WELL DATABASE AND MAPS OF SALT CYCLES AND POTASH ZONES OF THE PARADOX BASIN, UTAH

by Terry W. Massoth

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Cover photo: *Processing plant at Intrepid Potash's Moab operation.*

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WELL DATABASE AND MAPS OF SALT CYCLES AND POTASH ZONES OF THE PARADOX BASIN, UTAH

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ABSTRACT

The Paradox Formation of the Pennsylvanian Hermosa Group contains vast amounts of halite and a number of interbedded potash zones in the Paradox Basin of Utah and Colorado. These cyclic evaporite deposits were first discovered in the early 1920s, and have since been the subject of periodic exploration, yet with production limited to only Intrepid Potash's Cane Creek mine near Moab, Utah. The U.S. Geological Survey has estimated that the Paradox Basin contains approximately 2 billion tons of potash resource; however, the location and depth of such deposits are poorly defined, thus hampering exploration efforts. Sharply higher potash prices in recent years have created a worldwide potash exploration boom, including the Paradox Basin of Utah.

The Utah Geological Survey has funded research in the past few years to develop a basin-wide stratigraphic well database of 29 salt cycle tops and bases, incorporating data from more than 600 petroleum and potash exploration wells within the Utah portion of the basin. Initially, a master correlation section transecting the basin longitudinally from its northwestern Emery County edge to its southeastern San Juan County edge was created, and is presented here for future reference. Wireline geophysical logs from over 300 wells across the basin, but exclusive of the fold and fault belt, were reviewed and salt cycles correlated following salt cycle nomenclature developed by Robert Hite, formerly with the U.S. Geological Survey. Expanding upon the stratigraphic data in the well database, potash zones within salt cycles S5, S6, S9, S13, S16, S18, and S19, or those generally shallower than 10,000 feet deep, were correlated and mapped for thickness. Salt cycles S5 and S19 were also mapped for structure and depth. Mapping was exclusive of the fold and fault belt. A short transverse crossing correlation section was also generated in northern San Juan County.

This work, which identifies areas with the shallowest, thickest, and potentially richest potash deposits, may help guide future exploration and land management actions. However, no discussions are presented for potash resources or reserves, nor for exploration targets or strategies, nor for potential conflicts with oil and gas resources. Additionally, no interpretations regarding depositional environments, or other reasons for locations, thicknesses, depths, and grades of salt cycles and potash zones are given. No depictions of surface ownership or mineral ownership are shown. The reader is cautioned that the well database, maps, and correlation sections are intended as basin-wide guides and are not a substitute for detailed site-specific investigation work.

INTRODUCTION

Location of Study Area

The study area is limited to the Utah portion of the Paradox Basin, a depositional basin that covers an area of approximately 11,000 square miles of southeast Utah and southwest Colorado, and which extends a short distance into northwestern New Mexico. Within the Utah part of the basin, well data collection was restricted to the structurally simpler area along the southwest flank, outside the fold and fault belt (figure 1). The study area is sparsely populated with only a few small towns. Access to the basin is fair with major highways crossing the area and an east-west railroad line crossing the northern end of the basin, with a spur extending southeastward along the approximate axis of the basin to the Intrepid Potash mine near Moab, Utah.

Background

This study is a second phase of work building on an initial study by Massoth and Tripp (2011), which started development of a publicly available salt cycle well database of the Utah portion of the Paradox Basin. On May 20, 2011, the author submitted to the Utah Geological Survey (UGS) a proposal to update the previous study's database and to create a set of salt and potash thickness, structure, and depth maps, and to construct one or more representative basin-wide longitudinal correlation cross sections. The proposed project was funded under State of Utah Contract number 112609, signed in June 2011, and the following materials present the results of the new work.

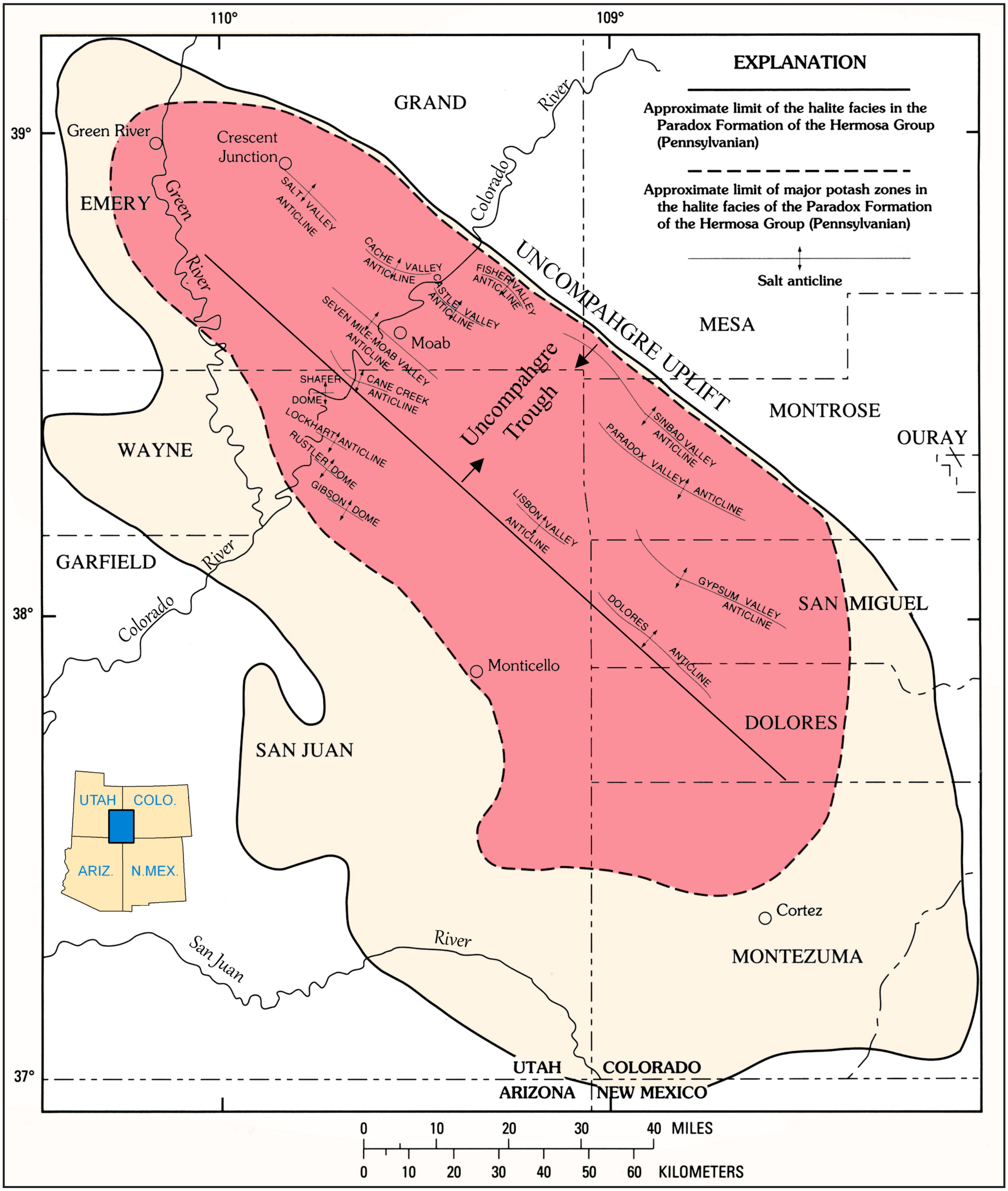

Figure 1. *Paradox Basin location map (after Raup and Hite, 1992).*

Purpose and Scope of Project

The purpose of this study was to expand a stratigraphic database of the tops and bases of salt cycles and potentially economic potash zones in the Pennsylvanian Paradox Formation of the Hermosa Group from selected oil and gas wells in the Utah portion of the Paradox Basin, and to create a regional set of associated maps and cross sections.

The products of the study include:

1. A spreadsheet of wells penetrating the Paradox salt sequence with interpretations of depths to the top and base of individual correlated salt cycles. The spreadsheet also includes depths of the top and base of potash zones within selected salt cycles, and quality data, either published or estimated. This spreadsheet is included as an Excel (.xls) file.
2. A project base map showing well locations, the locations of two cross sections, the land grid, and other basic geographic information. This base map is an Adobe (.pdf) file.
3. A master northwest-southeast trending longitudinal correlation section depicting oil and gas well wireline log responses, the salt cycle and potash zone intervals, which were initially derived from the correlation scheme of Hite (1961) and other previous investigators. This master section was used as a guide in correlating the strata for the majority of the database's wells. The master section and one transverse section are presented as Adobe (.pdf) files.
4. A set of maps portraying thickness of selected salt cycles and potash zones, as well as structure contour and depth maps of the uppermost persistent and lowermost persistent potash-bearing Paradox Formation salt cycles studied. These maps are provided as Adobe (.pdf) files.
5. A report in Adobe .pdf format describing the study's methodology, problems encountered, recommendations for future work, and references.

The author primarily used oil and gas well data and downhole geophysical wireline logs downloaded from the Utah Division of Oil, Gas, and Mining (DOGM) website. Not all oil and gas wells in the Paradox Basin were reviewed; only a geographically distributed subset that were felt to be representative and deep enough to penetrate the full salt section of the basin were examined in detail. Many wells were found to penetrate only the uppermost sets of salt cycles. A few Colorado petroleum wells from the area near the border with Utah were also reviewed and are incorporated in the well database from the records of the Colorado Oil and Gas Commission (Scott, 2003). Some data were included from potash drill holes, but most of this type of data was found to be confidential and not readily available.

This study focused on identifying and correlating depth to tops and thicknesses for potash present within the shallower of the 29 Paradox Basin salt cycles. Information on potash zones 5, 6, 9,13,16,18, and 19 are included in the spreadsheet and were used to generate potash thickness maps. No salt or potash cores were evaluated for the database. All measurements are in feet and miles; no metric conversions are included in this report.

Previous Studies

Geologists and engineers have extensively studied the Paradox Basin due to its interesting geology, petroleum and potash resources, salt tectonics, and potential for use for high-level nuclear waste disposal. Although there are hundreds of geologic reports and maps for the Paradox Basin, there are a few particularly good basic overviews of the Paradox Basin geology of Utah. These include Elston and Shoemaker (1961), Woodward-Clyde Consultants, Inc. (1979), Baars and Stevenson (1981), Raup and Hite (1992, 1996), Doelling (2001, 2004), Hintze (2005), and Hintze and Kowallis (2009). Good general discussions of the basin's potash resources include Hite (1960, 1961), Ritzma and Doelling (1969), Hite and Cater (1972), Hite and Lohman (1973), Britt (1977), Hite and Buckner (1981), and Anderson (2008).

GENERAL GEOLOGY

Thick salt deposits of Middle Pennsylvanian age are present in an area of approximately 11,000 square miles in the Paradox Basin of southeast Utah and southwest Colorado. The salt deposits consist of cyclical sequences of thick halite units separated by thin units of black shale, dolomite, and anhydrite. Over much of the Paradox Basin the salt deposits occur at depths over 5000 feet (ft). Many halite units are several hundred ft thick and several locally contain economically valuable potash deposits, usually in their uppermost levels. The greatest thicknesses of salt and associated rocks are found in a trough-like depression bordering the ancestral Uncompahgre Uplift (figure 1) along the northeast margin of the basin (Hite and Lohman, 1973).

In the Paradox Basin, a wedge-shaped sequence of sedimentary rocks overlies a basement complex of Precambrian crystalline rocks. Paleozoic and Mesozoic rocks dominate the sedimentary sequence; there are also local Tertiary intrusives as well as Quaternary cover. The units of interest in this study are in the Paradox Formation of the Hermosa Group (figure 2). The Paradox Formation ranges in thickness from 500 ft to more than 10,000 ft; the evaporite section is more than 5000 ft thick in places. There are up to 29 salt cycles in the Paradox Formation (numbers increase with

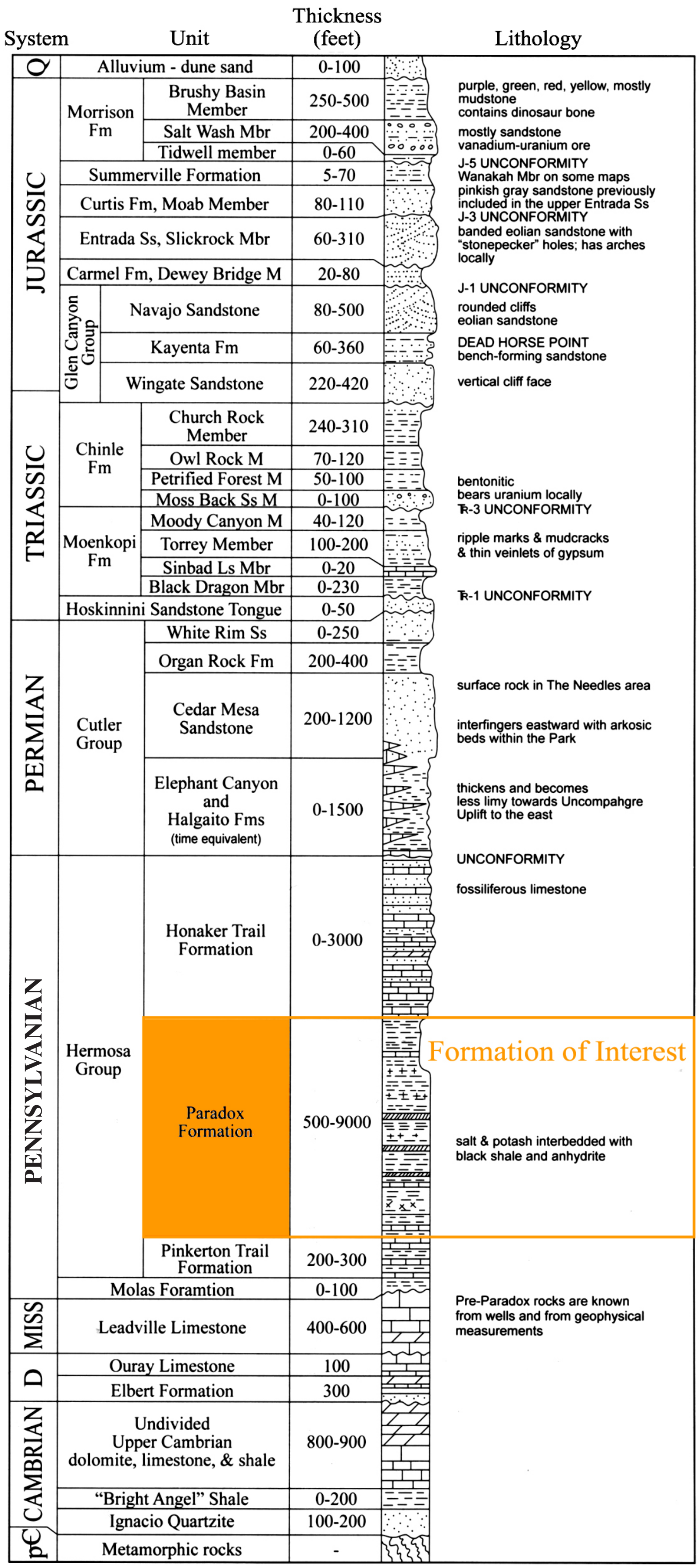

Figure 2. *Regional stratigraphic column (from Hintze and Kowallis, 2009; used with permission).*

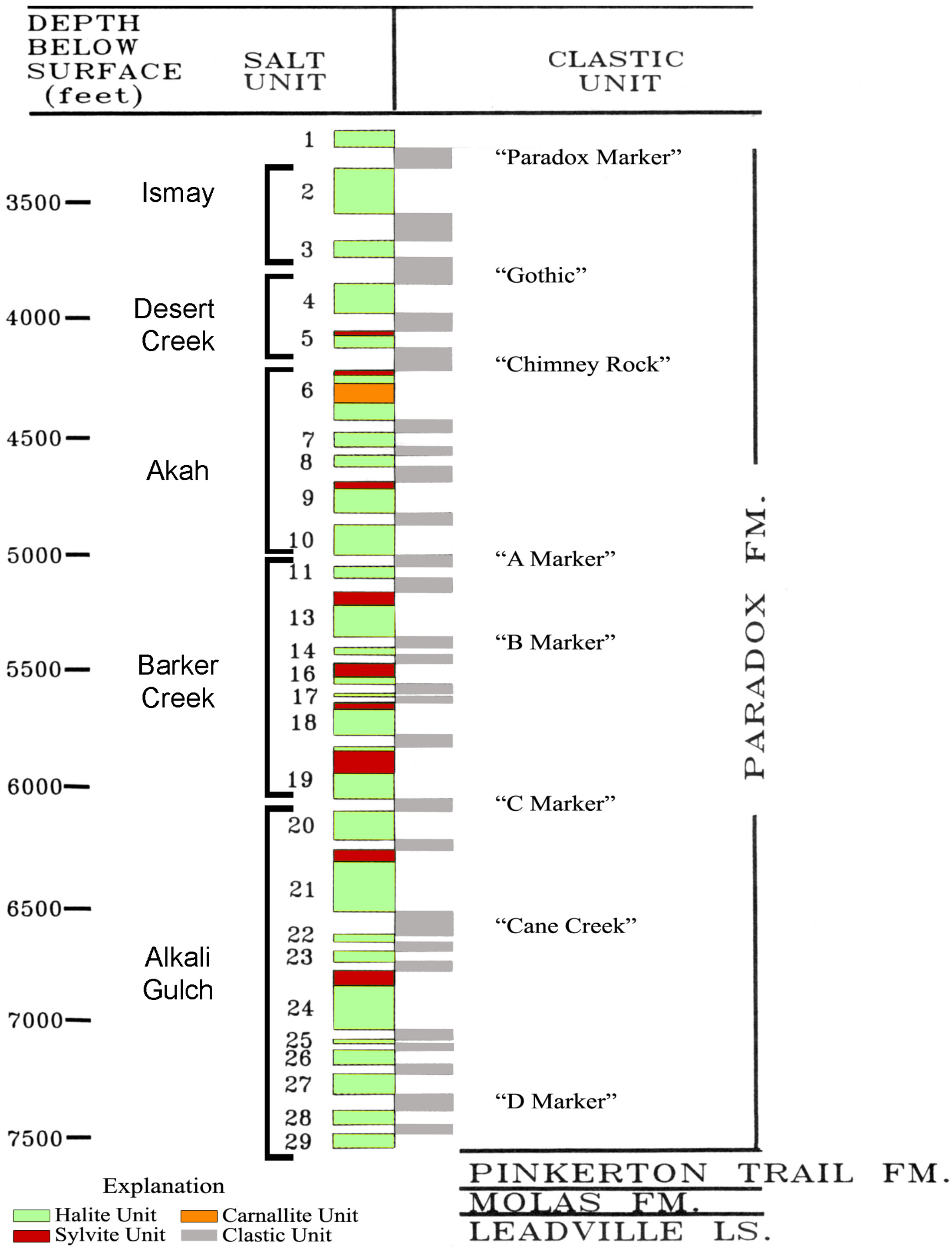

Figure 3. *Detailed salt stratigraphy (after Morgan and others, 1991).*

increasing depth), and as many as 18 cycles may contain a potash zone, though only five may be persistent enough to contain potentially economic potash. Not all cycles are present at every location. Figure 3 shows a detailed version of the Paradox Formation salt cycle stratigraphy.

"Along the northeast margin of the basin, bordering the Uncompahgre Uplift, the salt-bearing rocks of the Paradox Formation are faulted down against the Precambrian core of the uplift and covered by a thick wedge of coarse Permian age clastics. The top of the salt in this area is from 14,000 to 15,000 feet below surface. In the rest of the basin depths to the salt average about 5,000 to 6,000 feet, except in salt anticlines where locally it is brought up to within 500 feet of the surface" (Hite and Lohman, 1973).

METHODS

Database

Oil and gas well locations and wireline log data from the DOGM web site were downloaded August 1, 2011, for this study, and data from several UGS potash-related files were reviewed in March 2011. This newer data was then incorporated in the database of the previous study (Massoth and Tripp, 2011), which was downloaded from DOGM on July 8, 2010. The author is aware of several companies that have posted results of recent potash exploration drilling in the Paradox Basin; however these data are not incorporated into this study.

Listed below is a condensed version of the steps followed in last year's study, and continued in this year's, to compile and organize oil and gas well and wireline data into the salt cycle and potash zone well stratigraphic data spreadsheet included with this report.

1. Select oil and gas well to be evaluated.
2. Go to the DOGM website, at http://www.ogm.utah.gov, to review data available.
3. Download well header data and wireline logs of interest.
4. Open the well wireline log in an appropriate software viewing package.
5. Inspect the selected well wireline log and compare it to logs from adjacent wells. Use of previously published and correlated well logs is suggested; especially helpful were wells studied by Hite and Cater (1972), and Raup and Hite (1996).
6. Compare the log to the idealized Paradox salt sequence. Figure 6 of Morgan and others (1991) is an excellent stratigraphic guide to follow when working with well logs.
7. Look for and identify features characteristic of individual salt cycles. Some general and some more specific observations concerning log responses or characteristics of the different salt cycles were presented in Massoth and Tripp (2011).
8. Correlate the salt cycles. Daniels and others (1980), Figure 7 of BPB Instruments (1981), and Nelson (2007) give good discussions on wireline logging responses for interpreting evaporite deposits. Table 1 is a synthesis of parameters from these references. Note that not all potash minerals listed in the table may be present in the Paradox Basin.
9. Annotate the paper wireline logs in pencil, marking the various salt cycles, marker beds, and potash zones.
10. Compile the depths to the tops of the various salt cycles, interbeds, and potash zones from the oil and gas well data, or potash exploration-hole data, into an Excel spreadsheet (see table 2 for data used).

Make note of the reference elevation from which the log data is displayed on the wireline logs. This information is usually included in a log's header data. For all but a handful of logs from this study, the reference datum was a well's "Kelly Bushing" (KB). In a few cases it was a well's "Drilling Floor" (DF), or the actual ground level (GL); in only a few instances was no reference elevation information given.

The regional-scale structure and depth contour maps generated from this study's well database simply used the reference elevation as quoted on the well logs. As noted above, for all but a handful of wells this reference elevation was the KB. Any errors caused by not rigorously applying an absolutely common reference datum for every well to construct these maps are small compared to the 500 ft contouring interval on the maps, kriging surface trend artifacts, or the elevation accuracy of the Digital Elevation Models (DEMs).

In addition to tracking salt cycle tops and bases (the top of the next deeper clastic unit directly below a salt cycle is the same as the salt cycle's base), this study also recorded data for potash zones associated with salt cycles S5, S6, S9, S13, S16, S18, and S19. Potash zone tops and bases, thicknesses, potash type if reported from publicly available documents, and maximum American Petroleum Institute (API) unit value of the natural gamma ray wireline log response were recorded. Many pre-1960 well wireline logs did not utilize current industry standard API scaling, so for those logs no maximum API value was available to record in the well database. For such logs, a subjective description ("weak", "moderate", or "strong") of the magnitude of the maximum deflection of the gamma log curve was recorded. Potash analytical data obtained from published documents were also incorporated into the well database.

Table 1. *General log responses and characteristics of evaporite rock sequences (sources from Nurmi, 1978; Harben and Bates, 1990).*

Rock or Mineral	Density (Log)	Gamma Ray (Log)	Water Content	Neutron (Log)	Sonic (Log)	Resistivity (Log)	K2O, Equiv.	Remarks
(units)	(g/cc)	(API)	(relative)	(ΦN)	(ms/ft)	(relative)	(%)	
Anhydrite	2.98	0	Very low	0	50	High	0	Common ore contaminant
Gypsum	2.35	0	Intermed	49	52	High	0	Common ore contaminant
Halite	2.03	0	Very low	0	67	High	0	Principal ore contaminant
Sylvite	1.86	500	Low	0	74	Low	63	Principal ore mineral
Carnallite	1.57	200	High	65	78	Low	17	Ore mineral & contaminant
Polyhalite	2.81	180	High	15	58	Intermed	16	Ore mineral & contaminant
Langbeinite	2.82	275	Low	0	52		23	Important ore mineral
Kainite	2.12	225	High	45	70		19	Important ore mineral
Shale	2.2–2.8	80 to 140	Intermed	25 to 60	70 to 150	Low	0	Possible ore contaminant
Limestone	2.54	5 to 10	Low	10	62	Variable	0	Possible ore contaminant
Dolomite	2.88	10 to 20	Low	4	44	Variable	0	Possible ore contaminant

Table 2. *Drill data categories used in this study (added to or delete from 2011 version; several duplicated wells shown on last year's study [Massoth and Tripp, 2011] have been deleted from the current listing).*

	Oil & Gas Wells		Potash Exploration Holes	
State/County	Spreadsheet	Printed Logs	Spreadsheet	Printed Logs
UTAH				
Emery	24 (+7)	19 (+4)	0	0
Grand	160 (-24)	97 (+9)	56	0
San Juan	436 (+33)	182 (+111)	51	0
Wayne	7 (+5)	6 (+6)	0	0
Utah Subtotal	627 (+21)	304 (+130)	107	0
COLORADO				
Montezuma	5 (+5)	5 (+5)	0	0
San Miguel	2 (+2)	2 (+2)	0	0
Colorado Subtotal	7 (+7)	7 (+7)	0	0
Totals	634 (+28)	311 (+137)	107	0

For some wells, deeper potash zones were recognized in salt cycles, such as S21, S24, and occasionally even a few deeper cycles, yet these deeper potash zones were not as rigorously tracked in the same detail as the shallower zones, and they are only mentioned as comments in relevant cells of the database, as these deeper potash zones will probably not be as economic as the shallower zones.

Table 3 (after Harben and Bates, 1990) lists the potash minerals commonly found in evaporite rock sequences. Note that not all potash minerals listed in the table may be present in the Paradox Basin. Sylvite, sylvinite, and carnallite are known mineral occurrences in the basin.

The well database spreadsheet consists of a main sheet or tab, titled "Paradox Salt and Potash db," and three subsidiary tabs consisting of calculated cells derived from the main tab. These subsidiary tabs are linked to the main tab, such that changes in certain cells of the main tab affect certain cells of the subsidiary tabs.

The **main tab**, "Paradox Salt and Potash db," groups the study's wells alphabetically by county, and within counties numerically by API well number. In the spreadsheet, each row or line contains data for an individual well; each column is a particular attribute or characteristic related to a well, or the salt or potash revealed from it. Columns show relevant well header and location information (in UTM NAD83 Zone 12 datum), and literature references (especially noted are Hite [1960, 1972] or Britt [1977] interpreted wells that were used extensively for salt cycle and potash zone top and base data, respectively). The central part of the table lists depth data related to salt cycle tops and selected potash zone tops and bases for all salt cycles and their intervening non-salt clastic units. Additional columns report DOGM-recorded depths to the tops of the Honaker Trail (or Hermosa), Pinkerton Trail Member, Molas Member, and Mississippian Leadville Limestone.

The tops and bases of salts were nominally measured from the well log to the nearest five-foot depth for this study. Suspected potash zones within the salt cycles were noted to the nearest one-foot depth. Potash zones for this study were mapped as "gross" thickness and not "net" thickness intervals, meaning that the thicknesses of one or more beds of halite or clastic units interbedded within the potash zone were not subtracted from the overall potash zone thickness. Individual potash beds are not specifically tabulated. Potash zone thicknesses are shown as a formula-calculated field; also recorded in the well database are alternate thicknesses and estimations of potash zone grades reported from literature. Several additional columns report the presence of faults in wells, if noted from literature, wells with suspected repeated salt cycles or repeated interbeds, wells with core or cuttings samples that exist at the UGS' Utah Core Research Center, and comments concerning the presence of deep potash zones in salt cycles S20 to S29.

Far right-hand columns in the well database main tab are calculated cells used for gridding, posting, or mapping purposes.

Seven wells from Colorado near the border with Utah are included as rows of data below the Utah wells. These were included to limit possible edge effects of gridding and thus aid in contouring the salt cycle and potash zone maps.

Note that the top of the "Akah Oil Zone" as identified in the database table is herein defined as identical to the top of salt cycle S6. There are often thin inter-bedded anhydrites and carbonates, and possibly shales or other clastics, present above S6 salt and yet below the "true" petroleum-industry-recognized base of the Chimney Rock marker bed shale. If an oil and gas resource researcher desires to map the true thickness of only the shale of the Chimney Rock marker bed, further definition beyond the scope of this study's database of the top of the "Akah Oil Zone" will be required. In the case of the few included Colorado oil and gas wells, where the Colorado Geological Survey (Scott, 2003) has identified the top of the "Akah Oil Zone" separately from the top of S6 salt cycle, these separate and different tops are displayed in

Table 3. *Potash minerals often found in evaporite rock sequences.*

Mineral or Compound	Chemical Formula	Potassium Oxide (K_2O%, equiv.)	Potassium Chloride (KCl%)
Potassium Oxide	K_2O	100.00	
Sylvite	KCl	63.17	100
Sylvinite	KCl + NaCl	10 to 35	~50
Leonite	$K_2SO_4 \cdot MgSO_4 \cdot 4H_2O$	25.68	
Langbeinite	$K_2SO_4 \cdot 2MgSO_4$	22.69	
Kainite	$4KCl \cdot 4MgSO_4 \cdot 11H_2O$	19.26	
Carnallite	$KCl \cdot MgCl_2 \cdot 6H_2O$	16.95	
Polyhalite	$K_2SO_4 \cdot MgSO_4 \cdot 2CaSO_4 \cdot 2H_2O$	15.62	

the well database. These same comments apply for the other Paradox Basin "oil zone" marker beds.

Finally, a listing of abbreviations used in the body of the main tab is included following the Colorado wells. Below the abbreviation listing are several thousand rows of "dummy" zero values entered to aid in gridding the zero edges of salt cycle and potash zone maps; these data lines can be ignored for other purposes.

The **three subsidiary tabs**, labeled "salt thicknesses," "salt interburden thicknesses," and "salt structure & depth," are dominantly populated with calculated cell values derived from data entered on the main "Paradox Salt and Potash db" tab. These additional tabs were created to facilitate thickness, structure, and depth gridding and mapping, and were placed in separate stand-alone tabs due to column limitations in Excel for the main tab. Minimum, average, and maximum statistics for thicknesses and depths are calculated at the bottoms of these tabs.

Maps

Golden Software, Inc's (http://www.goldensoftware.com/products/surfer/surfer.shtml) Surfer 9 mapping software was used to generate the maps for this study. All mapping utilized UTM Zone 12 NAD83 datum. Kriging was the geostatistical gridding method used, as it produced visually appealing maps from the database's irregularly spaced data. Note that seven oil and gas wells from western Colorado were used to minimize edge effects of gridding and contouring, but these points are not shown on the maps.

Base Map (plate 1)

Plate 1 displays the well locations for all DOGM web site-listed oil and gas wells in the Paradox Basin and identifies which wells and which potash exploration holes were used in the study. It further identifies the Hite oil and gas correlation wells used, and shows the township and section land survey grid, counties, major paved roads, railroads, key cities and towns, major rivers, the correlation sections generated, and the fold and fault belt.

The base map also distinguishes wells with at least one salt cycle (green dots), wells with at least one potash zone (red dots), and wells with neither salt cycles nor potash zones (gray dots). Note that some wells used in this study (listed in the database and shown on this map and subsequent maps) may have drilled to upper salts yet might not have been drilled deep enough to reach the uppermost potash zones.

A portion of the basin adjacent to the Uncompahgre Uplift is outlined as the "Fold and Fault Belt." Previous workers have identified this part of the basin as a complexly folded and faulted region, making correlations of salt cycles and potash zones there extremely difficult, if not impossible. This "belt" is approximately coincident with the "Uncompahgre Trough" of Raup and Hite (1996). This region's southwestern edge, as depicted on this and following maps of this study, is arbitrarily drawn, though generally it follows the trend of major northwest-southeast fold axes and faults. The "Fold and Fault Belt" region captures oil and gas wells which are not correlatable due to extreme salt flowage, folding, and/or faulting. On this study's maps, these wells are shown with black "X" symbols. Some wells may have thick potash zones, yet those zones may be very discontinuous laterally. The region's other edges are defined by the Utah-Colorado state line and the Hite salt facies edge against the Uncompahgre Uplift. The portion of the Paradox Basin south and west of the "Fold and Fault Belt" region does contain numerous folds and faults; however, they appear to be less severe than those of the "Fold and Fault Belt" and thus salt cycle correlations are possible and more certain in that region of the basin.

The Paradox Formation salt facies zero edge line (black dashed line digitized from Raup and Hite's [1992] "Approximate limit of salt facies of Paradox Fm.") as shown on last year's study base map (Massoth and Tripp, 2011) has been adjusted slightly outward, as determined by the salt thickness mapping of this study. An accurate redefinition of this salt facies zero edge was not an objective of this study, and few wells near this line exist or were purposely studied. Other non-mapped salt cycles might alter this line further.

The Paradox Formation potash facies zero edge line (purple dashed line digitized from Raup and Hite's [1992] "Approximate limit of potash zones in the salt facies of Paradox Fm.") as shown on last year's study base map has also been adjusted outward slightly, as determined by the potash zone thickness mapping of this study.

Note that few of the numerous wells located south of T31S in San Juan County, inside the "potash" line, show the presence of potash on this map. The majority of these particular wells have been incorporated from an existing database (Anderson, 2008) which only identified a topmost salt, and did not correlate that top salt to a particular salt cycle. Also, a considerable percentage of these wells in this southern portion of the Paradox Basin penetrate just the uppermost part of the Paradox Formation, notably only the Ismay and Desert Creek oil zones, so that any deeper prospective potash zones have not been penetrated, and thus provide no data for inclusion in the current database. This same condition applies also to certain wells in Grand County.

Finally, at least two anomalous wells are shown on the map: the well in Section 31, T. 28 S., R. 21 E. (4303710860) and the well in Section 2, T. 28 S., R. 23 E. (4303710196). Halite in the upper salt cycles of these wells is represented by anhydrite, and thus not classed as "salt" in this study. Additionally, the salt cycles in these two wells are significantly thinner compared to nearby wells. Some faults and folds exist in the vicinity of these wells and perhaps have caused these anomalous salt thicknesses. For these particular locations, the anhydrites are mapped as "salts" for the thickness, structure, and depth maps. Other similar stratigraphic anomalies are no doubt present elsewhere in the Paradox Basin.

Salt Mapping (plates 2 through 12)

Salt cycle thickness mapping is presented for salt cycles S5, S6, S9, S13, S16, S18, and S19, as these are the salt cycles which host potentially economic potash zones at depths less than 10,000 ft. Salt structure and salt depth mapping is limited to salt cycles S5 and S19, to bracket the uppermost and lowermost conditions of the salt cycles and associated potash deposits.

Salt thickness mapping: (plates 2 through 8) The steps used to generate the salt thickness maps included:

1. Subtract depth to the base of a particular salt cycle in the well database from the depth to the top of the salt cycle and record this calculated thickness in a designated database tab and column. If the particular salt cycle was not present in a well that had been drilled to an appropriate depth, then a zero (0 ft) thickness was recorded. In some cases, a non-numeric text descriptor was recorded in place of a salt thickness value, such as "NDE" for wells not drilled deep enough for a particular salt cycle, or "?" for wells with difficult-to-evaluate wireline logs or where log data were lacking. These values or descriptors were then posted above the well data location in green font on the map.
2. Post a color-keyed "presence-absence" symbol at the well data location. A green dot at the site indicates a particular salt cycle is present, a gray dot indicates the absence of a salt cycle, and a non-color dot indicates insufficient data.
3. Grid the salt thickness data. The kriging method was used to interpolate salt thicknesses between wells in this study. Surfer 9 default gridding parameters were determined by the software and accepted; grid size was 65 rows ("y" direction) by 100 columns ("x" direction) yielding 6200 grid nodes calculated; grid spacing was 8500 ft x 8500 ft; no anisotropy was applied during the gridding. Note that while the kriging method of gridding is very good, it is not an exact interpolator; therefore, some portions of the contour lines are not exactly faithful to all data point values posted.
4. Contour and plot the gridded salt thickness data. For salt thickness mapping, green contour lines were plotted at a contour interval of 50 ft. The one-hundred-foot thickness contour lines are bolded. The zero thickness line was initially assumed to be the Raup and Hite (1992) "salt facies" extent line. Zero-thickness data points were generated along this salt extent line and used to initially constrain a particular salt cycle's zero thickness edge line.

   However, in a few instances, a well that contained a salt cycle of positive thickness was either very close to, or even "beyond" the original salt extent line of Raup and Hite (1992). In these cases, several "dummy" zero thickness values were digitized at selected points outside of the original salt extent line to better constrain a particular salt cycle's zero thickness edge line, and also its 50 ft thickness line. The gridding process resulted in multiple highly-crenulated zero-thickness polygons and line segments, so these gridding artifacts were removed for greater map clarity. Thus, a particular salt cycle's zero edge thickness line is not shown on the maps, but instead the regional zero salt facies extent line is shown.

   The salt cycle thickness contour lines have been "clipped" at the edge of the "Fold and Fault Belt" region in the northeastern portion of the Paradox Basin. Difficulties in correlating salt cycles preclude accurate mapping in this region.
5. Repeat the above steps for the next salt cycle.

Table 4 lists minimum, average, and maximum salt and clastic interbed thicknesses derived from the well database for Utah wells. Zero thickness data points were not used for the calculated values in this table. Thickness values are rounded to the nearest 5 feet.

Raup and Hite (1996) report the existence of an additional "two younger, thin halite beds near the depocenter of the basin", bringing the total number of known salt cycles to 31. These additional salt cycles were not observed or compiled from the wells of this database.

Salt structure mapping: (plates 9 and 10) Structure contour maps are presented for two Paradox Formation salt cycles. One was made on the top of S5 salt cycle, the uppermost persistent potash-bearing salt cycle. The other was made on the top of S19 salt cycle, the lowermost studied potash-bearing salt cycle. Pertinent structural features such as mapped regional faults and anticlines taken from Utah Geological Survey GIS data sources are also shown within the extent of the salt-bearing portion of the Paradox Basin. Any effects of such structures were not considered in the generation of the structure contour maps. The folds shown were taken from the La Sal and Moab 1:100,000 digital geo-

Table 4. *Paradox Formation salt cycle and interbed thickness statistics (data in feet). Salt cycles with yellow highlighting indicate those with thickness contour maps.*

Salt	Minimum	Average	Maximum	Interbed	Minimum	Average	Maximum
S1	10	80	270	S1 to S2	20	80	190
S2	5	125	760	S2 to S3	10	75	300
S3	5	65	315	S3 to S4	5	70	270
S4	5	55	390	S4 to S5	5	40	180
S5	5	85	855	S5 to S6	15	75	240
S6	20	210	990	S6 to S7	5	25	145
S7	5	70	175	S7 to S8	5	10	40
S8	5	45	175	S8 to S9	5	45	125
S9	15	120	1085	S9 to S10	5	40	115
S10	5	115	640	S10 to S11	5	35	175
S11	5	30	135	S11 to S12	5	15	65
S12	5	10	65	S12 to S13	5	20	90
S13	10	125	580	S13 to S14	5	25	70
S14	5	60	330	S14 to S15	5	15	125
S15	5	40	775	S15 to S16	5	20	120
S16	10	125	295	S16 to S17	5	15	90
S17	5	35	315	S17 to S18	5	10	110
S18	25	225	835	S18 to S19	5	20	610
S19	10	215	1055	S19 to S20	5	45	245
S20	10	100	380	S20 to S21	5	20	180
S21	5	235	1820	S21 to S22	25	90	265
S22	5	45	300	S22 to S23	5	15	60
S23	5	60	265	S23 to S24	5	25	125
S24	15	85	485	S24 to S25	5	15	150
S25	10	50	150	S25 to S26	5	25	170
S26	20	75	240	S26 to S27	5	30	225
S27	10	115	835	S27 to S28	15	45	155
S28	15	120	240	S28 to S29	15	40	100
S29	20	185	415				

logic maps (Doelling, 2001, 2004).

The steps used to generate the salt cycle top structure maps included:

1. Subtract the depth of the top of S5 salt cycle in the well database from the well reference elevation (KB) and record the derived salt top elevation in a separate tab of the database spreadsheet. In some cases, a non-numeric text descriptor was recorded in place of a salt top elevation value (e.g., "NDE" for wells not deep enough for a particular salt cycle, or "?" for wells with difficult to evaluate wireline logs, or "ND" where no log data were available). These values or descriptors were then posted above the well data location in green font on the maps.
2. Post a color-keyed "presence-absence" symbol for the S5 salt cycle at the well data location. A green dot at the site indicates a salt cycle is present, a gray dot for the absence of a salt cycle, and a non-color dot indicates insufficient data.
3. Grid the S5 salt cycle top elevation data. The kriging method was used in this study and default gridding parameters were determined by the software and accepted. The grid size for S5 was 55 rows ("y") by 100 columns ("x") yielding 5500 grid nodes calculated; grid spacing was 7700 ft x 7700 ft; no anisotropy was applied during the gridding. For S19 mapping, the grid size was 65 rows ("x") by 100 columns ("y") yielding 6500 grid nodes calculated; grid spacing was 6100 ft x 6100 ft; no isotropy was applied during the gridding.
4. Contour and plot the gridded salt top elevation data.

For the top of salt structure maps, green contour lines were plotted at a contour interval of 500 ft. The 1000 ft contour lines are bolded. Gridding extends in north-south and east-west directions only as far as data are available, such that in some portions of the basin the contour lines end before they reach the salt facies zero edge line. The structure contour lines are clipped at the "salt facies extent line" and at the border with the "Fold and Fault belt" region in the northeastern portion of the basin.

5. Repeat the above steps for S19 salt cycle.

Salt depth mapping: (plates 11 and 12) Two depth-to-the-top-of-salt maps are presented. One was made of the depth to the top of S5 salt cycle, the uppermost persistent potash-bearing Paradox Formation salt cycle. The other was made of the depth to the top of S19 salt cycle, the lowermost persistent potash-bearing salt cycle studied.
The steps used to generate the depth to salt cycle top contour maps included:

1. Download 90-m DEM files covering the mapped area online from the Automated Geographic Resource Center (AGRC, 2012). The "90-m" designation describes the horizontal distance between elevation grid nodes. Six 1 degree by 1 degree blocks (1:250,000 scale quads) were required for complete basin coverage. Steps after accessing the AGRC main page included navigating to "GIS Data & Resources", then "Download GIS Data from SGID", then "Raster GIS Data" and "Elevation/Terrain", then "10, 30, & 90 Meter Elevation Model (DEM)", then downloading from the FTP site and converting the .exe files into .dem files. Note that these "1 degree DEM data have an absolute accuracy of 130 meters horizontally and 30 meters vertically" (USGS, 2012). These accuracies equate to 425 ft horizontally and 98 ft vertically.

   The ".dem" files were combined by "mosaicing" within Surfer 9 mapping software, then the DEM extent was clipped to match the lateral extent of the salt/potash maps, and then the grid elevation values were converted from meter to feet data. The DEM grid parameters were noted, because an identical top of salt cycle structure grid is required to perform a "grid-to-grid math" operation, e.g., to subtract the salt cycle top elevation grid from the ground elevation DEM grid, the result being a grid with nodes populated with depths from the ground surface to top of the salt cycle.

   The salt top depth recorded in the well database was then posted in brown font above the corresponding well locations on the map. In some cases, a non-numeric text descriptor was recorded in place of a salt depth value (e.g., "NDE" for wells not deep enough for a particular salt cycle, or "?" for wells with difficult to evaluate wireline logs or with only a topmost salt pick, or "ND" where data was lacking).

2. Post a color-keyed "presence-absence" symbol for the S5 salt cycle at the well data location. A green dot at the site indicates a salt cycle is present, a gray dot for the absence of a salt cycle, and a non-color dot indicates insufficient data.

3. Re-grid the S5 salt cycle top structure data. For this mapping, using the DEM grid parameters previously recorded, yielded a grid size of 2788 rows ("y") by 1484 ("x") columns yielding 4,137,392 grid nodes calculated. The DEM grid spacing of 295 ft x 295 ft was used; no anisotropy was applied during the gridding. The top structure of S5 was also re-gridded with the exact lateral extent of the DEM grid.

4. Use "Grid math" operation to create the new calculated grid for the depth to the top of S5 at the DEM grid nodes.

5. Contour and plot the depth to the top of salt data on the map. For the depth to the top of salt contour mapping, brown contour lines were plotted at a contour interval of 500 ft. Contour depth lines at 1000, 3000, 5000, 7000, 9000, 11,000, and 13,000 ft are bolded. Gridding extends in north-south and east-west directions only as far as well data are available, such that in places the contour lines end before they reach the salt facies extent line. In most other instances, the contour lines are clipped at the salt facies extent line and at the border with the "Fold and Fault Belt" region in the northeastern portion of the Paradox Basin.

6. Repeat the above steps for S19 salt cycle.

Depth mapping for the other salt cycles was not carried out because the vertical accuracy of the DEM and the trending phenomenon created with the use of the kriging method during gridding could result in portrayals of stratigraphically deeper salt cycles being at shallower depths than a stratigraphically shallower salt. This effect might be apparent in those parts of the basin with very sparse data, and especially for closely spaced salt cycles such as S5 and S6, or S18 and S19. For instance, such mapping might show the depth to the top of S6 in some regions of the basin less than the depth to the top of S5. Since this report also provides information on the average thickness and separation between salt cycles (table 4), the reader can use these statistics in combination with the upper and lower salt depth maps to get an approximate idea of the depth of other unmapped salts.

Potash Mapping

Potash zone mapping is presented for potash present in salt cycles S5, S6, S9, S13, S16, S18, and S19. While potash is known in deeper salt cycles S20, S21, S24, and S27, those zones were not tabulated in detail or mapped herein, because these deeper potash zones were considered of lesser exploration interest than shallower ones.

Note that the Hite potash facies extent line (Raup and Hite, 1992), as shown on the Massoth and Tripp (2011) base map, has been adjusted outward and altered slightly, as determined by this study's potash thickness mapping. Mapping additional potash zones might alter this extent line further.

Potash thickness mapping: (plates 13 through 19) The steps used to generate the potash thickness contour maps included:

1. Generate a potash zone "extent line" by gridding "presence-absence" values at well data points. Note that potash zone thickness data are recorded in the well database. If the zone thickness is greater than zero for a particular well, a "1" was entered in a designated database column and cell. If the particular potash zone is not present in a well, then a zero ("0") thickness was entered. These potash thickness data values were then gridded and the "0.5" contour line (midpoint between "presence" and "absence" data points) was used to conservatively estimate a particular potash zone's extent. This extent line was then digitized and the various north and east coordinates were assigned thickness values of zero. Note that some potash zones may have various isolated pods (polygons) of potash, such that there is more than one extent line. If this was so, the same procedure was used to generate all polygon extent lines for a particular potash zone. The potash extent coordinates and their zero thickness values are recorded below the Abbreviation Listing in the main tab ("Paradox Salt and Potash db") of the database. Plot the "extent line" on the map.
2. Post a color-keyed "presence-absence" symbol at the well data location. A pink dot at the site indicates a potash zone is present, a gray dot indicates the absence of a potash zone. Note that in a few cases where an isolated single well location is plotted as having a potash zone, a contour line might not be drawn around it as the lateral extent of the single point might not constitute enough areal extent to encompass a sufficiently large set of nodes that could be contoured within a polygon around that single point.
3. Grid the potash zone thickness data. The kriging method was used with gridding default parameters determined by the software and accepted; grid size was 100 rows ("y") by 53 columns ("x") yielding 5300 grid nodes; grid spacing was 8300 ft x 8300 ft; no anisotropy was applied during the gridding.
4. Contour and plot the thickness data on the map. For potash zone thickness mapping, a red contour line was used with contour intervals of 5, 10, or 20 ft, depending on the overall thickness of the individual potash interval. Note that potash zone thickness lines have been clipped at the border of the "Fold and Fault Belt" region in the northeastern portion of the Paradox basin. The gridding-derived zero thickness contour line is not shown on the map for the same reasons as noted previously, but instead the "potash extent" determined in step 1 was used as the mapped zero edge.

   Also shown on the potash zone thickness maps are symbols and/or annotations related to estimated grade. A potash zone's maximum API value (for those wireline logs with standard API scalings, usually from 0 on the left edge to 100, 160, or 200 API units on the right edge) was used as an estimator of a potash zone's maximum grade. Estimated potash maximum grades were categorized within a well symbol with colored dot fills as follows:

   Gray = no potash in mapped zone

   Pink = potash present, but log not in current API industry-standard scaling

   Yellow = less than 99 maximum API value

   Orange = 100 to 199 maximum API value

   Red = greater than 200 maximum API value

   For some wells potash rock core analytical values from published literature (red text in data table main tab) are posted as black text above and generally centered over the data location, or estimated potash grades calculated from well logs from published literature (black text in data table) (Anderson, 2008; Nelson, 2007) are posted, also as black text on the map. Note that some maps have areas with dense data points, such that the potash grade values are over-posted or otherwise difficult to read. Interested researchers may want to create their own GIS map in order to better visualize all these values.
5. Repeat the above steps for each potash zone.

Table 5 lists minimum, average, and maximum gross potash zone thicknesses derived from the well data spreadsheet. Thickness data are rounded to the nearest 1 foot.

Note that the maximum thickness values in the table 5 are "gross" interval values and not "net" potash values. Report-

Table 5. Paradox Formation potash zone thickness statistics (data in feet).

Potash in Salt Cycle	Minimum	Average	Maximum
S5	0	3	58
S6	0	34	290
S9	0	5	60
S13	0	20	127
S16	0	16	130
S18	0	7	83
S19	0	23	435

ing "net" potash bed thicknesses instead of "gross" potash zone thicknesses was beyond the scope of this study. Also, many of the thicker intervals are "weak" to "moderate" in estimated grade, and may contain ore contaminant minerals as well as potash.

Finally, due to suspect or uncorrelatable potash zones within the "Fold and Fault Belt," many potash zones appear to thin from the general axis of the basin northeastward toward this region. This is solely due to the fact that potash zones within the belt have not been correlated and thus, by default, map as zero thickness in the gridding process.

Cross Sections

One two-part longitudinal and one transverse correlation section were made to help depict the extent and continuity of the salt cycles and potash zones in the basin. The longitudinal section was constructed to generally follow the depositional axis of the basin, and to incorporate many of the wells previously interpreted by Robert Hite (1960, 1972).

Master Correlation Section (plates 20a and 20b)

A northwest-southeast oriented longitudinal "master" correlation section, located approximately through the axis of the Paradox Basin, was established by Massoth and Tripp (2011) but not published. That section is presented here in two segments; a northern portion (Plate 20a) dominantly in Grand County, Utah, and a southern portion (Plate 20b) in San Juan County, Utah. One well, 4303710573, the northernmost San Juan County well, is shown on both sections to facilitate overlapping of the sections.

The section was initially constructed at the UGS by Rebekah Wood utilizing NeuraSection software, and subsequently completed by Stephanie Carney (UGS) utilizing Petra software. The datum for the section is the top of the Gothic Shale (base of S3); a smaller inset structural section shows the strata hung on their actual elevations above sea level. "TIFF" images from the DOGM well log collection are portrayed and the various salt cycles, shale markers and clastic interbeds, and potash zones are shown correlated well-to-well. The vertical scale (1" = 300') and horizontal scale (1" = 6000') of the section result in a vertical exaggeration of 20:1. At these scales pertinent potash zones still show reasonably.

All of Hite's (1960, 1961, 1972, [Raup and Hite, 1996]) published correlated wells from the Utah portion of the Paradox Basin were incorporated into the correlation section. Indeed, those wells were identified early-on by Massoth and Tripp (2011) as key wells from which to build basin-wide salt cycle correlations. Wells that reached the Leadville Limestone, thus penetrating the full Paradox Formation, were also given preference in choosing candidate wells for the cross sections.

All of the salt cycles are labeled on the cross sections; salt cycles S5, S6, S9, S13, S16, S18, and S19 are highlighted with green color fill, and their associated potentially economic potash zones are shown with red color fill. The carnallite marker bed of S6 salt cycle is shown with orange color fill. Note that although potash zones on the cross sections are shown as continuous between any two adjacent wells, the potash zones (possibly composed of one or more individual potash beds) may in fact thicken, thin, or pinch out in the intervals between any two adjacent wells. The major shale marker beds (Gothic Shale, Chimney Rock, Marker A, Marker B, Marker C, Marker D, and the Cane Creek) are highlighted in gray color fill. The Leadville Limestone (or its equivalent) is shown with an arbitrary 200-ft-thick blue color fill.

The overall observation from the longitudinal correlation section is that the evaporite section thins towards the northern and southern basin edges, and that occasional, anomalously thick salt and potash areas presumably are due to salt flowage related to folding and faulting.

Transverse Correlation Section (plate 21)

One transverse section located in northern San Juan County was generated where there are few published cross sections. Generation procedures and presentation are similar to those described for the longitudinal section. The well with API number 4303710436 is the tie point well for both sections.

RESULTS

An extensive stratigraphic well database in Excel format was created with depths and elevations for the top and base of salt cycles, intervening clastic marker beds, and potash zones of the Paradox Formation in the Utah portion of the Paradox Basin. More than 600 oil and gas wells and potash exploration holes, including 28 new ones, are incorporated into the database, and their distribution is shown on plate 1.

Wireline geophysical well logs from more than 300 oil and gas wells in the Utah portion of the Paradox Basin were reviewed and salt cycles correlated following Hite's salt cycle nomenclature. Potash zones within the salt cycles were also correlated. Salt cycle data were collected from previous studies, some of which include only the depth of the first or uppermost, but uncorrelated, salt cycle encountered. All paper copies of the wells studied are filed at the UGS.

A base map (plate 1) displaying which wells are included in the database, and further identifying which wells encountered one or more salt cycles or potash zones, is provided. New thickness maps are provided on salt cycles (plates 2 to 8) and potash zones (plates 13 to 19) for S5, S6, S9, S13, S16, S18, and S19. These thickness maps show the salts, and their associated potash zones, are thickest in a belt about 6 to 15 miles wide that lies immediately southwest of the boundary of the "Fold and Fault Belt." Thick potash is associated with the thickest part of a salt cycle, and the potash beds mapped are best developed where the associated salt is generally at least 80 ft thick or greater.

Structure (plates 9 and 10) and depth (plates 11 and 12) maps are also provided for the top of salt cycles S5 and S19. The depth to the top of salt cycle S5 ranges from as little as 1000 ft locally along the Colorado River (T. 31 S., R. 18 E.) to over 10,000 ft near the boundary with the "Fold and Fault Belt" (T. 21S., R. 18 E.), and is commonly at least 5000 ft deep over much of the study area. The depth to the top of salt cycle S19 ranges from less than 3000 ft locally along the Colorado River to over 12,000 ft near the boundary with the "Fold and Fault Belt", or over 11,000 ft under the Abajo Mountains (T. 34 S., R. 22 E.), and is commonly at least 7000 ft deep over much of the study area.

Finally, two correlation sections are provided transecting the Utah portion of the Paradox Basin; one longer longitudinal section (plates 20a and 20b), and a shorter transverse section (plate 21).

Some problems were encountered with the methodology and available data during this project, and they are listed below:

- The DOGM well database is not entirely complete; there are several instances of known oil and gas wells not currently listed in the DOGM online database. Additionally, not all available geophysical wireline well logs are in the DOGM online database.
- In the accompanying well data spreadsheet, some of the fields could not always be populated, as information from either DOGM or the log headers were absent. Examples of some missing data are: UTM coordinates (rare); quarter-quarter section designations; well total depths; or ground, Kelly bushing, or derrick floor elevations.
- Some salt cycles are thickened and/or repeated by flowage, folding, and/or faulting, and the spreadsheet does not adequately capture where salt thicknesses are anomalous due to these circumstances.
- There is a large difference in drill data density over the basin; some areas possess multiple wells per township, while other townships have not a single well. This fact makes regional mapping of the entire basin at the chosen map scale difficult, and the fine details of those areas with high data density may not be adequately portrayed at the current regional scale of mapping. Also, the gridding and contouring methods employed do not always honor some posted data point values.
- Time and budget constraints allowed only a handful of wells to be reviewed in the "Fold and Fault Belt," and most previous workers were not able to correlate individual salt cycles there. Additional lengthy study might be able to assign some salt cycle correlations for additional wells in this part of the basin that are not included in the existing well database.
- Many salt cycles were found to have anhydrite layers either directly above, directly below, or both above and below the main halite bed of a particular salt cycle. This is especially apparent for salt cycles S2 through S4, S11 and S12, and several salt cycles below the Cane Creek Marker Bed. Due to facies changes, some salt cycle intervals are actually anhydrite according to wireline well log signatures. Some previous workers include these anhydrite layers with a salt cycle and reference the anhydrite's top (or base) as the top (or base) of a salt cycle. This study's spreadsheet database only uses the actual salt (halite) as the top and base of a cycle.
- The top of the "Akah Oil Zone", as identified in this well database, is herein defined as the same as the top of salt cycle S6. There probably are thinly bedded anhydrite and carbonate layers, and possibly shale layers, present above S6 and yet below the "true" base of the Chimney Rock Marker Bed. If an interested researcher desires

to map the true thickness of only the shale layers of the Chimney Rock Marker Bed, further definition of the top of the "Akah Oil Zone" beyond what is available in this spreadsheet will be required. In the case of the few included Colorado oil and gas wells, where the Colorado Geological Survey (Scott, 2003) has identified the top of the "Akah Oil Zone" separately from the top of S6, these separate and different tops are captured in this well database. The same above comments are applicable for other oil zones such as the "Ismay" or "Desert Creek."

- Correlations of salt cycles below the Cane Creek Marker Bed are difficult, not the focus of this study, and are less reliably recorded in the database.
- Some comments for data cells in the spreadsheet do not display fully when "mousing" or "cursoring" over them. The author is unsure of the cause, and does not know of a "universal" remedy for viewing all such comments. Some comment cells may need to be adjusted individually to properly view them.

RECOMMENDATIONS

- Compilation and incorporation of any additional oil and gas wells drilled in the Paradox Basin since the DOGM well database was downloaded (August 1, 2011) for this study could be completed.
- Study of the dozens of additional oil and gas wells in Grand and San Juan Counties, Utah, and many from bordering Colorado counties, could be made and incorporated into the well database.
- Study of the numerous, not yet reviewed, oil and gas wells south of T. 31 S. in San Juan County, especially those wells lying within the "potash" extent line, could be undertaken. Most of these wells in the current database only have the depth to the top of the uppermost uncorrelated salt identified. A considerable percentage of these wells in this southern portion of the Paradox Basin penetrate just the upper part of the Paradox Formation, most often just the Ismay and Desert Creek oil zones, so that any deeper salt cycles and potash zones could not be adequately studied.
- Searches could be made via private data vendors for select well logs not in the DOGM database. For important wells without DOGM logs, purchase of key well logs might be warranted.
- Attempts at gridding salt cycle and potash zone thickness data with a basinal anisotropy may yield more realistic maps, especially if regions of higher data density are mapped in more detail.
- Creation of additional appropriate transverse "basin-crossing" correlation sections could show the effects of transiting from basin-edge to basin-center. However, section generation within the "Fold and Fault Belt" is not recommended due to difficulty with salt cycle correlation.
- Creation of additional derivative maps could be very informative. Examples include: gross and net cumulative salt thickness, gross and net cumulative potash thickness, structure and depth to individual potash zones, areal distributions of each salt cycle, or structure on top of the Mississippian local "basement."
- Estimates of potash zone grade could be made more quantitative by more detailed analysis of a well's suite of wireline logs. If enough wells with both potash core chemical analyses and wireline logs can be located and studied in the Paradox Basin, a basin-specific correlation or "cross plot" might be possible, such as gamma ray log response versus K_2O content. Additionally, wells with older non-standard API units for the natural gamma-ray wireline log could be converted to standard API units.
- Incorporation of potash data from on-line reports of exploration drilling by mineral companies currently active in the basin, and archived private data not previously accessible, would enhance the database.
- Study of the deeper potash zones in salt cycles S20, S21, S24, and S27 might be undertaken, and incorporation of that data made into the well database.

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APPENDIX

Well data spreadsheet

on CD: Appendix - Paradox Salt and Potash database.xls

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PLATE 2

Well Database and Maps of Salt Cycles and Potash Zones of the Paradox Basin, Utah

S5 Salt Cycle Thickness Map

EXPLANATION

- Oil and Gas well (in database)
- Oil and Gas well from DOGM, unclassified
- Potash exploration hole (in database)
- Hite correlation well
- Well with no salt cycle present — note: well might not be deep enough to fully intercept salt cycle
- Well with salt cycle present
- 110 — thickness of salt (ft); data point
- Salt thickness contour (CI=50ft)
- Approximate limit of salt facies of Paradox Fm.
- Master correlation and transverse sections generally following R. Hite well selections
- Well in "Fold and Fault Belt"
- Area encompassing regional "Fold and Fault Belt"

Base: UTM Zone 12, NAD83. Boundary tics in meters. Utah Automated Geographic Reference Center (AGRC) GIS data
Wells: DOGM data, 01August2011

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UGS Grant/Contract Number #112609 — June 2012

INDEX MAP
UTAH
Detailed Area

SCALE
1 : 250,000
0 1 2 3 4 5 6 7 8 9 10 miles
0 1 2 3 4 5 6 7 8 9 10 kilometers

PLATE 3

Well Database and Maps of Salt Cycles and Potash Zones of the Paradox Basin, Utah

S6 Salt Cycle Thickness Map

EXPLANATION

- Oil and Gas well (in database)
- Oil and Gas well from DOGM, unclassified
- Potash exploration hole (in database)
- Hite correlation well
- Well with no salt cycle present
  note: well might not be deep enough to fully intercept salt cycle
- Well with salt cycle present
- 110 thickness of salt (ft); data point
- Salt thickness contour (CI=50ft)
- Approximate limit of salt facies of Paradox Fm.
- Master correlation and transverse sections generally following R. Hite well selections
- Well in "Fold and Fault Belt"
- Area encompassing regional "Fold and Fault Belt"

Base: UTM Zone 12, NAD83. Boundary tics in meters. Utah Automated Geographic Reference Center (AGRC) GIS data
Wells: DOGM data, 01August2011

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June 2012

SCALE
1 : 250,000
0 1 2 3 4 5 6 7 8 9 10 miles
0 1 2 3 4 5 6 7 8 9 10 kilometers

PLATE 4

Well Database and Maps of Salt Cycles and Potash Zones of the Paradox Basin, Utah

S9 Salt Cycle Thickness Map

EXPLANATION

- Oil and Gas well (in database)
- Oil and Gas well from DOGM, unclassified
- Potash exploration hole (in database)
- Hite correlation well
- Well with no salt cycle present (note: well might not be deep enough to fully intercept salt cycle)
- Well with salt cycle present
- 110 thickness of salt (ft); data point
- Salt thickness contour (CI=50ft)
- Approximate limit of salt facies of Paradox Fm.
- Master correlation and transverse sections generally following R. Hite well selections
- Well in "Fold and Fault Belt"
- Area encompassing regional "Fold and Fault Belt"

Base: UTM Zone 12, NAD83. Boundary tics in meters. Utah Automated Geographic Reference Center (AGRC) GIS data
Wells: DOGM data, 01August2011

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UGS Grant/Contract Number #112609 June 2012

INDEX MAP
UTAH
Detailed Area

SCALE
1 : 250,000
0 1 2 3 4 5 6 7 8 9 10 miles
0 1 2 3 4 5 6 7 8 9 10 kilometers

PLATE 5

Well Database and Maps of Salt Cycles and Potash Zones of the Paradox Basin, Utah

S13 Salt Cycle Thickness Map

EXPLANATION

- Oil and Gas well (in database)
- Oil and Gas well from DOGM, unclassified
- Potash exploration hole (in database)
- Hite correlation well
- Well with no salt cycle present
  note: well might not be deep enough to fully intercept salt cycle
- Well with salt cycle present
- 110 thickness of salt (ft)
- data point
- Salt thickness contour (CI=50ft)
- Approximate limit of salt facies of Paradox Fm.
- Master correlation and transverse sections generally following R. Hite well selections
- Well in "Fold and Fault Belt"
- Area encompassing regional "Fold and Fault Belt"

Base: UTM Zone 12, NAD83.
Boundary tics in meters.
Utah Automated Geographic Reference Center (AGRC) GIS data
Wells: DOGM data, 01August2011

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PLATE 6

Well Database and Maps of Salt Cycles and Potash Zones of the Paradox Basin, Utah

S16 Salt Cycle Thickness Map

EXPLANATION

- Oil and Gas well (in database)
- Oil and Gas well from DOGM, unclassified
- Potash exploration hole (in database)
- Hite correlation well
- Well with no salt cycle present
  note: well might not be deep enough to fully intercept salt cycle
- Well with salt cycle present
- 110 — thickness of salt (ft); data point
- Salt thickness contour (CI=50ft)
- Approximate limit of salt facies of Paradox Fm.
- Master correlation and transverse sections generally following R. Hite well selections
- Well in "Fold and Fault Belt"
- Area encompassing regional "Fold and Fault Belt"

Base: UTM Zone 12, NAD83. Boundary tics in meters. Utah Automated Geographic Reference Center (AGRC) GIS data
Wells: DOGM data, 01August2011

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PLATE 7
Well Database and Maps of Salt Cycles and Potash Zones of the Paradox Basin, Utah
S18 Salt Cycle Thickness Map
EXPLANATION
Oil and Gas well (in database)
Oil and Gas well from DOGM, unclassified
Potash exploration hole (in database)
Hite correlation well
Well with no salt cycle present
note: well might not be deep enough to fully intercept salt cycle
Well with salt cycle present
110
thickness of salt (ft)
data point
Salt thickness contour (CI=50ft)
Approximate limit of salt facies of Paradox Fm.
Master correlation and transverse sections generally following R. Hite well selections
Well in "Fold and Fault Belt"
Area encompassing regional "Fold and Fault Belt"
Base: UTM Zone 12, NAD83. Boundary tics in meters. Utah Automated Geographic Reference Center (AGRC) GIS data
Wells: DOGM data, 01August2011
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UGS Grant/Contract Number #112609
June 2012
INDEX MAP
UTAH
Detailed Area
SCALE
1 : 250,000
0 1 2 3 4 5 6 7 8 9 10 miles
0 1 2 3 4 5 6 7 8 9 10 kilometers
CARBON
UINTAH
EMERY
GRAND
WAYNE
GARFIELD
KANE
SAN JUAN
Fold and Fault Belt
Master correlation section generally following R. Hite well selections
Intrepid Potash workings


CARBON
UINTAH
EMERY
GRAND
WAYNE
GARFIELD
KANE
SAN JUAN
Fold and Fault Belt
Master correlation section generally following R. Hite well selections
Intrepid Potash workings
PLATE 8
Well Database and Maps of Salt Cycles and Potash Zones of the Paradox Basin, Utah
S19 Salt Cycle Thickness Map
EXPLANATION
Oil and Gas well (in database)
Oil and Gas well from DOGM, unclassified
Potash exploration hole (in database)
Hite correlation well
Well with no salt cycle present
note: well might not be deep enough to fully intercept salt cycle
Well with salt cycle present
110 thickness of salt (ft)
data point
Salt thickness contour (CI=50ft)
Approximate limit of salt facies of Paradox Fm.
Master correlation and transverse sections generally following R. Hite well selections
Well in "Fold and Fault Belt"
Area encompassing regional "Fold and Fault Belt"
Base: UTM Zone 12, NAD83. Boundary tics in meters. Utah Automated Geographic Reference Center (AGRC) GIS data
Wells: DOGM data, 01August2011
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UGS Grant/Contract Number #112609
June 2012
INDEX MAP
UTAH
Detailed Area
SCALE
1 : 250,000
0 1 2 3 4 5 6 7 8 9 10 miles
0 1 2 3 4 5 6 7 8 9 10 kilometers


PLATE 9
Well Database and Maps of Salt Cycles and Potash Zones of the Paradox Basin, Utah
S5 Salt Top Structure Map
EXPLANATION
Oil and Gas well (well in database)
Oil and Gas well from DOGM, unclassified
Potash exploration hole (hole in database)
Hite correlation well
Well with no salt cycle present
Well with salt cycle present
-2000
elevation at top of salt (ft above sea level)
data point
Top salt structure contour (CI=500ft)
Mapped faults
Mapped anticlines
Approximate limit of salt facies of Paradox Fm.
Master correlation and transverse sections generally following R. Hite well selections
Well in "Fold and Fault Belt"
Area encompassing regional "Fold and Fault Belt"
Base: UTM Zone 12, NAD83. Boundary tics in meters. Utah Automated Geographic Reference Center (AGRC) GIS data
Wells: DOGM data, 01August2011
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Salt Lake City, Utah 84102
UGS Grant/Contract Number #112609
June 2012
INDEX MAP
UTAH
Detailed Area
SCALE
1 : 250,000
0 1 2 3 4 5 6 7 8 9 10 miles
0 1 2 3 4 5 6 7 8 9 10 kilometers
CARBON
UINTAH
EMERY
GRAND
WAYNE
GARFIELD
SAN JUAN
KANE
Fold and Fault Belt
Intrepid Potash workings
Master correlation section generally following R. Hite well selections

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Plate 10
Utah Geological Survey Open-File Report 600
Well Database and Maps of Salt Cycles and Potash Zones of Paradox Basin, Utah

PLATE 11

Well Database and Maps of Salt Cycles and Potash Zones of the Paradox Basin, Utah

S5 Salt Depth to Top Map

EXPLANATION

- Oil and Gas well (well in database)
- Oil and Gas well from DOGM, unclassified
- Potash exploration hole (hole in database)
- Hite correlation well
- Well with no salt cycle present
- Well with salt cycle present
- 5500 — depth to top of salt (ft); data point
- Depth to Top of contour (CI=500ft) (contour lines bolded at 1000ft, 4000ft, 7000ft, and 10000ft)
- Approximate limit of salt facies of Paradox Fm.
- Master correlation and transverse sections generally following R. Hite well selections
- Well in "Fold and Fault Belt"
- Area encompassing regional "Fold and Fault Belt"

Base: UTM Zone 12, NAD83. Boundary tics in meters. Utah Automated Geographic Reference Center (AGRC) GIS data
Wells: DOGM data, 01August2011

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PLATE 12

Well Database and Maps of Salt Cycles and Potash Zones of the Paradox Basin, Utah

S19 Salt Depth to Top Map

EXPLANATION

- Oil and Gas well (well in database)
- Oil and Gas well from DOGM, unclassified
- Potash exploration hole (hole in database)
- Hite correlation well
- Well with no salt cycle present
- Well with salt cycle present
- 5500 depth to top of salt (ft)
- data point
- Depth to Top of contour (CI=500ft) (contour lines bolded at 1000ft, 4000ft, 7000ft, and 10000ft)
- Approximate limit of salt facies of Paradox Fm.
- Master correlation and transverse sections generally following R. Hite well selections
- Well in "Fold and Fault Belt"
- Area encompassing regional "Fold and Fault Belt"

Base: UTM Zone 12, NAD83. Boundary tics in meters. Utah Automated Geographic Reference Center (AGRC) GIS data
Wells: DOGM data, 01August2011

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CARBON
UINTAH
EMERY
GRAND
WAYNE
GARFIELD
KANE
SAN JUAN
GRAND
SAN JUAN
Fold and Fault Belt
Fold and Fault Belt
Master correlation section generally following R. Hite well selections
Intrepid Potash workings
15ft (5318.5-5331) @ 30.6
14.5ft (5513.5-5528) @ 15.2
11ft (4842-4853) @ 25.0
12.5ft (5476-5488) @ 21.5
8ft (5342.5-5350.5) @ 11.9
PLATE 13
Well Database and Maps of Salt Cycles and Potash Zones of the Paradox Basin, Utah
S5 Potash Zone Thickness Map
EXPLANATION
Oil and Gas well (well in database)
Oil and Gas well from DOGM, unclassified
Potash exploration hole (hole in database)
Hite correlation well
Well with no potash in mapped zone
Well with potash but no API value determined
Well with potash zone at <100 API maximum
Well with potash zone at 100-200 API maximum
Well with potash zone at >200 API maximum
15ft (5316.5-5331)@30.6
analytical value (K20%)
data point
17
potash zone thickness (ft)
Potash thickness contour (CI=5ft)
Approximate limit of salt facies of Paradox Fm.
Master correlation and transverse sections generally following R. Hite well selections
Well in Fold and Fault Belt
Area encompassing regional "Fold and Fault Belt"
Base: UTM Zone 12, NAD83. Boundary tics in meters. Utah Automated Geographic Reference Center (AGRC) GIS data
Wells: DOGM data, 01August2011
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UGS Grant/Contract Number #112609
June 2012
INDEX MAP
UTAH
Detailed Area
N
SCALE
1 : 250,000
0 1 2 3 4 5 6 7 8 9 10 miles
0 1 2 3 4 5 6 7 8 9 10 kilometers
520000
530000
540000
550000
560000
570000
580000
590000
600000
610000
620000
630000
640000
650000
660000
670000
4380000
4370000
4360000
4350000
4340000
4330000
4320000
4310000
4300000
4290000
4280000
4270000
4260000
4250000
4240000
4230000
4220000
4210000
4200000
4190000
4180000
4170000
4160000
4150000
4140000
4130000
4120000
4110000
4100000


CARBON
EMERY
UINTAH
GRAND
WAYNE
GARFIELD
SAN JUAN
KANE
Fold and Fault Belt
Master correlation section generally following R. Hite well selections
Intrepid Potash workings
5.5ft @ 9.6%K2O
28ft @ 2.0%K2O
PLATE 14
Well Database and Maps of Salt Cycles and Potash Zones of the Paradox Basin, Utah
S6 Potash Zone Thickness Map
EXPLANATION
Oil and Gas well (well in database)
Oil and Gas well from DOGM, unclassified
Potash exploration hole (hole in database)
Hite correlation well
Well with no potash in mapped zone
Well with potash but no API value determined
Well with potash zone at <100 API maximum
Well with potash zone at 100-200 API maximum
Well with potash zone at >200 API maximum
15ft (5316.5-5331)@30.6
analytical value (K20%)
data point
17
potash zone thickness (ft)
Potash thickness contour (CI=20ft)
Approximate limit of salt facies of Paradox Fm.
Master correlation and transverse sections generally following R. Hite well selections
Well in Fold and Fault Belt
Area encompassing regional "Fold and Fault Belt"
Base: UTM Zone 12, NAD83. Boundary tics in meters. Utah Automated Geographic Reference Center (AGRC) GIS data
Wells: DOGM data, 01August2011
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INDEX MAP
UTAH
Detailed Area
SCALE
1 : 250,000
0 1 2 3 4 5 6 7 8 9 10 miles
0 1 2 3 4 5 6 7 8 9 10 kilometers

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PLATE 16
Well Database and Maps of Salt Cycles and Potash Zones of the Paradox Basin, Utah
S13 Potash Zone Thickness Map
EXPLANATION
Oil and Gas well (well in database)
Oil and Gas well from DOGM, unclassified
Potash exploration hole (hole in database)
Hite correlation well
Well with no potash in mapped zone
Well with potash but no API value determined
Well with potash zone at <100 API maximum
Well with potash zone at 100-200 API maximum
Well with potash zone at >200 API maximum
15ft (5316.5-5331)@30.6
analytical value (K20%)
data point
17
potash zone thickness (ft)
Potash thickness contour (CI=10ft)
Approximate limit of salt facies of Paradox Fm.
Master correlation and transverse sections generally following R. Hite well selections
Well in Fold and Fault Belt
Area encompassing regional "Fold and Fault Belt"
Base: UTM Zone 12, NAD83. Boundary tics in meters. Utah Automated Geographic Reference Center (AGRC) GIS data Wells: DOGM data, 01August2011
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June 2012
INDEX MAP
UTAH
Detailed Area
SCALE
1 : 250,000
0 1 2 3 4 5 6 7 8 9 10 miles
0 1 2 3 4 5 6 7 8 9 10 kilometers
CARBON
EMERY
UINTAH
GRAND
WAYNE
GARFIELD
KANE
SAN JUAN
Fold and Fault Belt
Master correlation section generally following R. Hite well selections
Intrepid Potash workings

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Plate 17
Utah Geological Survey Open-File Report 600
Well Database and Maps of Salt Cycles and Potash Zones of Paradox Basin, Utah

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Plate 19
Utah Geological Survey Open-File Report 600
Well Database and Maps of Salt Cycles and Potash Zones of Paradox Basin, Utah

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Master Longitudinal Cross Section
North Portion

Well Database and Maps of Salt Cycles and Potash Zones of the Paradox Basin, Utah
by
Terry W. Massoth
Consulting Geologist
2012

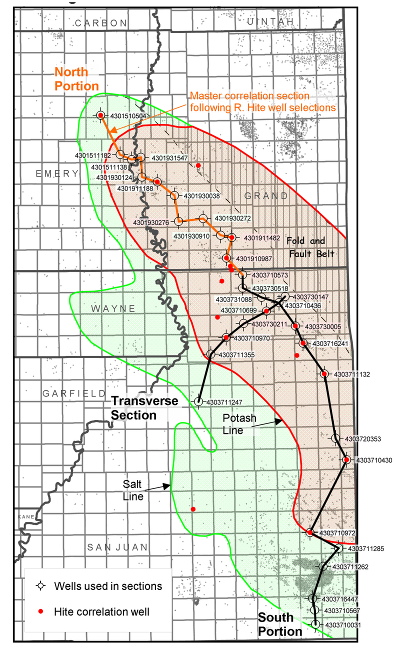
Vertical Exaggeration 20:1

0 6000 12000 18000 24000 30000 ft
9000 m
0 9 km
5 miles

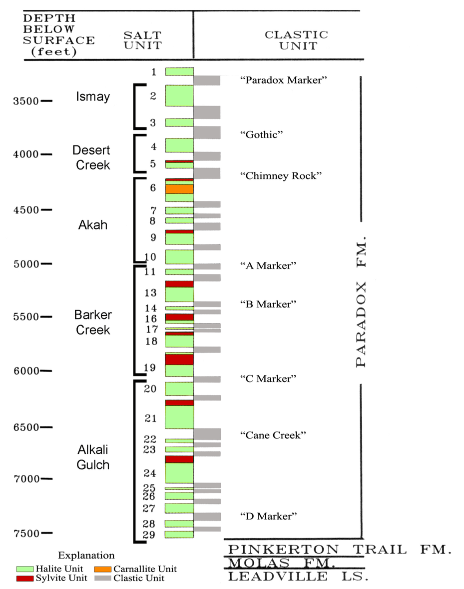
EXPLANATION

(green)	Salt cycle with potentially economic potash zones (labeled according to Hite nomenclature; only zones S5, S6, S9, S13, S16, S18, and S19 color filled; other salt cycles may contain potash zones)
(red)	Potash zones in S5, S9, S13, S16, S18, and S19
(orange)	Carnallite potash zone in S6
(gray)	Key marker bed
(blue)	Mississippian limestone (arbitrarily shown as 200 ft thick)

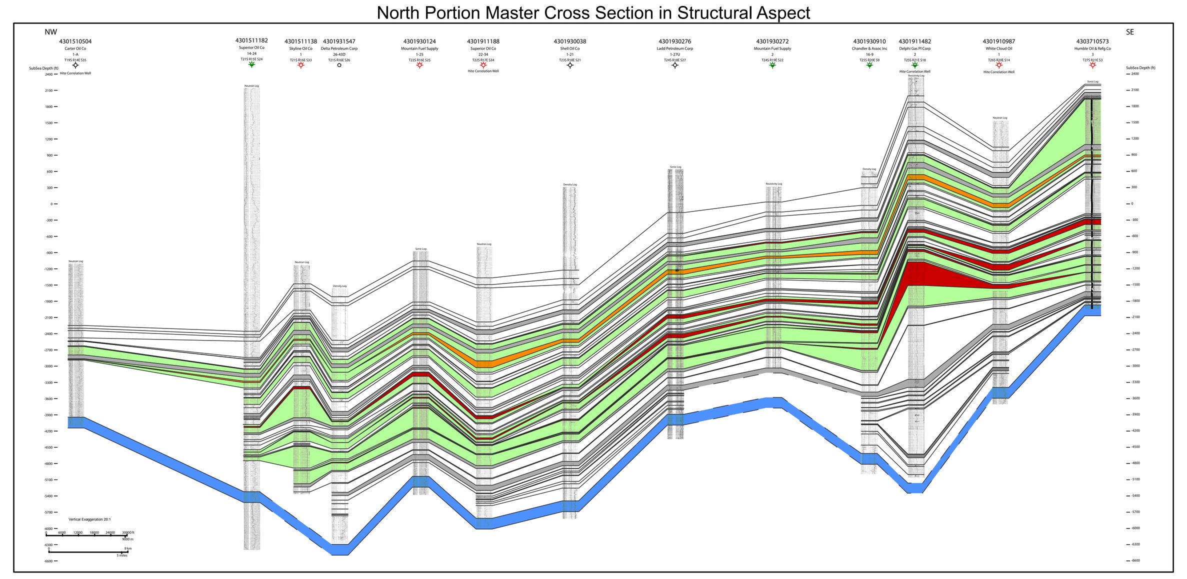
Master Longitudinal Cross Section - North Portion



Generalized Stratigraphic Column



North Portion Master Cross Section in Structural Aspect



UTAH GEOLOGICAL SURVEY
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Master Longitudinal Cross Section
South Portion

UTAH GEOLOGICAL SURVEY
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Plate 21
Utah Geological Survey Open-File Report 600
Well Database and Maps of Salt Cycles and Potash Zones of Paradox Basin, Utah

Transverse Cross Section

Well Database and Maps of Salt Cycles and Potash Zones of the Paradox Basin, Utah
by
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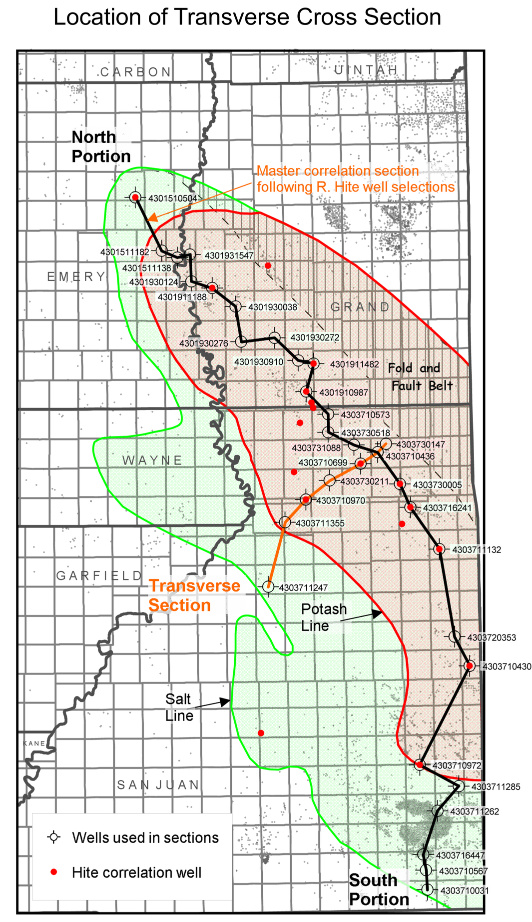
Consulting Geologist
2012

Vertical Exaggeration 20:1

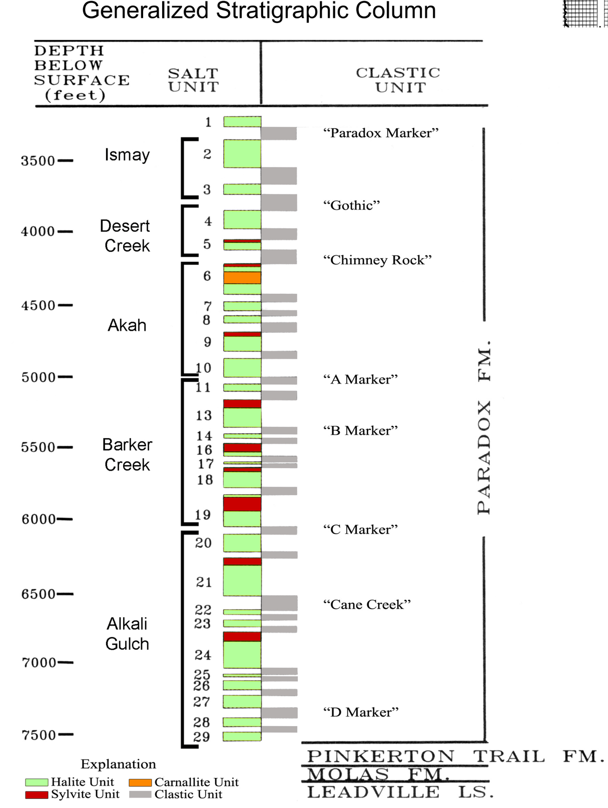
0 6000 12000 18000 24000 30000 ft
9000 m

0 9 km
5 miles

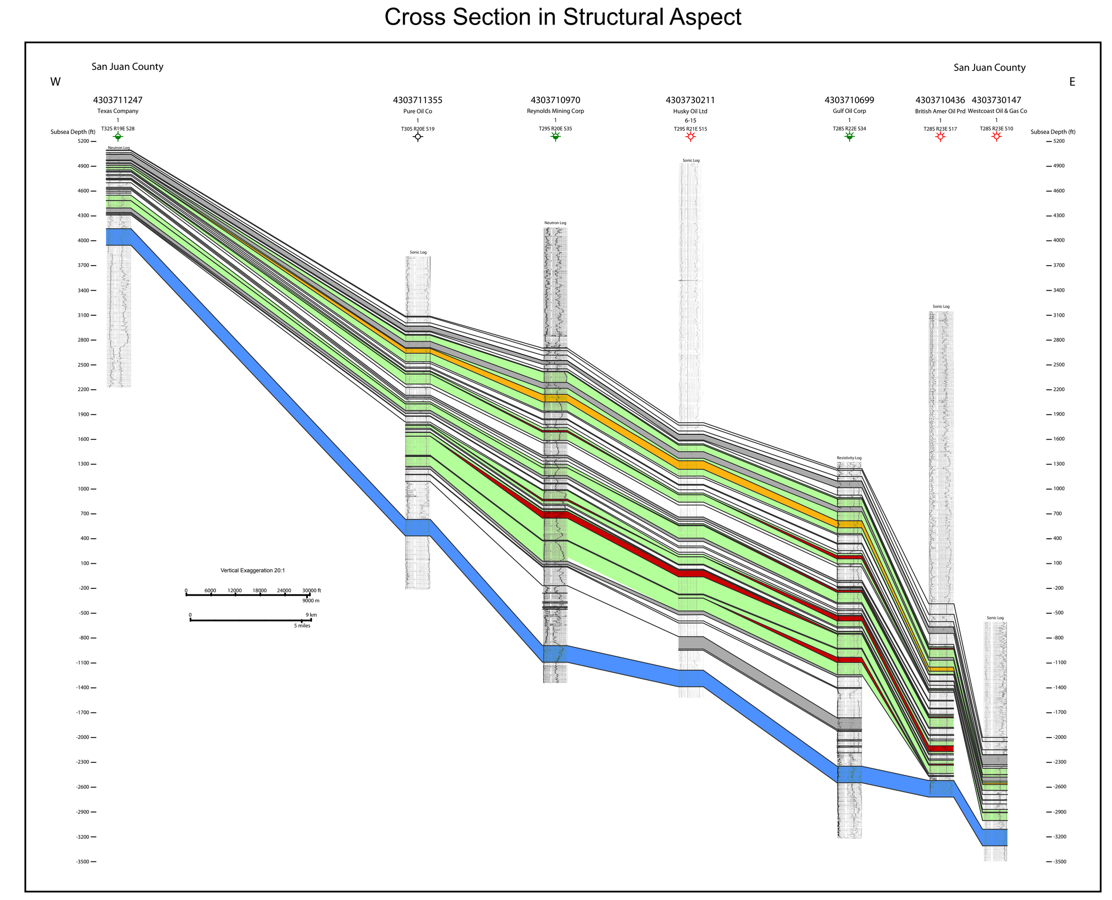
Location of Transverse Cross Section



Generalized Stratigraphic Column



Cross Section in Structural Aspect



EXPLANATION

- Salt cycle with potentially economic potash zones (labeled according to Hite nomenclature; only zones S5, S6, S9, S13, S16, S18, and S19 color filled; other salt cycles may contain potash zones)
- Potash zones in S5, S9, S13, S16, S18, and S19
- Carnallite potash zone in S6
- Key marker bed
- Mississippian limestone (arbitrarily shown as 200 ft thick)