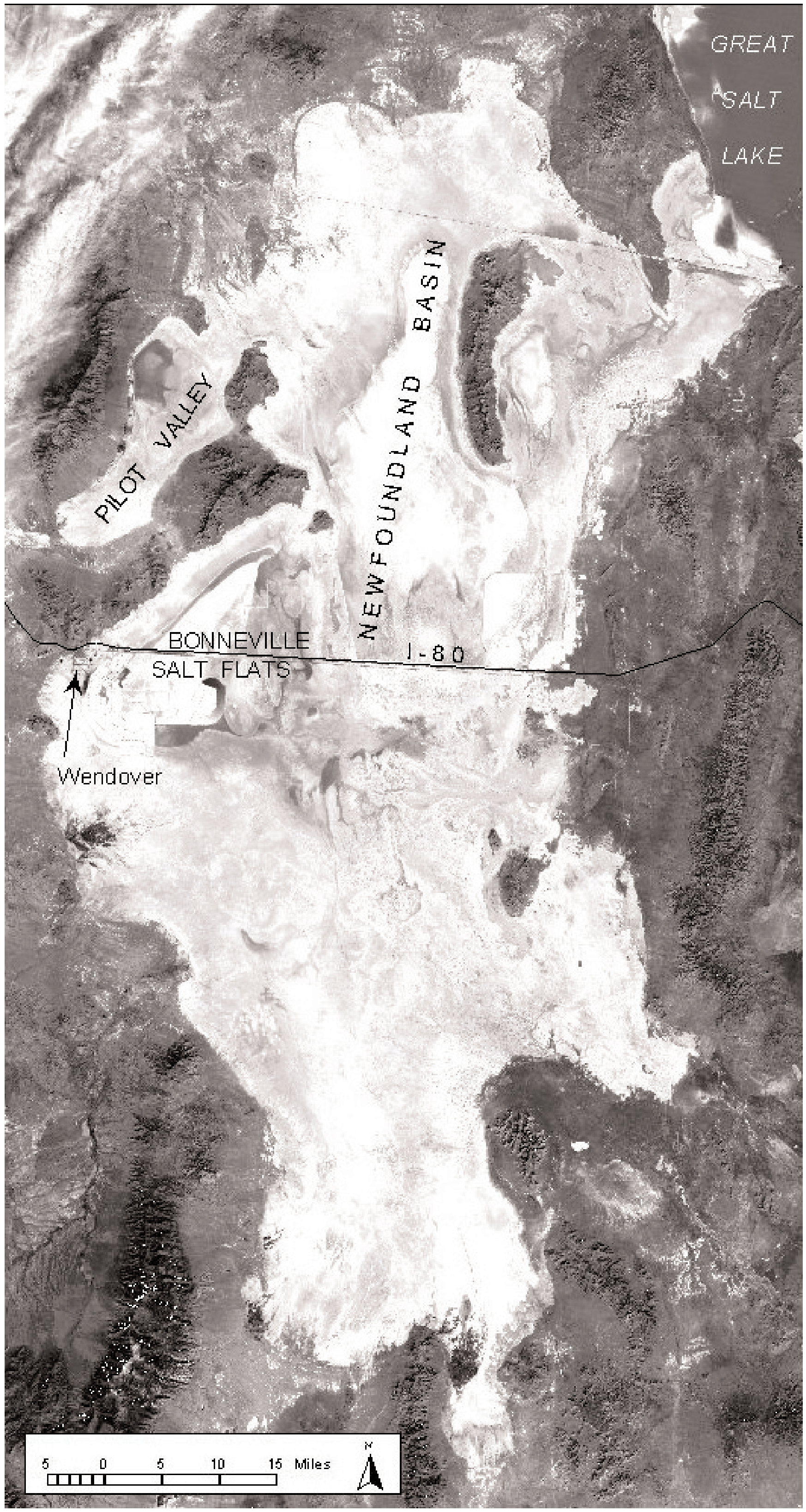

Figure 1. *A portion of the Great Salt Lake Desert showing several sub-basin locations (Bonneville Salt Flats, Pilot Valley, and Newfoundland Basin).*

influence of the Salt Laydown Project on possible changes in the BSF salt-crust thickness. The scope of the study included: 1) determination of salt-crust areas and volumes from 1988 and 2003 salt-crust boundary and bore hole thickness data using kriging, 2) comparison of differences between 1988 and 2003 salt-crust boundaries and respective volumes, 3) evaluation and comparison of three different salt-crust volumetric calculation methods, 4) comparison of predicted 2003 salt-crust volume (based on an average annual depletion rate proposed in Brooks, 1991) with Geographic Information System (GIS)-determined 2003 salt-crust volume, and 5) examination of relationships between salt-crust thickness study results and Salt Laydown Project results.

Previous Work

In 1960 and 1974, the Utah State Department of Highways (now Utah Department of Transportation - UDOT) conducted salt-crust thickness and areal-extent studies of the BSF. In both the 1960 and 1974 studies, 108 holes were drilled and distributed along 15 transect lines that were perpendicular to the axis of the International Track and spaced at one-mile intervals marked by mile posts (figure 2). Salt-crust thickness measurements were made using a five-foot pole with a hook on its end (figures 3a and 3b). This measurement method is referred to as the UDOT pole-measurement technique (details of the technique are summarized in “Methods”). Based on this measuring method and the bore-hole cuttings, the UDOT study described the salt crust as being composed of two halite strata, an upper stratum or “hard salt,” and a lower stratum or “soft salt.” McMillan (1974) reported 1960 and 1974 salt-crust areas (with thickness equal to or greater than 0.1 foot) were about 38 and 36 square miles, respectively. He further reported that salt-crust area and volume between 1960 and 1974 decreased by 9 and 15%, respectively.

During 1988, BLM attempted to replicate the UDOT studies with a 118-hole drilling program so that a comparison to previous measurements could be made (figure 4). The 118 bore holes were distributed along transects similar to those established by UDOT for its 1960 and 1974 studies (see figure 2). Salt-crust thickness measurements were made using the UDOT pole-measurement technique, and the same UDOT stratum terminology was used to describe the salt crust. Based on BLM's 1988 study, Brooks (1991) reported 1) 1988 salt-crust area (with thickness equal to or greater than 1.0 foot) was about 30 square miles, and 2) salt-crust area and volume was estimated to have decreased by about 21% and 31%, respectively, between 1960 and 1988. Additionally, Brooks (1991) concluded that the salt-crust volume was decreasing at an average annual rate of 1.1% between the 1960 and 1988 measurements.

In a cooperative effort to preserve the character of the BSF, Reilly Industries Inc., and BLM entered into a Salt Laydown agreement in 1995 to help replenish salt to the BSF. This experimental project began transferring dissolved salt to the BSF in 1997, and as of May 2, 2002 transferred 6.2 million tons of salt to the BSF north of I-80 (White, 2004). The project was voluntarily continued through March 2005 by Reilly's successor, Intrepid Potash-Wendover LLC; consequently, an additional 0.8 million tons of salt were added to the five-year production for a total of 7 million tons delivered to the BSF.

Based on the first five years of the Salt Laydown Project, White (2004) concluded that sodium chloride salt in brine removed from the BSF for mineral extraction could be replenished. Specifically, a net mass of about 2 million tons of salt was added to the BSF shallow-brine aquifer and salt-crust system (i.e., 6.2 million tons transferred, minus 4.2 million tons removed by mineral extraction). On the basis of geochemical modeling, most of the Laydown salt tonnage was assimilated into the shallow-brine aquifer. Additionally, White (2004) reported that prior to the Salt Laydown Project, some of the brine removed from the BSF by mineral extraction was replaced by meteoric precipitation, which dissolved salt crust. He further reported that during the Salt Laydown Project, the amount of brine removed from the shallow-brine aquifer by mineral extraction was believed to be mostly replaced by Laydown brine, which approached halite saturation. Consequently the Lay-down brine helped minimize salt-crust dissolution while maintaining the mass balance of total dissolved salts in the shallow-brine aquifer (White, 2004).

White (2004) also described the following field observations regarding salt-crust composition and thickness:

- Rather than being composed of two halite strata (i.e., “hard salt” and “soft salt” as proposed by the 1960 - 1974 UDOT studies - McMillan, 1974), the salt crust is actually composed of at least five strata (three halite and two gypsum).

- The observed salt-crust strata sequence is: dense-cemented halite (salt-crust surface stratum), 1st uncemented fine-grained gypsum, cemented-coarse-porous halite, 2nd uncemented fine-grained gypsum, and uncemented-coarse halite (see White, 2003, appendix A6 for details).

- Minimal change in total salt-crust thickness between 1988 and 2002 was observed at 13 salt-crust monitoring sites.

- None of the salt-crust monitoring sites where multiple-year thickness measurements were taken showed the expected +2-inch increase in the surface halite stratum thickness that was predicted to occur at the end of the five-year Salt Laydown Project.

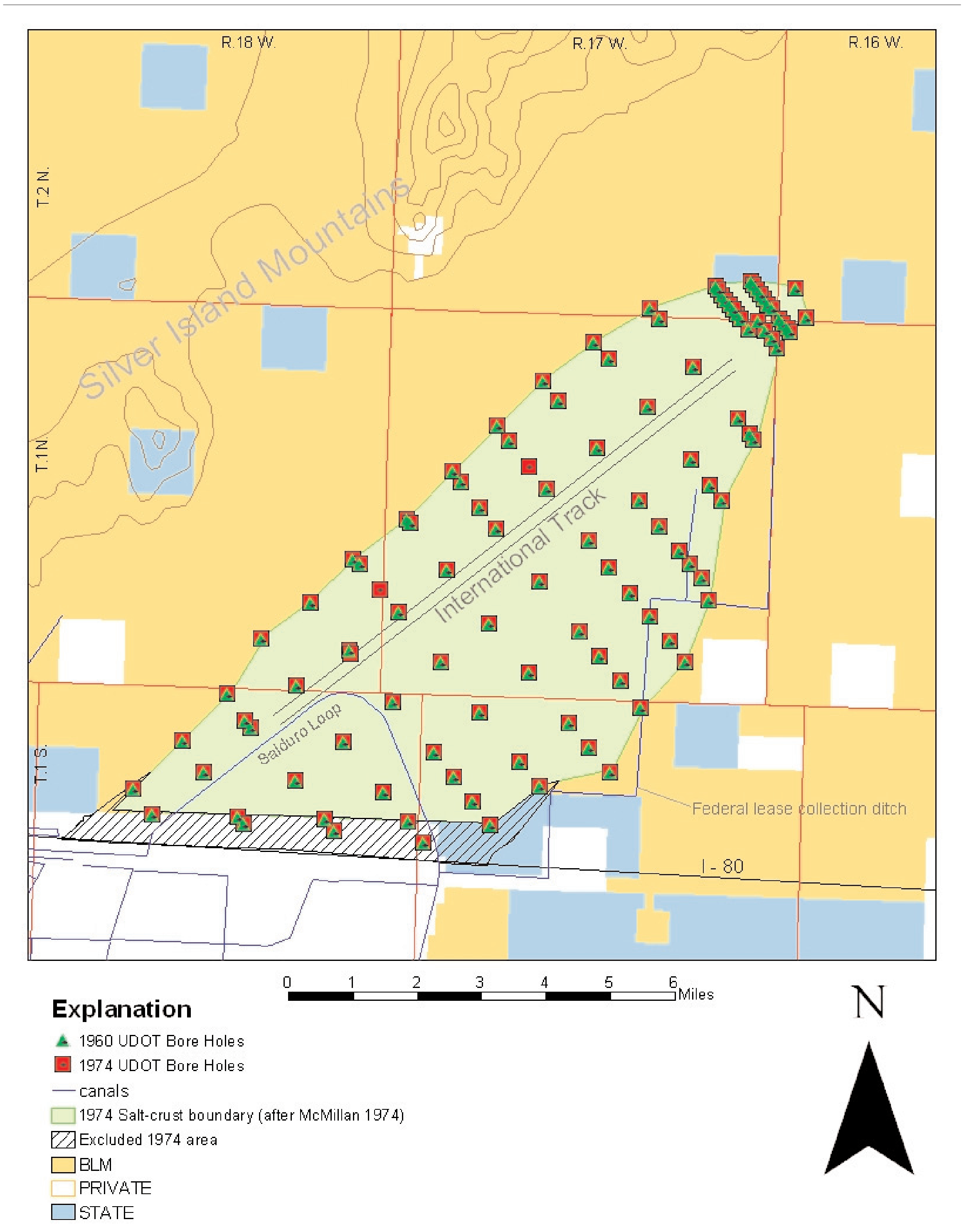

Figure 2. *Index map of the Bonneville Salt Flats showing the approximate 1974 salt-crust boundary (after McMillan 1974), and locations of the Salduro Loop, International Track, federal lease collection ditch, and the 1960 and 1974 Utah State Department of Highways (UDOT) bore holes.*

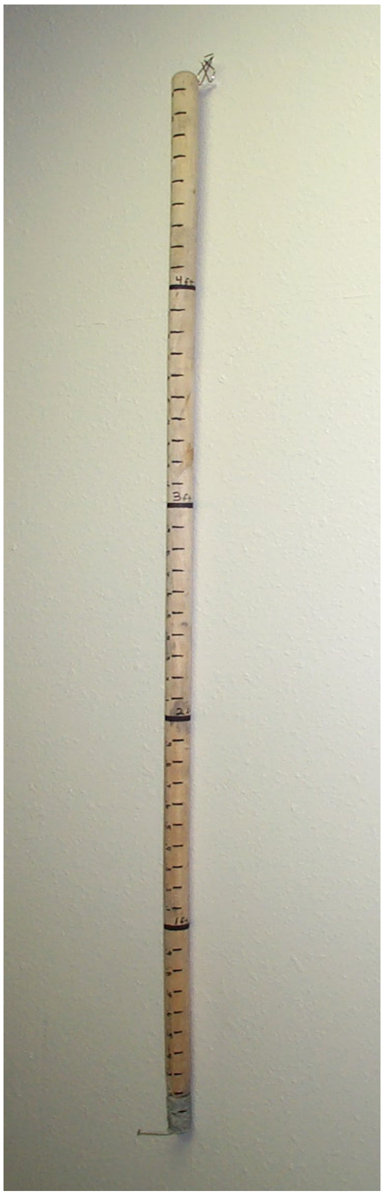

Figure 3a. *View showing entire length of UDOT 5-foot pole subdivided into 1-foot increments.*

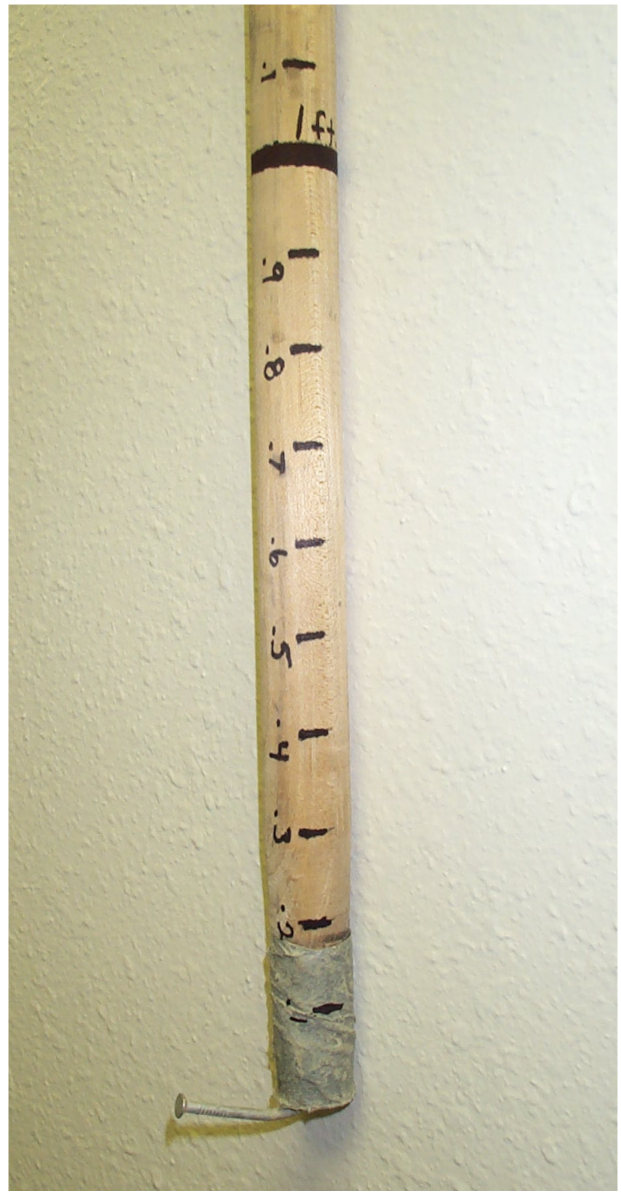

Figure 3b. *Close up of the UDOT 5-foot pole showing the hook on its lower end and the first 1-foot increment subdivided into tenths.*

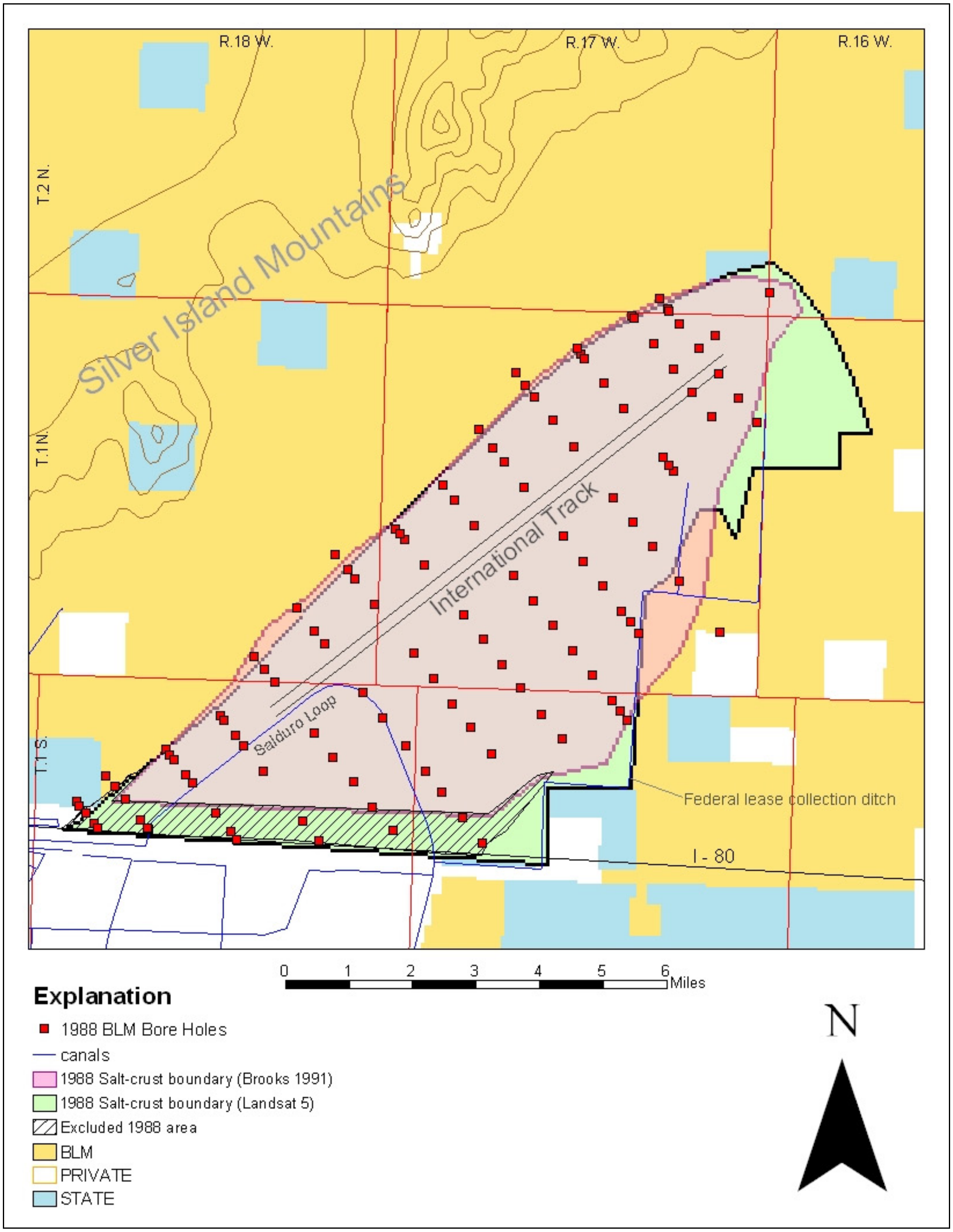

Figure 4. *Index map of the Bonneville Salt Flats showing the 1988 salt-crust boundary (Landsat 5 and Brooks versions), excluded 1988 area, and 1988 BLM bore-hole locations.*

METHODS

In the present study, changes in estimated salt quantities were made based on the volume of salt present. The volumetric determination required delineation of 1988 and 2003 salt-crust boundaries, determination of salt crust thickness at bore hole sites within these boundaries, and calculation of volume based on the thickness measurements within the 1988 and 2003 boundaries. Visual depiction of thickness differences between 1988 and 2003 measurements was made through use of isopach maps. (Use of specific product names in the following sections does not imply an endorsement by the Bureau of Land Management).

Boundary Selection

2003 Salt-Crust Boundary

The 2003 salt-crust boundary north of I-80 was determined by a Global Positioning System (GPS) survey using the Trimble GeoExplorer III GPS unit. To accomplish the GPS survey, the salt-crust boundary was traversed on a tracked all-terrain vehicle (ATV) while continuously collecting the GPS data with the GeoExplorer III. The salt-crust boundary was identified visually by following the mud-flat/salt-crust contact. The area within this boundary contained all of the visible salt crust extending north of I-80 (including the Salduro Loop) and east to the federal lease collection ditches (figure 5). The resulting salt-crust boundary was imported into ArcGIS 8.3 (ESRI 1999-2002), where it was used with 2003 mud-auger and UDOT-pole measured salt-crust thickness data (n = 69 and 55, respectively) to make 2003 salt-crust isopach (thickness contour) maps, and to calculate their respective volumes.

1988 Salt-Crust Boundary

Brooks (1991) defined the 1988 salt crust boundary as a calculation limit line that represented the extent of the salt crust north of I-80 in 1988. However, based on comparison with October 1988 Landsat 4-5 imagery (appendix A1) and 1988 bore hole thickness measurements (Brooks 1991), this limit line did not include all of the 1988 salt crust. Brooks excluded a four square-mile strip of salt crust north of I-80, which averaged about 2 feet thick and contained more than 5,400 acre-feet of salt crust. This four square-mile area is shown in figure 4, which was derived by overlapping the 1988 salt-crust boundary (defined by Brooks, 1991, p. 8) with the revised 1988 salt-crust boundary (digitized from October 1, 1988 Landsat 4-5 imagery) using the Union function of the ArcGIS Geoprocessing Wizard. Volume of the thickness grid within this excluded area was calculated using the ArcGIS 3D Analyst. The four square-mile area appears similar to the area excluded from UDOT volume and area calculations reported by McMillan (1974) (see figure 2). Unfortunately, no rationale was reported by either Brooks or McMillan to justify this exclusion. Further-more, when the 1988 salt-crust boundary defined by Brooks was compared with that contained in McMillan, they were nearly identical and in marked contrast to the observed boundary contained in 1988 Landsat 4-5 imagery.

To resolve the discrepancy between the 1988 salt-crust boundary defined by Brooks (1991) and the boundary observed in 1988 Landsat 4-5 imagery, we revised the 1988 salt-crust boundary by using the visible boundary shown on October 17, 1988 Landsat 4-5 imagery (appendix A1, figures A1.1 and A1.2A). This revised 1988 boundary was imported into ArcGIS 8.3 and used with 1988 UDOT-pole measured thickness data (Brooks 1991; n = 118) to make the 1988 salt-crust isopach map and calculate its volume. The only 1988 salt-crust volumetric computations that used the Brooks-defined 1988 boundary in this paper are contained in a comparison of three different volumetric calculation methods (see "Comparison of Planimeter vs Radian CPS/PC and Arc GIS Volumetric Calculation Methods").

2003 Bore-Hole Location and Salt-Crust Thickness Measurements

During October 2003, BLM drilled 69 of 72 planned bore holes into the BSF salt crust. The objective was to obtain current total salt-crust thickness measurements for comparison with thickness measurements by Brooks (1991) from the 118 bore holes he drilled during 1988. Total salt-crust thickness is defined as the distance from the surface of the salt-crust to its interface with underlying clay. The 1988 thickness measurements were selected for comparison because the 118 bore-hole locations had been surveyed and their Universal Transverse Mercator (UTM) coordinates recorded.

Bore-Hole Location and Drilling Methods

Because of time and personnel limitations, only 69 of 72 bore holes were actually drilled. The original 72 bore hole locations were selected from a GIS plot of 1988 bore holes (Brooks, 1991 - see figure 4) and distributed as evenly as possible throughout the areal extent of the BSF north of I-80 (figure 5). However, some gaps in the uniform distribution of the 2003 bore holes resulted because the racing community had established three racecourses on the Salt Flats that BLM did not wish to disturb (see figure 5). Consequently, any proposed bore hole locations that plotted on any of the three active racecourses were offset to their respective course margins. The 2003 bore hole locations were located with a Trimble GeoExplorer III GPS unit by matching the GPS coordinates with surveyed 1988 UTM coordinates for each bore hole (accuracy was typically within 1 meter).

Each of the 2003 bore holes was started with a motorized hand-held auger to drill through the dense, cemented halite surface stratum, and then completed with a hand-operated mud auger (figure 6). Stratigraphy

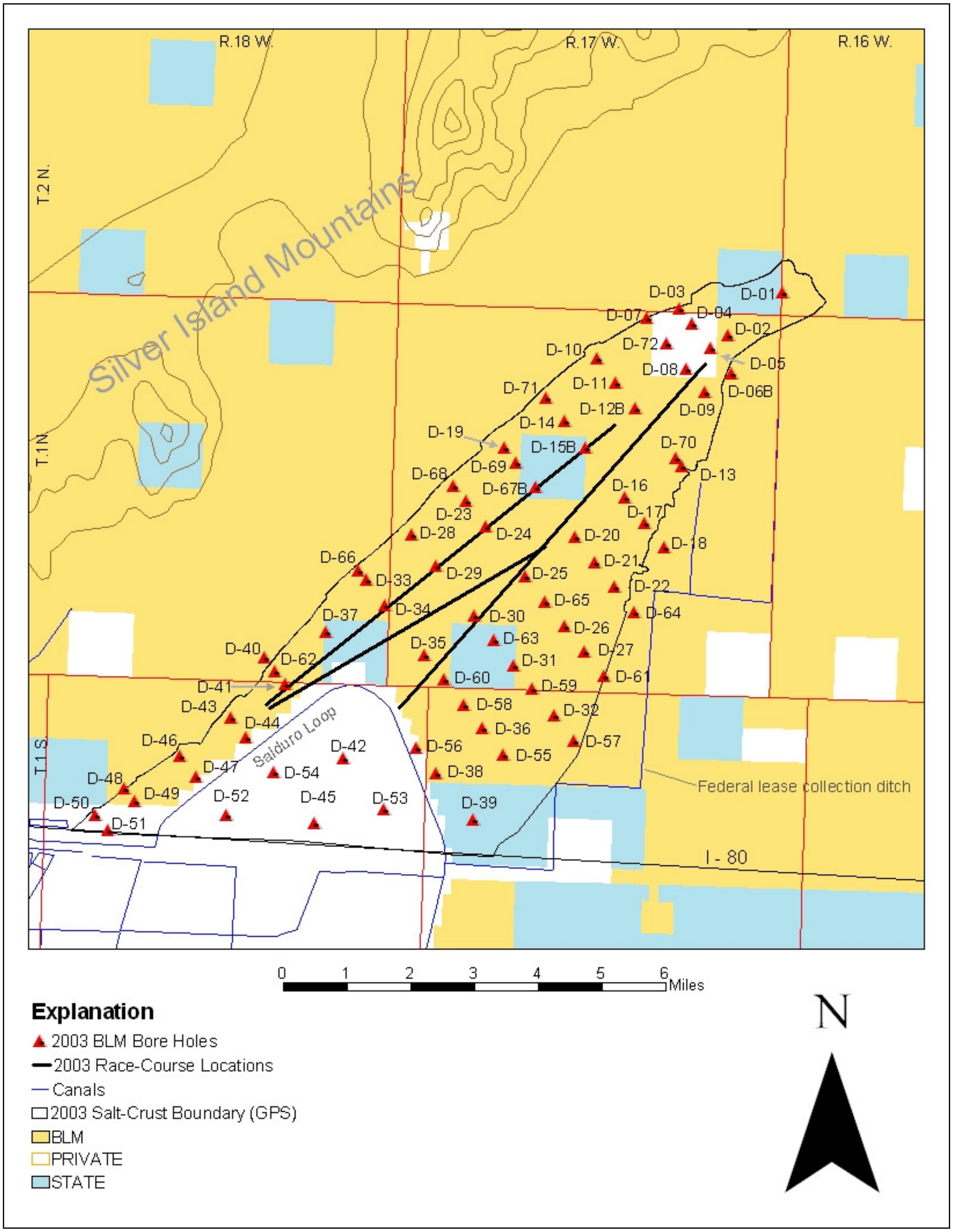

Figure 5. *Location of 2003 BLM bore holes, race courses, and 2003 salt-crust boundary.*

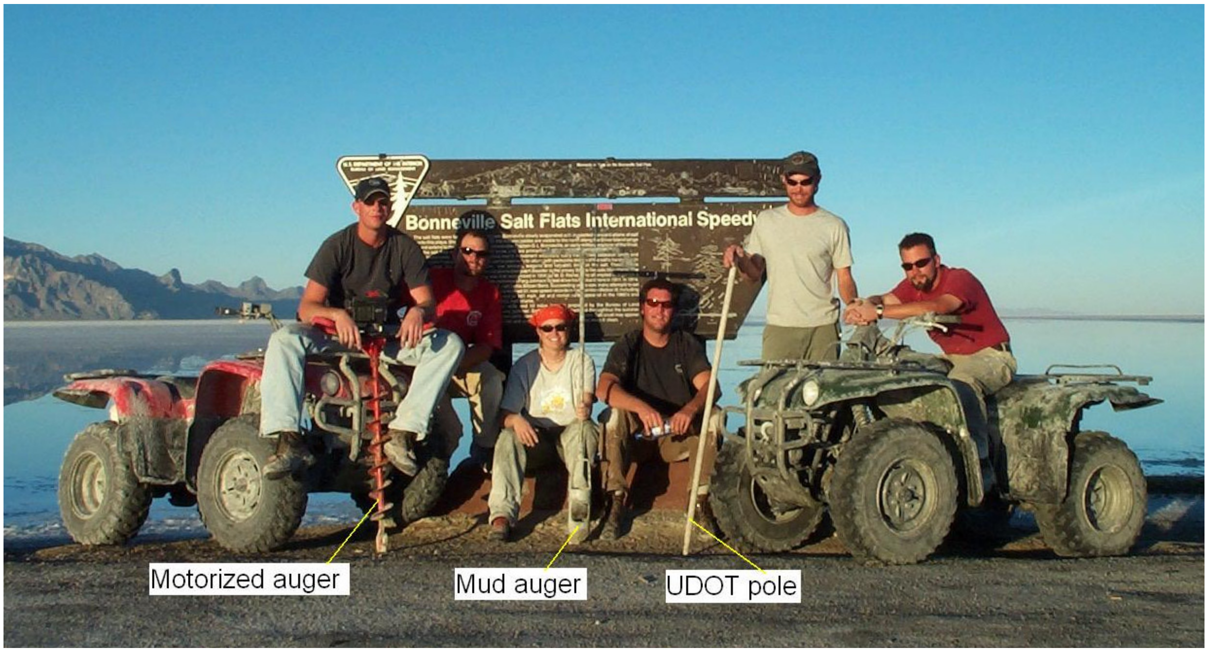

Figure 6. Equipment used to measure the 2003 salt-crust thickness.

of each bore hole was recorded by describing the sequence of sediments recovered from the mud auger as it drilled through the remaining halite and gypsum strata that comprise the salt crust (appendix A2). For the 69 bore holes drilled, thickness was first measured in each hole using the mud-auger method and then followed by measurement using the UDOT-pole method. Due to a lapse in communication, thickness in only 55 of the 69 holes was measured by the UDOT-pole method. Data from these 55 holes were used to compare the two measurement methods. Total salt-crust measurements by the two different techniques were made by two separate crew members so that neither could be biased by the other's results. Immediately after the mud auger was removed from the bore hole, a UDOT pole-measurement was made and recorded.

Representative Sampling

Because the 55 UDOT-pole measurements were less than the number of bore-hole measurements planned for the 2003 study, there was concern whether the 55 measurements would be a representative sampling of the original 118 bore-hole population. To address this concern, GIS determined salt-crust volumes were calculated using the revised 1988 salt-crust boundary determined from October 1988 Landsat 5 imagery and 1988 pole measurements from bore hole sites that matched those selected for the 2003 study (n = 55 and n = 72). The resulting two volumes were then compared with the GIS-determined volume from the total 1988 bore-hole population (n = 118). The respective volumes generated from 55, 72, and 118 bore-hole measurements differed by less than 2% (table 1). This comparison confirmed that no substantial error was introduced by using the smaller sets of 1988 bore hole data (n = 55 and 72) for volumetric calculations. Consequently, volumetric calculations from similar populations of bore hole measurements (i.e., n = 55 and 69) made during 2003 also should be valid.

Description of Measurement Methods

A marked difference in measurement technique characterizes the UDOT-pole versus mud-auger methods. The pole method relies solely on the tactile skill of the operator to discern the salt-crust/clay interface by “feeling” it with a hook, whereas the auger method actually recovers core containing the interface.

Table 1. Comparison of GIS-determined salt-crust volumes from UDOT-pole measurements made during 1988 from the total bore hole population (n = 118), and from 1988 bore hole sites that match those selected for the 2003 study (n= 55 and 72). The revised 1988 salt-crust boundary, which was determined from October 1988 Landsat 4-5 imagery was used in the volumetric calculations.

Number of bore holes, n	55	72	118
Salt-crust volume, ac-ft	59,611	60,434	59,635
Percent difference[1]	-0.04	+1.3	0.0

[1]Compared to volume generated from 118 bore-hole measurements.

UDOT-Pole Measurement Technique: The UDOT pole used in the 1988 and 2003 measurements was five feet long with a hook mounted on the bottom end. The pole was marked in one-foot increments that were each subdivided into tenths (figure 3a and 3b). The measurement method consisted of placing the pole in the bottom of the bore hole and dragging the hook end of the pole up the side of the bore hole, with the intent of catching the hook on the interface between the salt crust and underlying soft clay sediment. Once this interface was determined by "feel" with the hook, the pole was held in the bore hole at the position where the hook was caught at the interface. The thickness measurement was then made at the interception of the horizontal salt-crust surface with the marked footage on pole and recorded in tenths of feet.

Mud-Auger Measurement Technique: Total salt-crust thickness measurements were made with the mud auger (figure 7) as follows: 1) when the mud auger broke through the salt crust into the underlying clay (a marked change in ease of hand-turning the auger), the auger was left in the hole and the position of intersection of the horizontal salt-crust surface was marked on the hand-auger rod; 2) the mud auger was then removed from the bore hole and the mud- auger bucket was examined to confirm the presence of the clay/salt interface within the bucket; and 3) the distance between the clay/salt interface and the marked intersection of the horizontal salt-crust surface on the hand-auger rod was measured to the nearest tenth of a foot with an engineer's tape. This visual recovery of the clay/salt interface eliminated the inherent guesswork of determining this interface by feel as was attempted with the UDOT pole-measurement technique.

Isopach Map Construction and Volume-Area Calculation

Kriging

The ArcGIS Geostatistical Analyst extension (Johnson and others, 2001) was used to create salt-crust isopach (thickness contour) maps from both the 1988 (Brooks, 1991) and 2003 thickness data. Sources of the thickness data were the 1988 and 2003 UDOT-pole measurements (n = 118 and 55, respectively), and the 2003 mud-auger measurements (n = 69). The statistical method used to create each isopach map was ordinary kriging (differentiation between ordinary and simple kriging, and steps used in the kriging process for this study are described in appendix A3).

The resulting 1988 and 2003 kriged surfaces were converted to thickness grids so their respective area and volume could be determined. First, grid boundaries were established by using ArcGIS Spatial Analyst to "clip" the 1988 and 2003 grids to their respective salt-crust boundaries (i.e., the revised 1988 boundary based on Landsat 4-5-imagery, and the GPS-surveyed 2003 boundary). Then, respective 1988 and 2003 salt-crust areas and volumes were calculated by ArcGIS 3D Analyst from the clipped grid files. ArcGIS Spatial Analyst was also used to create equal-thickness contours from the 1988 and 2003 thickness grids for their respective isopach maps.

The objectives of creating the isopach maps were twofold: 1) to illustrate 1988 and 2003 salt-crust spatial distribution and thickness, and 2) to graphically depict thickness differences between the 2003 UDOT pole and mud-auger measurement techniques. The isopach maps illustrate salt-crust distribution and thickness differences with thickness contour lines that are graduated in 1-foot increments.

Comparison of Volumetric Calculation Methods

Brooks (1991) determined his estimation of 1988 salt crust volume from an isopach map generated using the Radian Corporation program CPS/PC v. 4.2. Data input to the CPS/PC program included Brooks' defined 1988 salt-crust boundary and 118 bore-hole measurements (UDOT-pole method). The CPS/PC program uses the least squares algorithm to extrapolate thickness values from the actual data points to grid nodes that comprise a rectangular grid that is superimposed over the data. However, instead of using the CPS/PC volumetric-calculation routine, Brooks (1991) estimated the salt-crust volume by measuring the areas comprising the CPS/PC-generated isopach map with a planimeter, and then multiplying each area by its average thickness.

Using the CPS/PC volumetric-calculation routine and Brooks' (1991) defined 1988 boundary and bore-hole data, Kohler determined an independent salt-crust volume, which was greater than that generated by Brooks using the planimeter method (J.F. Kohler, Chief, Solid Minerals, BLM Utah State Office, personal communication, March 2005). Because CPS/PC and GIS-determined salt-crust volumes are more statistically rigorous than Brooks' planimeter-determined method, a comparison was made of the volumes generated by all three methods. The GIS-generated volumetric computation for this comparison was made using Brooks' defined 1988 salt-crust boundary and 118 bore-hole measurements.

Calculation of Groundwater and Chemical Gradient

To estimate the rate of horizontal recharge to the BSF, an average groundwater and chemical gradient was calculated from 1925 bore-hole data that was part of a 405 bore hole program to evaluate potash brines in the Great Salt Lake Desert (Nolan c. 1926; 1927, plate 3). Sixteen bore holes selected from the 405-bore hole population and distributed along a 54-mile south to north transect were used to supply data for the calculations (figure 8). The 54-mile distance was measured south from the approximate center of the BSF to the southern extent of a 100-g/L-chloride contour line established by Nolan (1927, plate 3). Although Nolan reported the depth to groundwater (below ground level) in each bore hole (c. 1926), surface elevations were not included in

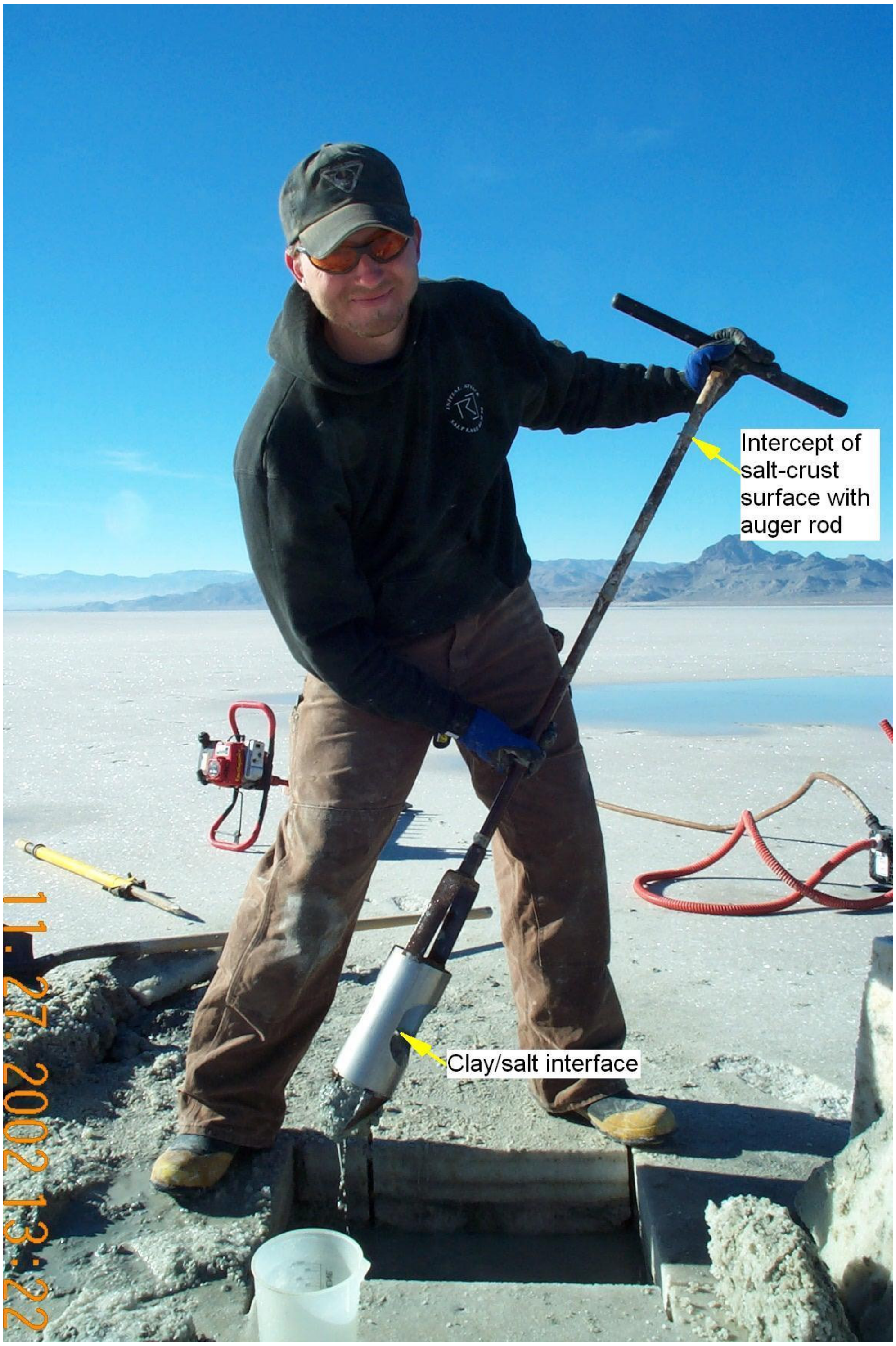

Figure 7. *View of the mud auger used to measure total salt-crust thickness.*

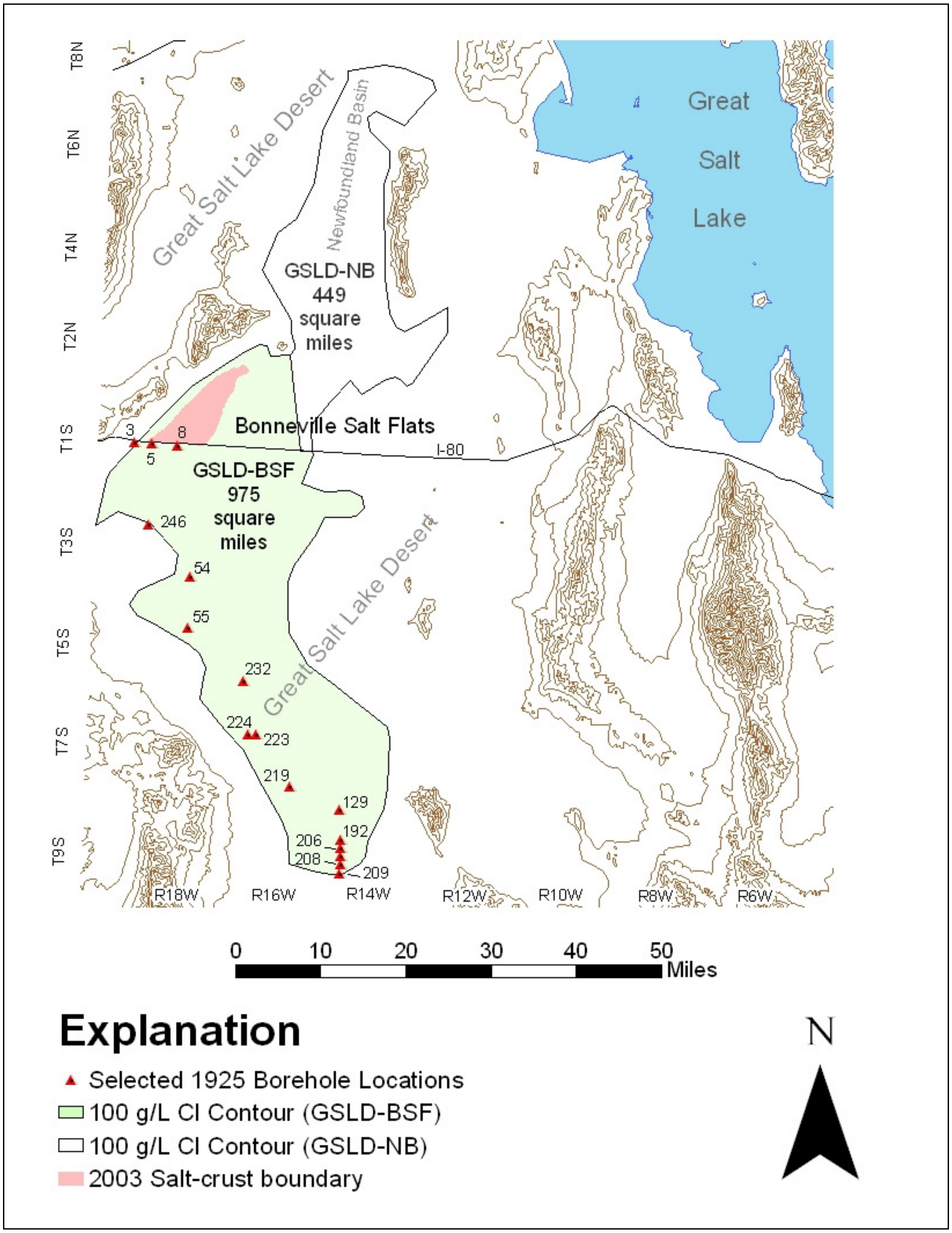

Figure 8. *Great Salt Lake Desert (GSLD) showing location of the 100 g/L chloride contour with respect to the Bonneville Salt Flats (BSF) (after Nolan 1927, Plate 3). The 100 g/L contoured area is separated into a northern and southern area because a topographic divide separates the BSF from the Newfoundland Basin. The BSF lies within the 975 mi² southern area (GSLD-BSF), while Newfoundland Basin (NB) is in the 449 mi² northern area (GSLD-NB).*

his data. Consequently, surface elevations were estimated to the nearest foot by replotting these 16 bore hole locations on current U.S. Geological Survey 7.5 minute topographic maps that covered the same bore-hole locations shown in Nolan (1927, plate 3). Groundwater elevation for each bore hole was determined by subtracting the depth to water from the surface elevation (appendix A4, table A4.1). Groundwater and chemical gradient computations are summarized in appendix A4.

RESULTS AND DISCUSSION

Introduction

We concluded from our analysis of 1988 and 2003 salt-crust measurements and their respective calculated volumes that 1) salt-crust volumes determined by the 2003 mud auger measurements were 7% larger than those determined by the 2003 UDOT pole measurements, 2) there was virtually no difference between salt-crust volumes determined by the 1988 and 2003 pole measurements, and 3) the Laydown Project produced no measurable change in salt crust thickness.

Comparison of Measurement Methods

Pole vs Auger Measurements

Accuracy of Measurements: Comparison of results from the two methods was provided by auger and pole measurements in 55 of the 69 bore holes drilled in 2003. Auger measurements of total salt-crust thickness exceeded comparative pole measurements in 27 or 49% of the 55 bore holes, while pole measurements exceeded their corresponding auger measurements in 23 or about 42% of the 55 bore holes. There was no difference between corresponding auger and pole measurements in 5 or 9% of the 55 bore holes (see appendix A2).

Auger measurements exceeded pole measurements in the 27 bore holes by an average of 2.3 inches, ranging from 0.1 to 13 inches. Nearly 60% or 16 of the 27 bore holes were situated in the thicker areas of salt crust (i.e., >2.0 feet - figure 9). Salt-crust stratigraphy in these areas was commonly characterized by presence of uncemented coarse porous halite stratum that formed the interface with the underlying clay. Sloughing of this uncemented halite caused a segment of the lower portion of these bore holes to cave during the short time interval between

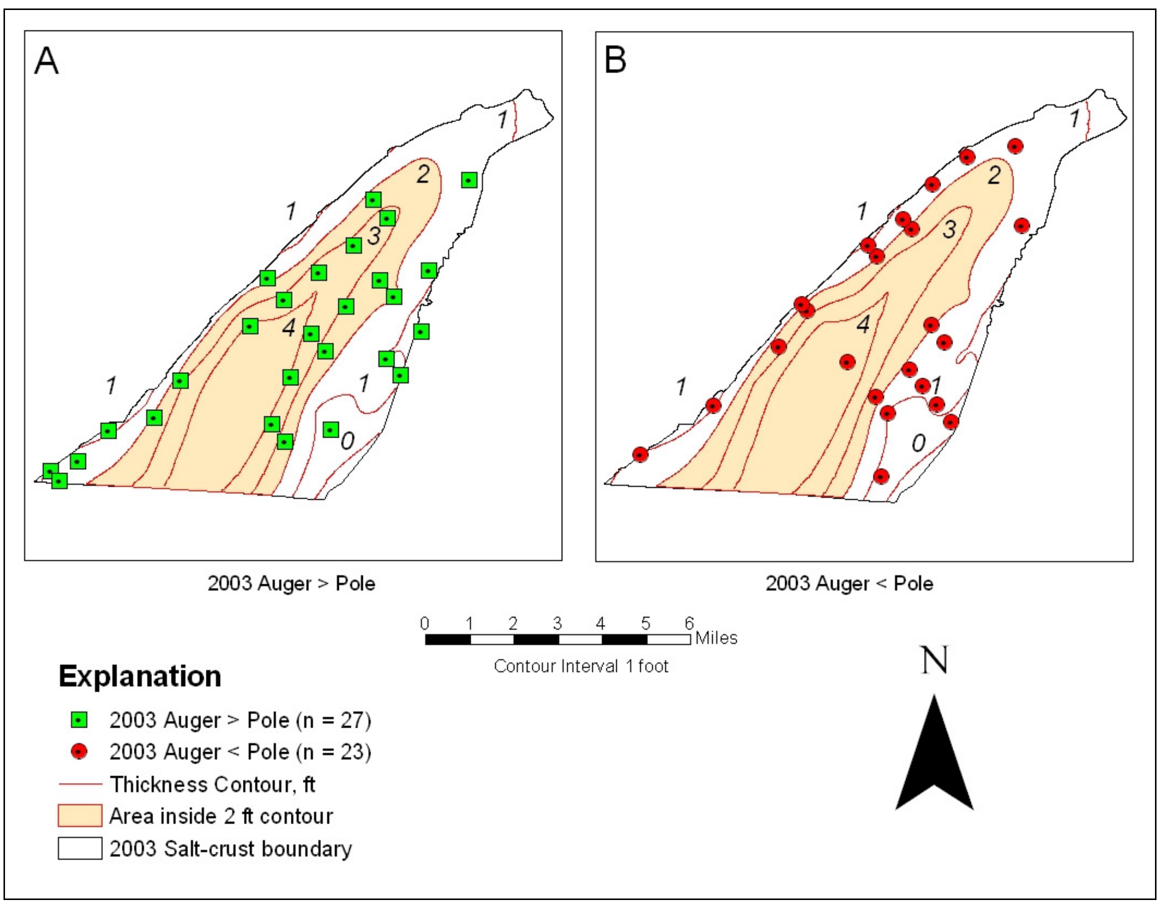

__Figure 9.__ Location of bore holes where pole measurements differ from auger measurements. Bore-hole locations are plotted on the 2003 salt-crust isopach generated from auger measurement technique.

removing the auger and inserting the pole (sloughing was observed in numerous mud-auger bore holes drilled by BLM during the Salt Laydown Project from 1998-2002). This effectively reduced the measured depth when using the pole-measurement technique. The 11 remaining bore holes were located mainly on the west and east margins of the thinner sections of the salt crust. Fine-grained gypsum strata with thicknesses that range from 7 to 14 inches formed the interface with the underlying clay. Underestimation of pole-measured thickness in these 11 holes may have been a matter of not being able to discern the gypsum/clay interface due to 1) mistaking the gypsum for clay, or 2) encountering resistant substrate within the gypsum stratum.

Conversely, pole measurements exceeded auger measurements in 23 bore holes by an average of 1.3 inches, ranging from 0.1 to 6.3 inches. About 78% or 18 of the 23 bore holes were located in the thinner areas of salt crust (i.e., <2.0 feet) on its west and east margins (see figure 9). However, salt-crust volume from these thinner areas represents a small percentage of the auger-measured total salt-crust volume (61,440 acre-feet) when compared with salt crust >2.0 feet (14,315 versus 47,125 acre-feet, or 23 and 77%, respectively) (appendix A5). Salt-crust stratigraphy in these thin salt-crust areas was typically characterized by about 1 to 3 inches of dense cemented halite surface stratum followed by 10 or more inches of fine-grained gypsum crystal stratum whose bottom surface formed the interface with the underlying clay. Because of gypsum crystal angularity and presence of a small amount of clay that acts as a binder, these holes had a tendency to stay open rather than cave. Overestimation of total salt-crust thickness by the pole method in these 18 bore holes might be due to lack of tactile difference between the fine-grained gypsum/clay interface, and possibly "hooking" onto some resistant substrate below the gypsum/clay interface. The five remaining bore holes were located in thicker sections of the salt crust. Four bore holes had more than 12 inches of coarse halite strata overlying their respective salt/clay interfaces, while the remaining bore hole had 22 inches of fine-grained gypsum stratum overlying the clay. Why thickness was overestimated by the pole-measurement method in these five bore holes is currently unknown (especially in the four holes containing coarse salt at the salt/clay interface, which usually sloughed and resulted in underestimation of thickness).

To summarize, auger measurements exceeded comparative pole measurements in 49% of the 55 bore holes, while pole measurements exceeded their corresponding auger measurements in 42% of the 55 bore holes. Underestimation by pole method was mainly in thicker areas of salt crust, while overestimation was primarily in thinner salt crust. Thicker areas of salt crust made up 77% of the 2003 salt-crust volume, while thinner areas made up 23%. Consequently, underestimation of salt-crust thickness in the thicker areas of the Salt Flats had greater impact on subsequent GIS volumetric computations based on pole measurements than those from auger measurements (see "2003 Pole vs Auger-Derived Volumes by GIS").

Precision of Measurements - White (2004) summarized the difficulty replicating measurements made with the UDOT pole-measurement technique within the same hole and among multiple, closely-spaced holes. However, consistency of the auger-measurement technique was fortuitously demonstrated in multi-year thickness measurements made at Salt Laydown Project monitoring sites (table 2). Two sites with three consecutive years of salt-crust measurements (BLM-60, and BLM-93) had thicknesses that were within 0 to 2% of each other. A third site (BLM-46) had two years of matching measurements. Assuming that change in salt-crust thickness has been negligible (no significant change in salt-crust volume between 1988 and 2003; see "1988 Pole vs 2003 Pole-Derived Volume by GIS"), these measurements indicate a high degree of precision. Less precision is indicated by annual measurements at BLM-43C and BLM-44A (table 2).

Table 2. *Salt-crust thickness measurements during 2000-2002 at five Salt-Laydown-Project monitoring sites (thickness expressed in feet) using the mud-auger measurement technique. Monitoring site data are from White (2004).*

Location*	2000	2001	2002
BLM-43C	2.65	3.00	—
BLM-44A	—	2.20	2.60
BLM-46	2.00	2.00	—
BLM-60	1.63	1.63	1.60
BLM-93	3.50	3.50	3.50

*Existing monitoring wells BLM-43C through BLM-93 were used as reference points to locate bore holes from which salt-crust thickness measurements were made during the Salt Laydown Project.

Comparison of Salt-Crust Volumes by Measurement Method

To evaluate potential differences in salt-crust volumes due to differences in 2003 measurement methods and differences in time elapsed between 1988 and 2003 UDOT pole measurements, two comparisons were made. The first comparison examines salt-crust volume differences due to differences in accuracy and precision between 2003 UDOT-pole and 2003 mud-auger measurement methods. The second comparison evaluates volume differences/similarities generated from 1988 and 2003 UDOT pole measurements and revised 1988 and GPS-determined 2003 salt-crust boundaries. Additionally, volumes contained within 1 and 2-foot salt-crust thickness contours depicted in 1988 and 2003 isopach maps derived from their respective UDOT pole measurements were also compared.

2003 Pole vs 2003 Auger-Derived Volumes by GIS

GIS-determined total salt-crust volumes based on 2003 pole and auger measurements (n = 55 and 69, respectively) and 2003 GPS-measured boundary were 57,323 and 61,440 acre-feet, respectively (table 3). "Total" salt-crust volume includes all salt crust north of I-80 contained within the 0-ft thickness contour. Total salt-crust volume determined by the auger measurements was 7% larger than that determined by the UDOT pole measurements, representing a salt-mass difference of about 10 million tons (calculated using average salt-crust density of 109.8 pounds per cubic foot - Mason and Kipp, 1998).

This volume difference is consistent with data presented in the previous "Accuracy of Measurements" section. Specifically, when pole measurements were compared with auger measurements in the same bore holes, pole measurements underestimated salt-crust thickness in about 60% of bore holes drilled where salt crust thickness was >2 ft. GIS-derived isopach maps from 2003 pole and auger measurements show distribution and areal extent of salt crust as areas within specific thickness contours (figures 10A and 10B). Areas within the 2 and 3-ft contours have been highlighted because collectively they make up 77% of the salt crust volume and help normalize annual variation in position of the salt-crust boundary (0-ft contour) on the east margin of the BSF. The most visible difference between the two isopach maps was that the area within the 3-ft contour generated from pole measurements was 20% less than that from auger measurements. Furthermore, pole-measured volumes within the 2 and 3-ft thickness contours were respectively 10 and 30% less than that of the auger-measured volume (table 4). The significance of this underestimation by UDOT pole measurement is that it occurred in an area of salt crust thickness (>2 ft) that made up 77% of 2003 salt-crust volume, and would consequently result in measurable volumetric calculation error.

1988 Pole vs 2003 Pole-Derived Volume by GIS

Because salt-crust thickness was measured in 1988 and 2003 using the same method (UDOT pole), GIS-determined total salt-crust volumes from 1988 and 2003 UDOT pole measurements were compared to see if any measurable differences could be observed (see table 3). Comparison between measurements made with the same measurement technique helped normalize the difference observed in the previous section between UDOT-pole and mud-auger measurement methods. When compared with the 2003 pole-measured volume, the 1988 pole-measured volume was about 4% larger (59,635 vs 57,323 acre-feet). This is because the estimated salt-crust area derived from the October 1988 Landsat 4-5 imagery was about 16% larger than the GPS-measured 2003 salt-crust area.

The primary cause of this difference in area is believed due to the 1996 construction of a berm between the north end of the lease collection ditch and Floating Island as part of the Salt Laydown Project (R. Draper, Mill and Pond Superintendent, Intrepid Potash-Wendover LLC, personal communication, January 2006 - see appendix A1, figures A1.1 and A1.2A and B). Prior to the berm being constructed in 1996, the winter transient pond had an unrestricted path that allowed it to flow around the north end of the collection ditch. This annual transient pond usually forms in low areas of BSF from November through March or April (Lines, 1979), and is a combination of seasonal meteoric precipitation and shallow brine aquifer ponding on the BSF surface during the winter months (Mason and Kipp, 1998). Spring or early summer evaporation of the transient pond commonly resulted in a thin deposit of salt crust on the east side of the lease collection ditch that terminated eastward to a featheredge. While this thin deposit appeared to increase the areal extent of the salt crust, it was probably a transient feature that could likely be dissolved by seasonal meteoric precipitation.

Table 3. *Comparison of volume, mass, and area determined by ArcGIS 3D Analyst from 1988 - 2003 pole measurements and 2003 auger measurements of total salt crust; n = number of thickness measurements.*

SALT CRUST	3D ANALYST		
	1988 - Pole*	2003 - Pole#	2003 - Auger#
Total Salt-Crust Volume, ac-ft	59,635	57,323	61,440
Total Salt-Crust Volume Difference, %@	0	-4	+3
Tons, 10^6	143	137	147
Area, mi^2	45.9	38.5	38.4
n	118	55	69

*Computed using 1988 salt-crust boundary from October 1988 Landsat 4-5 imagery.
#Computed using 2003 salt-crust boundary.
@Compared to 1988 UDOT pole-determined volume.

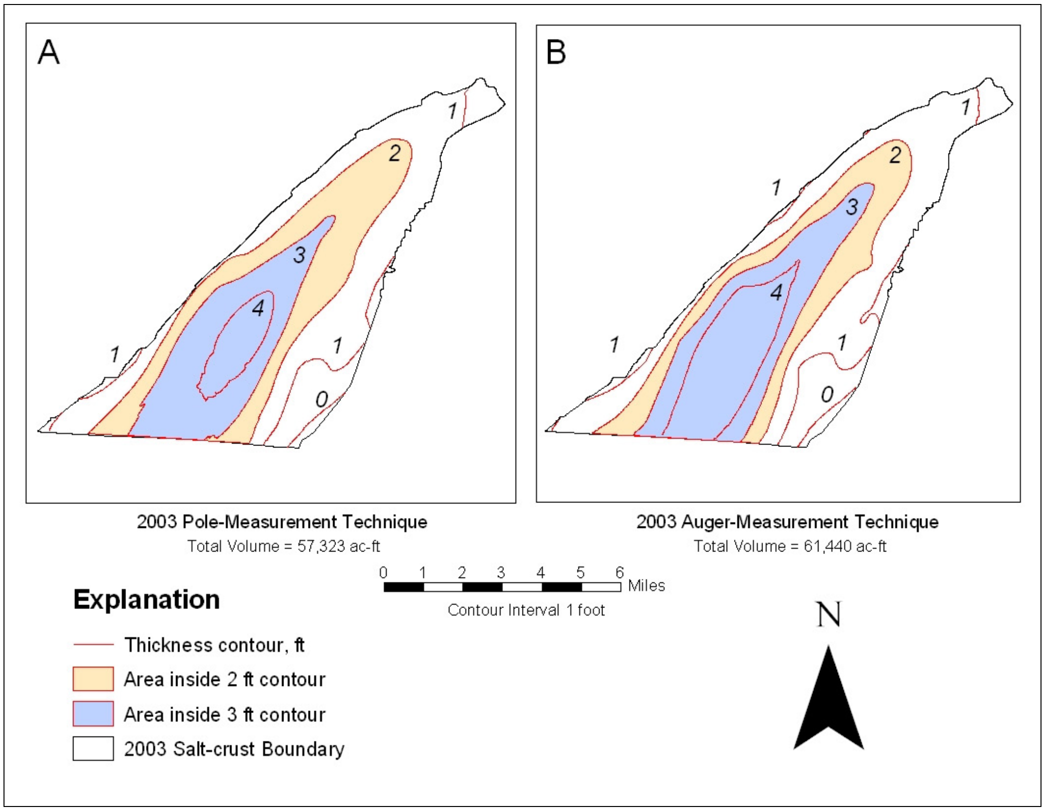

Figure 10. *Salt-crust isopach maps generated by GIS grids derived from 2003 bore-hole measurements: 10A was generated from pole measurements of 55 bore holes; 10B was generated from auger measurements of 69 bore holes.*

Table 4. *Comparison of volume, mass, and area determined by ArcGIS 3D Analyst from 1988 - 2003 pole measurements and 2003 auger measurements of salt crust with thickness >1 ft; n = number of thickness measurements.*

SALT CRUST	3D ANALYST		
	1988 - Pole*	2003 - Pole#	2003 - Auger#
Salt-Crust Volume (thickness >1 ft), ac-ft	54,054	55,462	59,465
Volume Difference (thickness >1 ft), %@	0	+2.5	+10.3
Tons, 10^6	129	133	142
Area, mi^2	32.1	34.6	34.4
Salt-Crust Volume (thickness >2 ft), ac-ft	43,589	42,903	47,125
Volume Difference (thickness >2 ft), %@	0	-1.6	+8.1
Tons, 10^6	104	103	113
Area, mi^2	21.4	21.6	21.4
Salt-Crust Volume (thickness >3 ft), ac-ft	27,376	25,589	33,620
Volume Difference (thickness >3 ft), %@	0	-6.9	+22.8
Tons, 10^6	65	61	80
Area, mi^2	11.5	10.9	13.1
n	118	55	69

*Computed using 1988 salt-crust boundary from October 1988 Landsat 4-5 imagery.
#Computed using 2003 salt-crust boundary.
@Compared to 1988 UDOT pole-determined volume.

Once the berm was constructed, the transient pond was usually restricted to the west side of the collection ditch, which limited the extent of the BSF salt crust. However, despite the 16% difference in salt-crust area due to the Laydown-related berm construction, GIS-determined total salt-crust volumes from 1988 and 2003 UDOT pole-measurement techniques (n = 118, and 55) differed by only 4% over a 15-year period. This is in marked contrast to the 15% volume decrease reported by McMillan (1974) during a 14-year period between 1960 and 1974.

The minimal volume change between 1988 and 2003 is further reinforced through examination of GIS-generated isopach maps from 1988 and 2003 pole measurements (figures 11A and 11B). To normalize effects on volume from shifts in 1988 and 2003 salt-crust boundary positions on the east margin of the BSF, areas within the 1 and 2-ft contours of both maps were examined for volume differences because they contain more than 90 and 70%, respectively, of the 1988 and 2003 salt-crust volumes measured by UDOT pole method. GIS-determined volumes within the 1-ft contour show that the 2003 pole volume is 2.5% more than the 1988 pole volume. Conversely, within the 2-ft contour the 2003 pole volume is 1.6% less than that of the 1988 pole volume (table 4). The fact that these volume differences between the 1 and 2-ft contour areas are less than 3% suggests that there is virtually no difference between 1988 and 2003 salt-crust volumes based on the UDOT pole measurement method.

Comparison of 1988 and 2003 Salt-Crust Thickness Studies

The ArcGIS-determined volume from 1988 UDOT-pole measurements (n = 118) and a revised 1988 salt-crust boundary digitized from October 1988 Landsat 4-5 imagery was 59,635 acre-feet. ArcGIS-determined volumes from 2003 UDOT-pole and mud-auger measurements (n = 55 and 69) and the GPS-measured 2003 salt-crust boundary were 57,323 and 61,440 acre-feet respectively. These ArcGIS-determined volumes were larger (13, 9, and 16%, respectively) and in marked contrast with the 1988 planimeter-determined volume of 52,757 acre-feet, which used a salt-crust boundary defined by Brooks (1991). To illustrate and evaluate the difference between the planimeter-determined volume used by Brooks and more statistically rigorous methods, a comparison was made between the planimeter method, and Radian CPS/PC and ArcGIS volumetric computation methods and summarized in the next section. Following this summary is an evaluation of salt-crust depletion predicted by Brooks (1991) in comparison with measured 2003 salt-crust volume.

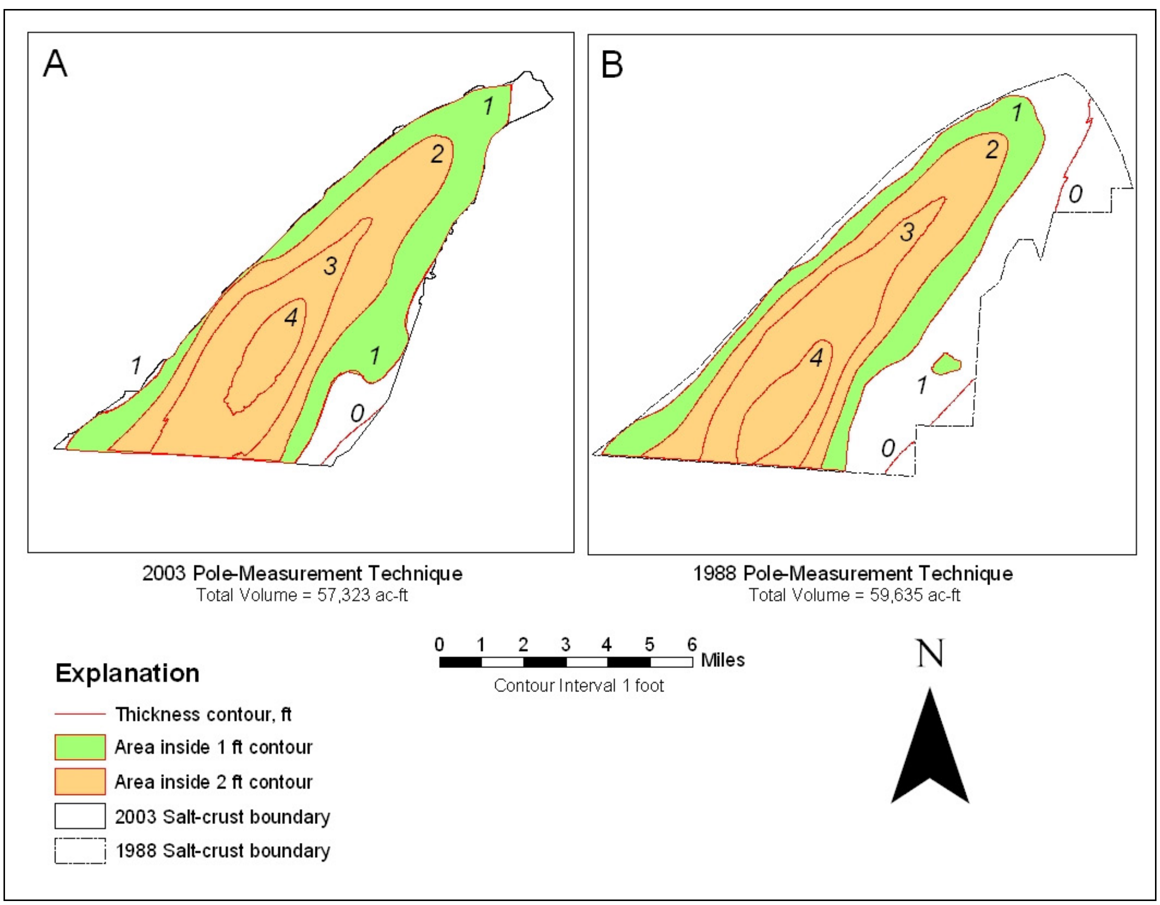

Figure 11. *Salt-crust isopach maps generated by GIS grids derived from 2003 and 1988 bore-hole measurements: 11A was generated from 2003 pole measurements of 55 bore holes; 11B was generated from 1988 pole measurements of 118 bore holes.*

Comparison of Planimeter vs Radian CPS/PC and ArcGIS Volumetric Calculation Methods

Because the 1988 salt-crust boundary (defined by Brooks 1991) did not include all salt crust north of I-80 (i.e., 4 square miles of area and more than 5,400 acre-feet of volume), and was substantially different from the boundary documented in 1988 Landsat 4-5 imagery, it is not the most appropriate boundary to be used for the 1988 volumetric determination. However, it is used here to normalize the comparison among three different volumetric computation methods.

Subsequent to Brooks' calculation of 1988 salt-crust volume using the planimeter method, the 1988 salt-crust volume was re-calculated from Brooks' 1988 boundary and thickness measurements (n = 118) using the Radian Corporation program CPS/PC v. 4.2. This re-calculation resulted in a volume nearly 7% larger than that generated by the planimeter method. Because of this difference in the 1988 volume determined by two different methods using the same salt-crust boundary and thickness data, a third volumetric-computation method (ArcGIS) having statistical rigor similar to the CPS/PC method was performed to provide a third value for comparison. When CPS/PC and ArcGIS -determined volumes were compared with the planimeter volume, they were both larger (an increase of about +7 and +3% was observed - table 5). Less than a 4% difference was observed between the CPS/PC, and ArcGIS-determined volumes.

In summary, volume differences produced by the three volumetric computation methods are thought largely a function of statistical rigor inherent to the CPS/PC and ArcGIS methods, contrasted with the simplified estimate obtained from the planimeter method.

Predicted 2003 Salt-Crust Volume Compared to Actual 2003 Salt-Crust Volume

The marked difference between Brooks' (1991) planimeter-determined salt-crust volume and later GIS-determined volumes is due to multiple factors. These include 1) differences in the boundary selected (i.e., 1988 boundary defined by Brooks vs 1988 boundary digitized from October 1988 Landsat 4-5 imagery, and exclusion of 4 square miles of existing salt crust area from Brooks' 1988 boundary), 2) differences in salt-crust thickness measurement-method accuracy and precision, and 3) contrast in statistical rigor between planimeter and GIS-determined salt-crust volumetric calculation. These differences in boundary selection, measurement method, and volumetric calculation lead to questions about Brooks' (1991) conclusion that salt-crust volume was being depleted at an annual rate of 1.1%.

Brooks (1991) concluded that the salt-crust volume was decreasing based on the difference in volume between the 1960 UDOT and 1988 BLM salt-crust thickness measurements. To compare this prediction with salt-crust conditions existing as of 2003, the following calculations were made:

- The 15 years elapsed from 1988 to 2003 were multiplied by the predicted depletion rate of 1.1% per year for a total predicted depletion percentage of 16.5%;

- The GIS-determined volume from 1988 UDOT pole measurements (n = 118) and the revised 1988 salt-crust boundary (digitized from October 1988 Landsat 4-5 imagery) was used because it was 13% greater than the planimeter-determined volume (59,635 vs 52,757 acre-feet);

- The total depletion percentage of 16.5% was subtracted from 100% and the result multiplied by the GIS-determined 1988 volume of 59,635 acre-feet;

- 83.5% of 59,635 acre-feet yielded 49,795 acre-feet of salt crust volume predicted for the year 2003.

Although a salt-crust volume of 49,795 acre-feet was predicted for 2003 based on the depletion rate of Brooks (1991), the GIS-determined volume for 2003 using auger thickness measurements and the 2003 salt-crust boundary was 61,440 acre-feet, or 19% greater than the predicted volume. This 19% difference represents a salt crust

Table 5. *Comparison of planimeter, Radian CPS/PC, and ArcGIS calculation methods. The 1988 boundary identified by Brooks (1991) was used in these volumetric computations.*

Calculation Method	Planimeter	Radian CPS/PC	ArcGIS
Data Set	**1988 pole**	**1988 pole**	**1988 pole**
Volume, ac-ft	52,757	56,200	54,063
Volume Difference, %@	0	+7	+3
Area, mi^2	42	42	42
n	118	118	118

@Compared to planimeter-determined volume mass of about 28 million tons. While it may be tempting to attribute some of this difference to salt contribution from the recent Salt Laydown Project, White (2002, 2004) concluded based on geochemical modeling that most of the Laydown tonnage (6.7 million tons through May 2003) actually resides in the aqueous phase of the shallow brine aquifer, rather than in the solid-phase salt crust.

On the basis of data presented in the previous discussion of pole versus auger-measurement accuracy and precision, the difference between depletion-rate predicted and GIS-determined 2003 salt-crust volume is more likely due to measurement error introduced through use of the UDOT pole-measurement technique. These volumetric discrepancies strongly suggest that a measurement error may have been introduced into the previous 1960 and 1974 UDOT and 1988 BLM salt-crust measurements. Additionally, documented measurement discrepancies between 2003 auger and 2003 pole-measurement techniques (appendix A2, tables A2.2.1 and A2.2.2) call into question the accuracy of corresponding salt-crust volumes derived solely from pole measurements that were subsequently used to make trend predictions for perceived depletion of the salt crust between 1960 and 1988. Furthermore, neither of the GIS-determined salt-crust volumes from 2003 auger and pole measurement techniques supports the 2003 volume predicted by Brooks' (1991) 1.1% average annual depletion rate (i.e., 61,440 and 57,323 vs 49,795 acre-feet).

Assessment of Kriging Accuracy

To evaluate the accuracy of the isopach maps, two methods were used to assess the degree of matching between predicted (kriged) and measured thickness values. The first method used the cross validation function of ArcGIS Geostatistical Wizard, and the second method used a comparison of empirical thickness data with predicted thickness values generated from kriging salt-crust thickness measurements (the 2003 isopach map generated from auger-measured thickness was used for both assessment methods).

Statistical Assessment - Cross Validation

Cross validation selected a single bore hole within the total bore-hole population and predicted its thickness by kriging the remaining population thickness values; this process was repeated by the cross-validation routine until each bore-hole thickness was predicted (see appendix A3). To assess goodness of the match between predicted and measured values, the following conditions should be met (actual cross validation values for 2003 kriged bore-hole data are in parentheses): 1) mean prediction error should be near zero (0.00129); 2) average standard error should be close to the root-mean-squared prediction error (0.49 and 0.4094, respectively); and 3) root-mean-squared standardized error should be close to 1.0 (0.8376). Resulting values in parentheses are within the prediction error limits and suggest acceptable agreement between the predicted and measured values.

Empirical vs Predicted Assessment

The second method was a cursory comparison of salt-crust thickness measurements taken at 13 Salt-Laydown-Project monitoring sites during 1998-2002, and their corresponding values at the same 13 sites plotted on an isopach map.

The isopach map was generated from a GIS thickness grid resulting from kriging the 2003 auger thickness measurements (n = 69). Isopach thickness values were determined by superimposing the monitoring site layer over the GIS thickness-grid layer (from which the 2003 isopach map was created) and querying the thickness-grid layer at each of the 13 monitoring site locations (table 6; figure 12). A total of 20 measurements were distributed among the 13 monitoring sites (multi-year thickness measurements were taken at seven of the 13 sites). An examination of the comparative data showed good agreement (i.e., up to +10% difference) between predicted and measured values for 14 out of 20, or 70% of the comparisons. Differences among the remaining 6 comparisons ranged from predicted greater than measured by 11 to 33%.

Relationship of Thickness Studies to the Salt Laydown Project

McMillan (1974) and Brooks (1991) reported that the BSF salt crust volume had decreased between 1960 and 1988 (see “Previous Work”). Consequently, the experimental Salt Laydown Project was designed to replenish salt to the BSF and began transferring sodium chloride as brine to the BSF in November 1997 (White 2002, 2004). The Project's objective over a five-year period was to transfer 7.5 million tons of sodium chloride to a 28 square-mile area of salt crust north of I-80 and add two inches to the salt crust's total thickness (Bingham 1991).

During five years of operation, the Laydown project delivered 6.2 million tons or 83% of the sodium chloride originally designed to be transferred to the BSF. Although multi-year thickness comparison measurements were made of the surface salt stratum (dense-cemented halite) at six monitoring well locations, none of these locations showed the predicted two-inch thickness increase at the end of five years despite the addition of 6.2 million tons of salt to the BSF (White, 2004). Based on these observations and geochemical modeling, White (2004) concluded that most of the Laydown salt (6.2 million tons) was assimilated into the shallow-brine aquifer, while a small amount (0.6 million tons) was accounted for in five square miles of new salt-crust area.

Despite replenishment of salt to the BSF by the Laydown project, short-term comparisons of total salt-crust thickness made at three of five monitoring locations examined during the Laydown project showed little or no

Table 6. Comparison between measured salt-crust thickness at 13 Salt-Laydown-Project monitoring sites and their corresponding predicted-thickness values from an Isopach map derived from 2003 auger -thickness measurements (n = 69; thickness expressed in feet). Monitoring site data are from White (2004, p. 249).

	Measured Thickness[2]					**Predicted/Measured**			
Location[1]	**1998**	**2000**	**2001**	**2002**	**Predicted 03 Auger**	**1998**	**2000**	**2001**	**2002**
BLM-43C	—	2.65	3.00	—	2.89	—	1.09	0.96	—
BLM-44A	—	—	2.20	2.60	2.33	—	—	1.06	0.90
BLM-46	—	2.00	2.00	—	1.91	—	0.96	0.96	—
BLM-48	—	—	1.10	—	1.29	—	—	1.17	—
BLM-60	—	1.63	1.63	1.60	1.59	—	0.98	0.98	0.99
BLM-71A	—	—	2.70	—	2.89	—	—	1.07	—
BLM-93	—	3.50	3.50	3.50	4.66	—	1.33	1.33	1.33
KSL-01	—	—	—	3.00	3.26	—	—	—	1.09
MB-1	1.04	—	—	—	1.15	1.11	—	—	—
MB-2	1.00	—	—	—	0.95	0.95	—	—	—
MB-3	1.58	—	—	—	1.59	1.01	—	—	—
MB-6	1.83	—	—	—	2.00	1.09	—	—	—
MB-7	3.00	—	—	—	3.79	1.26	—	—	—

[1]See figure 12: BLM-43C, etc. are monitoring wells used as reference points to locate repetitive bore-hole measurements; KSL-01 is the site of a one-time test pit near mile post 3 of the International Track; MB-1, etc. are geotechnical bore holes with one-time thickness measurements.

[2]All mud-auger measurements.

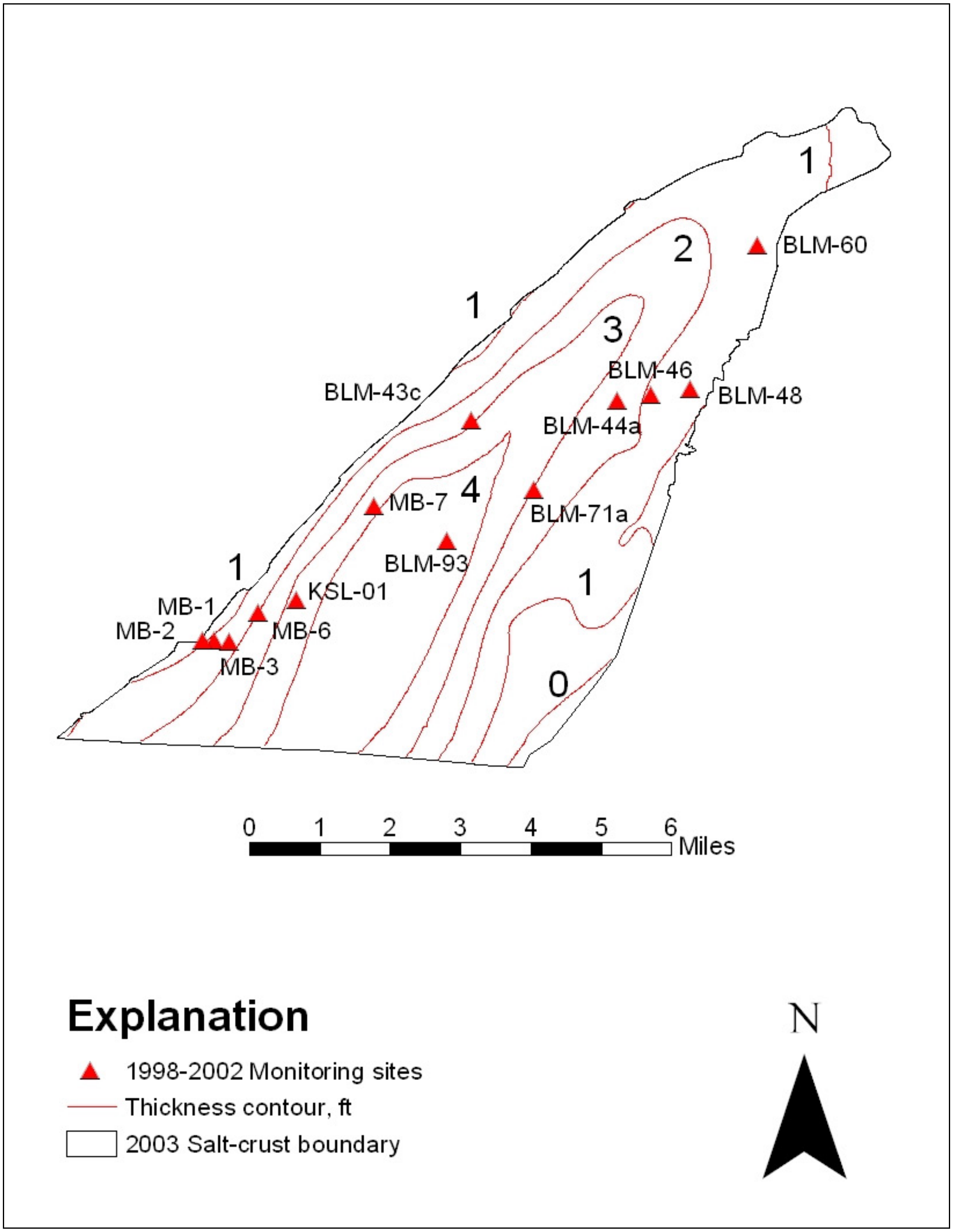

Figure 12. *Location of 1998-2002 Salt-Laydown Project monitoring sites. Salt-crust thickness measurements taken at these sites are compared with predicted (kriged) thicknesses at corresponding locations from the 2003 salt-crust isopach map.*

measurable difference in thickness during a three-year period of record (see table 2). More significantly, a long-term comparison of 1988 and 2003 salt-crust volumes described in this study showed that the two volumes were very similar (about a 4% difference using the same thickness-measurement technique) after an elapsed period of 15 years. Therefore, if little salt-crust volume change was observed during a long-term comparison period (i.e., 15 years), and no predicted thickness increase was measurable during the Laydown project, what is the current relationship between the solid-phase salt crust and brine withdrawal from the aqueous-phase shallow brine aquifer? To help provide some plausible answers, the following sections 1) examine the origins of the salt crust and shallow-brine aquifer to identify the sources of component ion species, 2) assess the areal extent of the shallow-brine aquifer to place its size and estimated dissolved salt mass in perspective with that of the BSF salt crust and surrounding playa, 3) examine the relationship between the salt crust and the shallow-brine aquifer, 4) quantify the amount of salt crust dissolved by 1-inch rainfall and its potential fate when withdrawn as brine from the federal lease collection ditch, and 5) evaluate the contribution of the Salt Laydown Project to maintenance of the ion mass balance in the shallow-brine aquifer bathing the BSF salt crust.

Origins of Salt Crust and Shallow-Brine Aquifer

The BSF salt crust and associated near-surface deposits resulted from the desiccation of Lake Bonneville (Mason and Kipp, 1998). As the drying of Lake Bonneville progressed, the salt crust was originally deposited in the center of the basin. Once the weight loading of the lake water on the basin floor was eliminated, upward isostatic rebound raised the east side of the Lake Bonneville Basin more than the west side. Consequently, the salt crust position was shifted west to its current location at the foot of the Silver Island Mountains (Eardley, 1962; Turk and others, 1973). This shifting was an iterative process involving repetitive dissolution of the salt crust from meteoric precipitation coupled with gradual westward shifting of the resulting brine pool and re-precipitated salt crust as the basin floor slowly rebounded.

Dissolved solids in the shallow-brine aquifer are believed to have originated from multiple sources. Nolan (1927) suggested a combination of dissolved solids transported by waters draining into a closed basin, and those leached from clay-bearing lacustrine sediments containing entrained brine that resulted from the multiple desiccation episodes of Lake Bonneville. He also concluded that quantitatively, the second source was more important as it supplied the sodium chloride that makes up the bulk of dissolved solids in the brine. Data presented by Turk and others (1973) substantiate Nolan's conclusion.

Other investigators suggested that the ultimate source of dissolved solids in the shallow-brine aquifer were the same as the source of the salts in the Great Salt Lake. Specifically, Feth (1959) believed that pre-Lake Bonneville bedded evaporite deposits provided most of the salt load to the Lake Bonneville Basin (e.g., bedded halite deposits in the Jurassic Arapien Shale have been documented to extend for tens of square miles in Juab, Sanpete, and Sevier Valleys). Jones (1966) concluded that presence of chloride, bicarbonate, and sulfate anions (Cl, HCO_3, and SO_4^{-2}) in highly concentrated lake or playa waters is a direct function of existing lithology and associated weathering processes within the contributing drainage areas (e.g., high percentages of chloride indicate sedimentary rocks of marine origin and solution processes; carbonate reflects igneous lithologies and the hydrolysis of primary silicates; predominance of sulfate suggests ore mineralization and acid alteration). All of these lithologic environments are present in the Lake Bonneville Basin.

In summary, major sources for ions comprising the solid and liquid phases of the salt crust and aquifer have been identified as 1) clay-bearing lacustrine sediments, 2) evaporate deposits in the basin, and 3) existing lithologies within the basin. Consequently, the next question must be, how large is the existing resource of salt ions in the liquid phase associated with the BSF?

Areal Extent of the Shallow-Brine Aquifer Connected with the Salt Flats

Based on brine samples collected from 405 shallow bore holes drilled at section corners along township and range lines in the Great Salt Lake Desert, Nolan (1927) outlined areas underlain by brines containing 60 to 100 grams per liter (g/L) of chloride. The area within the Great Salt Lake Desert (including the Bonneville Salt Flats) that is encompassed by the 100 g/L chloride contour is shown in figure 8. For purposes of this discussion, the brine contained within the 100 g/L chloride contour is assumed to represent the areal extent of the shallow-brine aquifer connected with the BSF. One rationale for this assumption is that the BSF is included within a playa that occupies the topographic low in the Great Salt Lake Desert, and consequently is the terminus for regional ground-water flow. A component of this flow has been suggested to originate from adjacent basins to the south and southwest (Gates and Kruer, 1981; Mason and Kipp, 1998), and a portion of this flowpath may coincide with most of the area south of the BSF contained within the 100 g/L chloride contour. To estimate the size of the shallow-brine aquifer resource connected with the BSF, the 100 g/L chloride contour was replotted using ArcGIS and its contained area calculated with ArcGIS 3D Analyst. Because a topographic high separates the BSF from Newfoundland Basin, the area of the Newfoundland Basin contained within the 100 g/L chloride contour (449 square miles) was not included in the area computations associated with the BSF. The rationale for separating the BSF from Newfoundland Basin was 1) lack of sufficient data to confirm the presence of a groundwater divide that coincides with this topographic high, and 2) the assumption that groundwater flow from Newfoundland Basin does not cross the topographic high. Consequently, the area of shallow-brine aquifer within the 100 g/L chloride contour that includes the BSF was determined to be 975 square miles.

The following assumptions were used to calculate salt tonnage contained in the brine within Nolan's 100 g/L chloride contour. The shallow-brine aquifer was assumed to have a depth of 20 feet, an average aquifer porosity of 45% (Mason and Kipp, 1998), and an average total-dissolved solids (TDS) concentration of 172 g/L. The 172 g/L value was based on linear regression of chloride ion with TDS concentration values from 65 monitoring-well samples collected from 1994 through 2000 (see appendix A6). Using the 975 square miles of 100 g/L chloride contour area mentioned above, the resulting dissolved salt tonnage was calculated to be 1.3 billion tons (appendix A6, eq. 1-4). This calculation varies linearly with each of the four variables: area, depth, porosity, and salt concentration. For example, published clay porosity values range from 40 to 70% (Freeze and Cherry, 1979). If a porosity of 60% were used, the resultant salt tonnage would increase by a third (i.e., 0.6/0.45 = 1.33). Tonnages calculated from the 172 g/L TDS representing the 100-g/L chloride contour are conservative because the dissolved salt concentration generally increases from the outer limit of the 100-g/L chloride contour area roughly towards the BSF playa (point of lowest elevation within the 100-g/L chloride area). Based on 1925 bore-hole data (Nolan c. 1926, 1927), a TDS concentration gradient of about 2 g/L per mile was determined to extend 54 miles north from the southern extent of the 100-g/L chloride contour to the Bonneville Salt Flats just north of I-80 (appendix A4). TDS concentrations along this 54-mile transect ranged from 194 to 337 g/L.

The following comparison provides perspective on the estimated mass of dissolved salt contained in the resource defined by Nolan's (1927) 100 g/L chloride contour, and that contained in the shallow-brine aquifer underlying the BSF salt crust and associated playa. Based on assumptions described in the next section, dissolved salt tonnage in the aquifer associated with 38 square miles of the BSF, and 80 square miles of area including the BSF and surrounding playa, is about 85 and 179 million tons, respectively. These two tonnages are 7 and 14%, respectively of the 1.3 billion-ton resource estimated to be contained within the 100 g/L chloride area associated with the BSF (see appendix A6).

While the 1.3 billion ton estimate is interesting from a comparative standpoint, the calculated dissolved salt tonnage is based on assumed storage within an estimated 20-foot thickness of the 975 square-mile area encompassed by the 100 g/L chloride contour and does not consider additional sources. However, two additional potential sources need to be considered: 1) Mason and Kipp (1998) suggested that some recharge to the shallow-brine aquifer may also be due to possible upward leakage of less concentrated brine from the underlying basin-fill aquifer, and 2) some horizontal recharge (with some salt transport) to the BSF playa from salt-bearing lacustrine sediments outside the periphery of the 100 g/L chloride area is probable; however it is most likely quite slow compared to recharge from infiltration of rainfall directly onto the BSF playa.

To provide some perspective on the rate of horizontal recharge, an average ground-water gradient was calculated from 1925 bore-hole data (Nolan c. 1926, 1927 - see appendix A4). Because the 405 bore holes drilled by Nolan (1927) were distributed over a large portion of the Great Salt Lake Desert, and brine samples were collected during a single field season, it seemed reasonable to determine the 1925 ground-water gradient from this data. An average ground-water gradient of 0.8 ft per mile was determined by identifying those bore holes distributed along and adjacent to a north-trending line that extends from the southern margin of the 100 g/L chloride contour, north 54 miles to the approximate center of the Bonneville Salt Flats (see figure 8). The objective of calculating a ground-water gradient was to use it along with hydraulic conductivity and porosity values from lacustrine sediments to estimate the average linear velocity (Freeze and Cherry, 1979) of ground-water flow over the 54-mile distance between the southern margin of the 100 g/L chloride contour and the Salt Flats. Unfortunately available hydraulic conductivity data does not currently extend beyond the limits of the Bonneville Salt Flats, and the estimate could not be made.

Relationship between Salt Crust and Shallow-Brine Aquifer

White (2004, p. 251) suggested that the shallow-brine aquifer maintains the salt crust and governs its strata morphology. Morphologic differences exhibited in the three halite strata comprising the salt crust are believed to be a result of the aquifer being in contact continuously with the uncemented-coarse halite stratum, and seasonally with cemented-course-porous and dense-cemented halite strata as the level of the shallow-brine aquifer fluctuates seasonally. The following conceptual model is suggested to help explain the morphologic differences observed in the salt crust stratigraphy:

- The relatively large loosely aggregated halite crystals comprising the uncemented-coarse halite stratum (lowest salt-crust stratum) are the result of slow, accretionary halite growth facilitated by continual immersion in the shallow aquifer brine; the most intense period of growth probably occurs during the late summer/early fall when effects of evaporation are maximized and the water table has receded below the overlying halite strata and the brine becomes more concentrated.

- The “worm-hole texture” texture of cemented-course-porous halite stratum (middle salt-crust stratum) is due to cyclic wetting and drying of this stratum caused by seasonal changes in water-table levels; upwelling of less concentrated brine during winter results in some halite dissolution, causing a "worm-hole texture;" as stratum becomes exposed to air, halite is reprecipitated when the water table recedes during summer as its volume is reduced by evaporation and brine becomes more dense.

• The compacted and thinly layered dense-cemented halite stratum (upper or surface salt-crust stratum) is a product of spring/early-summer evaporation of the winter transient pond and consequent precipitation of fine halite crystals that replenish the surface stratum; continual discharge of the shallow-brine aquifer to the surface of the salt crust during the summer helps add salt to the surface stratum by capillary action; as summer evaporation progresses and the groundwater level recedes below the salt-crust surface, brine contained in the dense-cemented halite stratum's intergranular pore spaces evaporates and precipitates additional halite that fills the pores and helps make the stratum more dense.

Effect of Brine Extraction on the Salt Crust

With the conceptual model in mind, the larger question is the nature of relationship between brine extraction from the federal-lease collection ditch and possible effects on the salt crust. The most difficult task in answering this question has been to measure the effects of brine extraction on salt crust quantity. Mason and Kipp (1998) estimated that salt (expressed as TDS) contained in the brine discharged to the federal lease collection ditch was about 850,000 tons annually. Both long-term and short-term comparisons of total salt-crust thickness have shown little overall difference in salt crust volume despite continued brine extraction. Specifically, 1988 and 2003 UDOT pole measurements indicated minimal change in salt-crust volume over this 15-year period (tables 3 and 4 in "Salt-Crust Volumes by GIS"). A short-term comparison also showed no significant change in total salt-crust thickness and volume when multi-year thickness measurements were made from 2000 through 2002 during the Salt Laydown Project (table 2 in "Precision of Measurements"). Mud-auger thickness measurements from three Salt Laydown Project monitoring sites during this three-year period were within 0 to 2% of each other.

Therefore, if little salt-crust volume change was observed during a long-term comparison period (i.e., 15 years), what actually happened to the salt crust when brine was removed from the shallow-brine aquifer? The following observations and results from geochemical modeling may provide some clues.

Amount and Fate of Salt Crust Dissolved by Simulated 1-inch Rainfall Event

The volume of brine removed by the lease collection ditch from adjacent salt crust and mud flats is replaced by inflow of an equivalent volume of brine from the shallow-brine aquifer. This removed brine volume is recharged mainly by infiltration of direct meteoric precipitation (rain) on the salt crust and adjacent mud flats (Turk, 1973; Lines, 1979; Mason and Kipp, 1998). However, as a result of this meteoric precipitation, some of the salt-crust surface stratum is subsequently dissolved (Turk, 1973; Mason and Kipp, 1998). To quantify the thickness of salt crust removed by meteoric precipitation events, White (2004) used the brine equilibrium model TEQUIL (Harvey and others, 1984; Moller and others, 1997) to estimate the thickness removed as the result of a 1-inch rainfall event. The 1-inch rainfall was selected because it exceeds the average monthly rainfall measured at Wendover, UT airport during the 1924-2001 period of record (White, 2004). Using the TEQUIL model, White simulated a condition where the 1-inch rainfall event fell on a 1-inch deep transient pond that typically covers the salt crust during the winter months.

Based on input parameters described by White (2004) results of the TEQUIL simulation suggest that a 1-inch rainfall would dissolve 0.143 inches of thickness from the salt-crust surface stratum (dense-cemented halite). The 0.143 inches of thickness removed translates into 694,335 tons of salt dissolved from of salt crust. The dissolved tonnage was derived by using a salt-crust density of 110 pounds per cubic foot (rounded from Mason and Kipp, 1998) and a salt-crust area of 38 square miles (the areal extent measured in 2003). This dissolved salt-crust tonnage (rounded to 700,000 tons) was then used to estimate its contribution to the shallow-brine aquifer and to the brine withdrawn from the federal-lease collection ditch. The following assumptions were made to obtain the tonnages listed by category in table 7.

• Because sodium and chloride make up more than 90% of the salt ions comprising the shallow-brine aquifer, an average total dissolved solids (TDS) concentration was used to calculate its salt tonnage in the following examples.

• The shallow-brine aquifer was assumed to have a depth of 20 feet, an average aquifer porosity of 45%, and an average total-dissolved solids concentration of 286 g/L (Mason and Kipp, 1998).

• The shallow-brine aquifer was limited to two different areas, 1) a 38 square-mile area representing the 2003 salt crust (excludes the lease collection ditch), and 2) an 80 square mile area representing the portion of the BSF playa where the shallow-brine aquifer was

Table 7. Distribution of salts (expressed as total dissolved solids - TDS) in the shallow-brine aquifer (SBA) before and after contribution from salt-crust dissolution, and in brine withdrawn from the federal-lease collection ditch; based on TEQUIL modeling of dissolution of salt crust by a 1-inch rainfall event (see related calculations in appendix A6). Tonnages have been rounded.

	SALT RESOURCE				DISCHARGE TO LEASE COLLECTION DITCH		
Location	**SBA area, mi^2**	**SBA TDS, tons**	**Rain-dissolved salt crust TDS, tons**	**SBA + dissolved salt crust TDS, tons**	**SBA TDS, tons**	**Salt Crust TDS, tons**	**Total TDS, tons**
2003 salt crust	38*	85,000,000	700,000	86,000,000	843,000	6,900	850,000
BSF playa#	80@	179,000,000	700,000	180,000,000	847,000	3,300	850,000

*Area of shallow-brine aquifer within the 2003 salt-crust boundary north of I-80.
#Includes both salt crust and surrounding mudflat.
@Area of the BSF playa north of I-80 where the shallow-brine aquifer was identified as being most concentrated (Mason and Kipp, 1998).

identified by Mason and Kipp (1998) as most concentrated (includes shallow-brine aquifer on both sides of the lease collection ditch).

To obtain maximum and minimum tonnage values for the dissolved salt-crust contribution to brine withdrawn from the lease collection ditch, the following rationale was used for artificially limiting the shallow-brine aquifer to the 38 and 80 square mile areas. The source of salt dissolved from the salt crust surface was restricted to its most-recently measured areal extent, which was 38 square miles in October 2003. Because the resulting transient pond is hydraulically connected to the shallow-brine aquifer, it was assumed that the salt crust dissolved in the transient pond would eventually become mixed with the shallow brine aquifer. Consequently, the first estimate of dissolved salt crust in brine withdrawn from the lease collection ditch (6,900 tons) was determined by limiting the volume of shallow-brine aquifer to that portion of the aquifer underlying 38 square miles of salt crust. Eastward flow of the transient pond is restricted by the lease collection ditch which bounds the east margin of the salt crust. Additionally, as part of the Laydown facility, a berm was constructed from the end of the lease collection ditch to Floating Island to prevent the transient pond from flowing around the north end of the ditch and ponding on its east side (this was mainly to prevent Laydown brine that was added to the transient pond during 1997-2002 from precipitating salt in areas other than the Salt Flats). Based on this physical restriction it was assumed that most of the salt crust dissolved into the shallow brine aquifer would be confined west of the lease collection ditch and might result in a slightly higher salt concentration in the brine on the west side of the ditch.

However, the lease collection ditch draws brine from both its east and west sides. Consequently, even if the salt concentration in the brine were slightly higher on the west side, brine flowing into the ditch from the east side would result in some dilution of the total brine volume removed. Therefore, the second estimate (3,300 tons) was based on mixing the dissolved salt crust tonnage with the shallow-brine aquifer salt tonnage contained within the 80 square-mile area that includes the BSF playa on both sides of the collection ditch (Mason and Kipp, 1998).

The contribution of dissolved salt crust to the shallow-brine aquifer underlying the 38 square miles of salt crust and the 80 square miles containing the lease collection ditch was calculated by dividing the dissolved salt-crust tonnage (about 0.7 million tons) by the sum of aquifer and dissolved salt-crust tonnage (86 and 180 million tons, respectively) to obtain a percentage contributed by the dissolved salt crust. That percentage was subsequently multiplied by 850,000 tons of TDS to obtain the amount that was contributed by salt-crust dissolution to brine withdrawn from the lease collection ditch (table 7). The 850,000 tons is from Mason and Kipp, 1998, who estimated that about 850,000 tons of TDS were removed annually from the shallow-brine aquifer mainly by seepage to the lease collection ditch east of the salt crust. This estimation suggests that a relatively small amount of the dissolved salt crust is actually removed by the lease collection ditch (i.e., of the 850,000 tons removed, 3,300 to 6,900 tons or 0.4 to 0.8%, respectively, represent dissolved salt crust from a 1-inch rainfall event). Therefore, most of the dissolved salt crust probably remains in the shallow-brine aquifer on the west side of the lease-collection ditch, and is subsequently reprecipitated at some later time as new salt crust from evaporation of the transient pond and from evaporation of discharge to the salt-crust surface by the shallow-brine aquifer. The minimal change in salt crust volume reported between 1988 and 2003 measurements may be due in part to the forgoing explanation that suggests little salt crust tonnage is removed via the lease collection ditch as a result of a 1-inch rainfall event.

Calculations indicate that 1% of salt crust dissolved is transported to the lease collection ditch. If the remaining percentage of the dissolved salt crust is eventually reprecipitated as new salt crust, the transported 1% represents a salt crust thickness of 0.00143 inches annually, or 0.02 inches over a 15-year period. The removed thickness is much smaller than the resolution of measuring techniques used in this study. Furthermore, calculations suggest that the rate of salt-crust removal to the collection ditch is very slow (i.e., a thousand-year period would be required to remove 1.43 inches). However, the calculated maximum annual decrease of salt-crust thickness is based on uniform salt-crust dissolution. Conditions summarized below indicate that uniform salt-crust dissolution does not actually occur over the entire Salt Flat surface. Specifically, the position of the transient pond changes periodically due to variations in the prevailing wind pattern, and a variety of dissolution mechanisms are reflected in several morphologic changes observed in the winter salt crust.

While dissolved tonnage calculated by TEQUIL is credible geochemically, removed thickness is assumed to be uniform over the existing salt-crust surface area. However, based on field examinations, uniform thickness removal is probably not the case. Rather, removal is more likely a combination of dissolution pits (figure 13) and formation of “spongy” skeleton texture in the salt-crust surface stratum resulting from halite dissolution at points of weakness in the salt-crust crystal lattice (e.g., open pore spaces, and imperfections in halite crystal lattice). Although dissolution pits exhibit measurable thickness reduction, their distribution seems limited to areas of salt crust that are affected by currents generated in the winter transient pond (e.g., areas of constriction such as the end of the county access road that extends into the west margin of the BSF and narrows the distance between it and the west limb of the Salduro Loop - see figure 2). By contrast, the spongy skeleton texture makes up a larger percentage of the winter salt crust surface. It also does not produce measurable thickness reduction because the skeletal frame of the crystal lattice is preserved through the winter, and refilled with salt precipitating from brine evaporation during the summer months. Preservation of skeletal thickness despite some reduction in salt-crust mass may also help explain observed minimal differences in volume calculated from 1988 and 2003 pole measurements.

Contribution of the Salt Laydown Project to Ion Mass Balance

Dissolution of halite by rain produces sodium and chloride ions that mix with the winter transient pond and eventually become incorporated into the shallow-brine aquifer (White, 2004, p. 259). If brine from the shallow-brine aquifer is removed from the Salt Flats north of I-80 through the federal-lease-collection ditch, then the total ion mass north of the interstate is decreased by some finite amount that would need to be replaced to maintain the ion mass balance. Consequently, if this withdrawal were to continue for decades without replenishment, one could reasonably conclude that the salt-crust mass north of I-80 could eventually be affected and show some level of impact. This impact would probably be exhibited in the form of gradual salt-crust volume reduction because the sodium-chloride ion balance in the shallow-brine aquifer (within the immediate vicinity of the Salt Flats) is probably maintained largely by salt-crust dissolution from seasonal meteoric precipitation. However, over the long term, this may not be the only recharge to the ion balance of the aquifer bathing the salt crust.

Additional recharge to the ion mass balance of the shallow brine aquifer within and adjacent to the Salt Flats is also likely due to the continual but infinitely slower recharge of salt ions from a combination of the following sources: 1) inward draining, ion-bearing waters into the enclosed basin (Nolan, 1927), 2) horizontal groundwater transport from upgradient portions of the shallow-brine aquifer contained within the Great Salt Lake Desert (Nolan, 1927; Gates and Kruer, 1981), and 3) possible upward leakage from the basin-fill aquifer (Mason and Kipp, 1998). It should be noted that horizontal subsurface inflow probably contributes only a small amount of annual recharge because of low permeabilities and small hydraulic gradients (Mason and Kipp, 1998).

However the more immediate question is, will this long-term recharge rate keep up with the rate of brine discharge to the lease collection ditch and continue to maintain the ion mass balance of the shallow brine aquifer that bathes the BSF without some level of intervention? The experimental 5-year Salt Laydown Project is an example of short-term intervention, which contributed to replenishment and consequent maintenance of ion mass balance in the shallow-brine aquifer on the north side of I-80 despite brine discharge to the lease collection ditch.

The Salt Laydown Project demonstrated that sodium chloride salt in brine removed from the BSF for mineral extraction can be replenished. Sodium and chloride ions in brine removed via the lease collection ditch were replaced with human-made sodium chloride brine that contained from about 16 to 22% sodium chloride (White 2003, appendix A5). Transferred Laydown-brine volumes ranged from 2,570 to 5,340 acre-feet per year. The significance of the Laydown Project is that salt-mass balance during the five-year experiment was maintained in quasi-steady state because 4.2 million tons of salt estimated to have been removed via the lease collection ditch was replaced by 6.2 million tons of Laydown salt. Additionally, difference between 6.2 and 4.2 million tons resulted in a net addition of 2 million tons of salt to the BSF shallow-brine aquifer and salt-crust system (White, 2004). This net addition and any future Laydown-brine

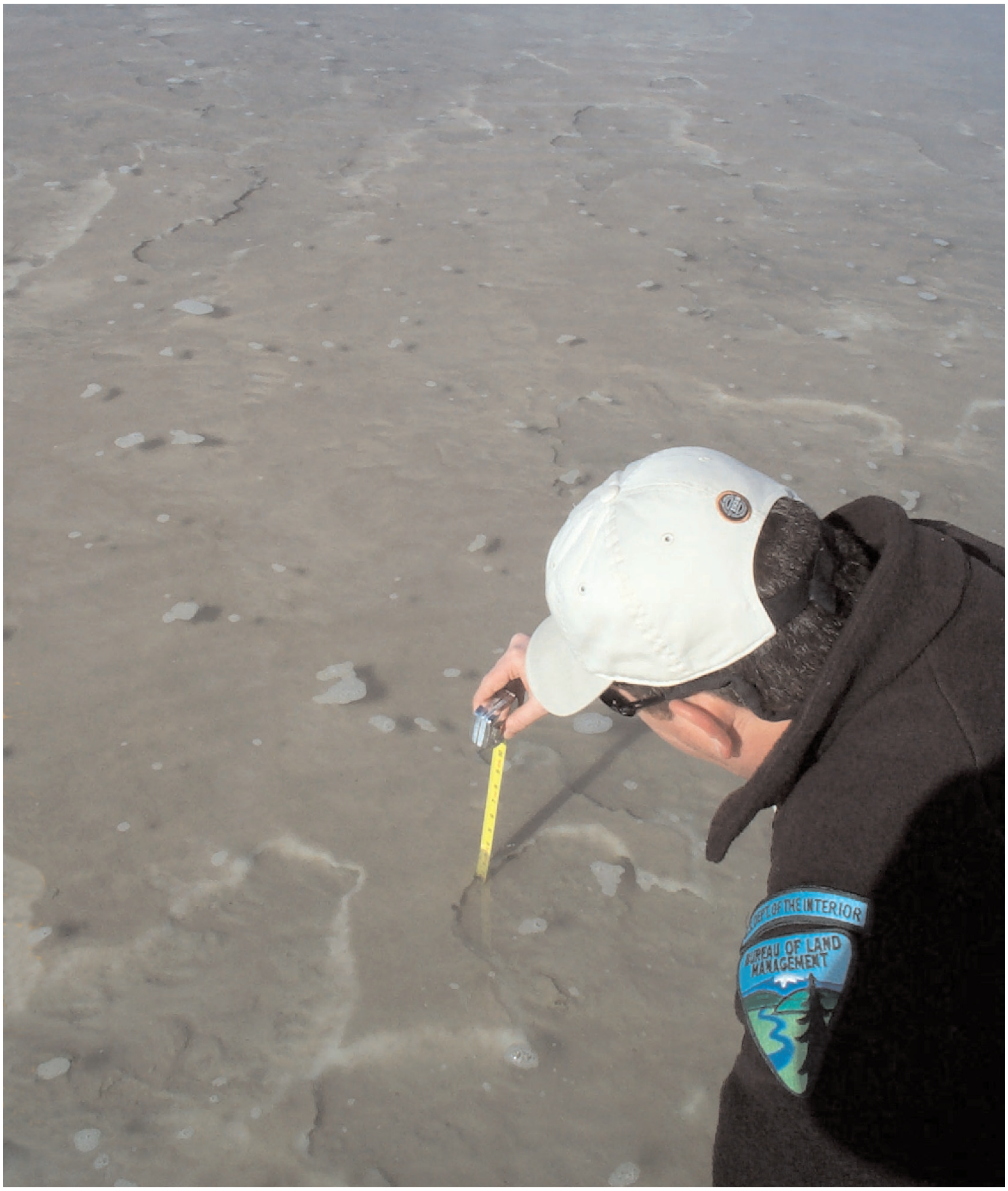

Figure 13. *Example of dissolution pits in the salt-crust surface stratum (dense-cemented halite) resulting from meteoric precipitation (rainfall).*

additions should help contribute to maintenance of the BSF's existing salt-mass balance.

RECOMMENDATIONS FOR FUTURE MONITORING STUDIES

To better assess changes in salt-crust volume over time, a salt-crust drilling program similar to that performed by BLM during October 2003 should be conducted on a regular schedule; specifically:

• The bore-hole drilling program should be conducted in the fall (late September or mid October) when effects of evaporation on the shallow-brine aquifer are at their peak.

• Every 10 years, 72 bore holes should be placed and drilled at the same locations as those used in the 2003 study. GIS-determined volumes should be obtained from these bore-hole measurements.

• Total salt-crust measurements from each bore hole should be made using the mud-auger measurement technique. Salt-crust and underlying clay stratigraphy and depth to groundwater for each bore hole should be described and recorded.

• Every two years, 25% of the 72 bore holes (18 bore holes) should be drilled at selected 2003 bore-hole locations that form two northwest to southeast trending transects that include west and east margins of the salt crust (e.g., from D-66 to D-55, and from D-19 to D-64 as shown in figure 4). The same locations for the 18 bore holes should be used every two years. Measurements from the 18 bore-hole locations every two years would provide interim data points to be compared with the successive 10-year bore-hole measurements.

• Concurrent with the bore-hole drilling program, the perimeter and area of the salt crust north of Interstate 80 should be determined by a GPS survey every two years.

• A new salt-crust isopach map should be generated every 10 years from the new bore-hole data using something like the ArcGIS Geostatistical Analyst to create a kriged surface, which is then converted to a grid and clipped to the new salt-crust perimeter.

Perform a minimum of twice-yearly brine sampling and groundwater-level measurements from monitoring wells screened in the basin-fill aquifer. The objective is to determine if a vertical upward gradient exists in the basin-fill aquifer by measuring any head differences between shallow and deep wells. If so, this would suggest some recharge of the shallow-brine aquifer by the basin-fill aquifer. Three sets of adjacent deep and shallow monitoring wells currently exist and could be used for this study. Their locations are (C-1-18)9adc-1 & 2, (B-1-17)23abd-2 & 4, and (B-1-17)31acc-2, 5 & 6. Slug tests should be performed in both shallow and deep wells to ensure that they continue to be functional.

At least 10 monitoring wells should be distributed on five-mile centers along the 54-mile distance between the southern margin of Nolan's (1927) 100 g/L contour and the south margin of the Bonneville Salt Flats. The objective of these wells is to provide hydraulic conductivity values of the lacustrine sediments containing the shallow brine aquifer along this 54-mile distance. The hydraulic conductivity values along with average porosity and the groundwater gradient would be used to calculate an estimated average linear velocity of the horizontal groundwater flow from the southern margin of Nolan's 100 g/L contour north towards the Bonneville Salt Flats. This average linear velocity would provide some perspective of the contribution of ions from the southern extent of the shallow brine aquifer to the ion mass balance of the Salt Flats.

CONCLUSIONS

Salt-Crust Thickness Study

The Bureau of Land Management conducted a bore-hole drilling program on the Bonneville Salt Flats in October 2003 to obtain current salt-crust thickness measurements for comparison with 1988 thickness measurements previously made by BLM. A total of 69 bore holes were drilled. As part of the 2003 study, two different thickness-measurement techniques were used and compared (mud auger and UDOT pole). The mud-auger measurement technique was used to determine salt-crust thickness in all 69 of the bore holes, while thickness measurements from the UDOT pole method were compared with those from the auger method in 55 of the 69 bore holes. Two primary conclusions resulted from this comparative study:

• GIS-determined volumes derived from 1988 and 2003 UDOT pole measurements showed minimal change (about 4% difference) in salt-crust volume over the 15-year period between 1988 and 2003 when the same measurement method was used and compared.

• When results from 2003 mud-auger and 2003 UDOT-pole measurements were compared, the GIS-determined volume derived from the auger measurements was 7% larger than that from the pole measurements.

Discrepancies between GIS-determined volumes from 2003 mud auger and 2003 UDOT pole-measurement techniques (i.e., 61,440 vs 57,323 acre-feet) strongly suggest that a measurement error may have also been introduced into the previous 1960-1974 UDOT and 1988 BLM salt-crust measurements where the pole method of measurement was used exclusively. These pole measurements were subsequently used to make trend predictions (i.e., the average annual 1.1% depletion rate) for perceived depletion of the salt crust between 1960 and 1988. However, the predicted 2003 salt-crust volume (49,795 acre-feet) based on the average annual depletion rate was not supported by the GIS-determined volumes from 2003 mud auger or 2003 UDOT pole measurements (i.e., 61,440 and 57,323 acre-feet, respectively). Furthermore, comparison of GIS volumes derived from measurements taken 15 years apart at the same locations using the same UDOT-pole measurement method, showed a minimal 4% change in salt-crust volume (i.e., 59,635 vs 57,323 acre-feet).

Comparison between mud auger and UDOT pole-measurement methods in the 55 bore holes drilled in 2003 also provided additional conclusions regarding differences in accuracy between the two measuring methods:

• Specifically, the UDOT pole method underestimated total salt-crust thickness in 27 bore holes and overestimated its thickness in 23 bore holes.

• Based on comparative measurements between methods, the error in "feeling" the clay/salt interface with the UDOT pole ranged from underestimating salt-crust thickness by as much as 13 inches and overestimating it by up to 6 inches.

• Underestimation typically resulted from sloughing of uncemented salt in bore holes located in thick salt crust, while overestimation commonly occurred in holes located in thin salt crust that remained open due to presence of fine-grained gypsum stratum.

• Consequently, the UDOT-pole method typically underestimated thickness in areas of thick salt crust (i.e., >2 ft), and usually overestimated thickness in the areas of thin salt crust (i.e., <2 ft) near the margins of the Salt Flats.

Because thicker areas of salt crust made up 77% of the 2003 salt-crust volume, while thinner areas made up 23%, underestimation of salt crust thickness in the thicker areas of the Salt Flats had greater impact on subsequent GIS volumetric computations based on pole measurements, as compared to those determined from auger measurements.

Based on the forgoing, total salt-crust thickness measurements should be made using the mud-auger rather than the UDOT-pole measurement technique. Additionally, 2003 mud-auger generated thickness data, corresponding GIS-determined salt-crust volume, and resulting salt-crust isopach map should be considered as preferred baseline data for any future salt-crust thickness studies.

Relationship of Salt-Crust Thickness Study to Salt Laydown Project

The purpose of the experimental Salt Laydown Project was to maintain salt-mass balance of the liquid and solid-phase components of the BSF system by replenishing brine removed through the federal-lease collection ditch. An objective included in the project was to add 2 inches to salt-crust total thickness over the five-year experimental period by transferring salt in the form of human-made brine to the BSF. Although salt-crust thickness was monitored annually during the project at multiple monitoring sites, none of these sites showed the predicted 2-inch thickness increase. This was despite addition of 6.2 million tons of salt to the BSF, and apparent maintenance of its salt mass balance during the experimental period. However, examination of results from the 2003 salt-crust thickness studies provides some useful insight to Salt Laydown Project results:

• Short-term comparisons of total salt-crust thickness made at monitoring locations examined during the Laydown project showed little or no measurable difference in thickness during a 3-year period of record.

• More significantly, a long-term comparison of 1988 and 2003 salt-crust volumes described in this study showed that the two volumes were very similar (about a 4% difference using the same UDOT-pole-measurement technique) after an elapsed period of 15 years.

The significance of these two observations is that despite brine withdrawal for mineral production, neither short nor long-term measurable changes in salt crust thickness could be documented. The inability to measure either short or long-term changes in salt-crust thickness may be due to a combination of factors that offset effects of brine withdrawal on the salt crust:

• Based on geochemical modeling, most of the Laydown salt was assimilated into the liquid phase of the shallow-brine aquifer, rather than adding measurable thickness to the salt crust; however, this assimilation helped preserve the ion mass balance in the shallow-brine aquifer associated with the salt crust.

• Field observations of salt-crust surface conditions resulting from meteoric precipitation during the winter show that salt-crust dissolution results in "spongy" skeleton texture; this texture is believed due to salt removal from points of weakness in the halite crystal lattice (however, loss of salt mass under these conditions does not necessarily result in loss of thickness, which would make documentation of salt-mass loss through thickness measurement ineffective).

• Brine-sample data collected in 1925 from 405 bore holes distributed throughout the Great Salt Lake Desert (including the BSF playa) suggests that the shallow-brine aquifer associated with the BSF is quite extensive (approximately 975 square miles) and could potentially contain as much as 1.3 billion tons of dissolved salt.

• Because the BSF is the terminus for regional groundwater flow, it is not inconceivable that some of the 1.3 billion tons of dissolved-salt resource could be a partial long-term source of ion recharge to the area of shallow-brine aquifer that bathes the BSF salt crust (although the rate of recharge would be quite slow); however, additional sources of ion recharge to the shallow brine aquifer may include possible upward leakage of the underlying basin-fill aquifer.

• The main source of ion recharge to the shallow-brine aquifer in the vicinity of the Salt Flats is dissolution of salt crust from rainfall directly onto the BSF.

• Geochemical modeling of a 1-inch rainfall event onto 38 square miles of the BSF resulted in nearly 700,000 tons of salt crust being dissolved, but less than 1% of this mass was estimated to be removed through the lease collection ditch, while more than 99% remained in the shallow brine aquifer associated with the salt crust.

Although both short and long-term measurements of salt-crust thickness have demonstrated little measurable change, maintenance of salt-crust volume in a quasi-steady state is tied to maintaining the ion mass balance of the shallow-brine aquifer associated with the BSF. While long-term recharge of salt is probably supplied by inward draining ion-bearing waters into the Great Salt Lake Desert, its rate is probably extremely slow. Consequently, as brine continues to be withdrawn through the lease collection ditch over tens of decades, long-term recharge of salt may not be able to keep up with this additional discharge and still maintain the mass balance in the shallow brine aquifer associated with the BSF salt crust without some degree of intervention.

The Laydown Project is an example of such intervention, and has demonstrated that sodium chloride in brine removed from the BSF for mineral extraction can be replenished. Although an addition of measurable thickness to the salt crust was not observed, the Laydown Project helped maintain the ion mass balance in the shallow-brine aquifer associated with the BSF by replacing 4.2 million tons of salt estimated to have been removed during the five-year project, while providing a net addition of 2 million tons of salt to the shallow brine aquifer. By preserving the ion mass balance and adding additional salt to the shallow-brine aquifer, the Salt Laydown Project has helped contribute to maintenance of the existing salt-crust volume.

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