GEOLOGICAL CHARACTERIZATION OF THE BIRDS NEST AQUIFER, UINTA BASIN, UTAH

ASSESSMENT OF THE AQUIFER'S POTENTIAL AS A SALINE WATER DISPOSAL ZONE

by Michael D. Vanden Berg, Danielle R. Lehle, Stephanie M. Carney, and Craig D. Morgan

SPECIAL STUDY 147
UTAH GEOLOGICAL SURVEY
a division of
UTAH DEPARTMENT OF NATURAL RESOURCES
2013

GEOLOGICAL CHARACTERIZATION OF THE BIRDS NEST AQUIFER, UINTA BASIN, UTAH

ASSESSMENT OF THE AQUIFER'S POTENTIAL AS A SALINE WATER DISPOSAL ZONE

by Michael D. Vanden Berg, Danielle R. Lehle, Stephanie M. Carney, and Craig D. Morgan

Cover photo: *The Birds Nest aquifer in outcrop along Evacuation Creek, eastern Uinta Basin, Utah. The cavities were created by the dissolution of nahcolite nodules.*

ISBN: 978-1-55791-874-1

SPECIAL STUDY 147
UTAH GEOLOGICAL SURVEY
a division of
UTAH DEPARTMENT OF NATURAL RESOURCES
2013

STATE OF UTAH
Gary R. Herbert, Governor

DEPARTMENT OF NATURAL RESOURCES
Michael Styler, Executive Director

UTAH GEOLOGICAL SURVEY
Richard G. Allis, Director

PUBLICATIONS
contact
Natural Resources Map & Bookstore
1594 W. North Temple
Salt Lake City, UT 84114
telephone: 801-537-3320
toll-free: 1-888-UTAH MAP
website: mapstore.utah.gov
email: geostore@utah.gov

UTAH GEOLOGICAL SURVEY
contact
1594 W. North Temple, Suite 3110
Salt Lake City, UT 84114
telephone: 801-537-3300
website: geology.utah.gov

CONTENTS

FIGURES

TABLES

PLATES

GEOLOGICAL CHARACTERIZATION OF THE BIRDS NEST AQUIFER, UINTA BASIN, UTAH

ASSESSMENT OF THE AQUIFER'S POTENTIAL AS A SALINE WATER DISPOSAL ZONE

by Michael D. Vanden Berg, Danielle R. Lehle, Stephanie M. Carney, and Craig D. Morgan

ABSTRACT

As petroleum production increases in the Uinta Basin, Utah, operators are pressed to establish suitable saline water disposal plans. Several natural gas operators have identified the Birds Nest aquifer in central Uintah County as a possible large-scale, saline water disposal zone; however, disposal into this aquifer poses unique challenges and risks.

The Birds Nest aquifer formed from the dissolution of saline minerals within a saline zone in the upper Green River Formation's Parachute Creek Member. Through the examination of core, outcrop, and geophysical logs, we determined that the aquifer is separated into an upper zone, covering about 410 square miles with an average thickness of 79 feet, and a more extensive lower zone, covering about 719 square miles with an average thickness of 84 feet. We generated several maps showing the aquifer's areal extent, thickness, outcrop extent, and depth.

Federal and state regulations stipulate that produced saline water can only be injected into an underground aquifer that already contains water having >10,000 mg/L total dissolved solids (TDS) concentration or is exempted under the Safe Drinking Water Act. Using water chemistry data collected from various sources, a 10,000 mg/L TDS boundary line was determined for the Birds Nest aquifer. Water in the southeast portion of the aquifer averages less than 10,000 mg/L TDS, down to a low of 1000 mg/L TDS, whereas water in the northwest portion averages higher than 10,000 mg/L TDS and locally exceeds 100,000 mg/L TDS. Since disposal can only take place north of the 10,000 mg/L TDS boundary line, the available areas suitable for saline water disposal within the upper and lower Birds Nest aquifer are reduced to 384 and 533 square miles, respectively.

Gilsonite, a solid hydrocarbon, occurs in veins ranging in thickness from a few inches to tens of feet. The veins originate from the rich oil shale beds of the upper Green River Formation and continue up to the surface, cross-cutting the Birds Nest aquifer. Questions remain as to how these veins might affect groundwater movement through the Birds Nest aquifer: whether they act as barriers to flow or whether they create vertical and/or horizontal pathways for water transmission. The assessment provided herein includes anecdotal evidence for both cases, barrier and conduit, depending on the type of gilsonite in the vein, vein thickness, and abundance of associated fractures. Unfortunately, very little is known about the gilsonite veins and fractures at depth in the areas suitable for saline water disposal.

The fact that the Birds Nest aquifer lies within the Uinta Basin's oil shale horizon raises questions as to how large-scale, saline water disposal into this zone might impact potential future oil shale development. Currently, all companies in Utah looking to develop an oil shale property are focused on areas near the outcrop of the Mahogany zone and plan to develop a surface/underground mine and surface retort, or employ surface modified *in-situ* technologies. Since disposal can only take place north of the 10,000 mg/L TDS boundary, active disposal will be several tens of miles northwest and down-dip of any proposed oil shale development site.

Oil shale technology could potentially advance to the point where the deeper deposits, located adjacent to active Birds Nest disposal operations, might become economic. If advances in *in-situ* technologies (retorting the oil shale within the ground) allow exploitation of these deeper deposits, the oil recovery zone will be limited to the lower R-8 rich oil shale zone and below, leaving 70–90 feet of impermeable oil shale between the retort zone and the lower Birds Nest aquifer, purposely avoiding the aquifer and problems associated with retorting shale within a zone filled with water and saline minerals. Therefore, the lean oil shale within the Birds Nest has little to no economic value. In addition, if technologies advance to the point where deep underground mines prove economic (oil prices would also need to be favorably high), the mined interval would most likely be centered on the Mahogany zone, roughly 1500–3000 feet deep in the area where saline water disposal can take place, with about 300 feet of impermeable oil shale between the mining horizon and the aquifer. The most pressing question is whether water in the

Birds Nest aquifer can migrate vertically through thick sequences of impermeable oil shale by way of fractures or gilsonite veins, potentially flooding operations stratigraphically below the Birds Nest. Any kind of water infiltration into the mining horizon could greatly affect the economics of these deeper deposits. The likelihood of such a scenario is remote but plausible, and will only increase as saline water disposal becomes more widespread.

INTRODUCTION

As Uinta Basin petroleum production increases—natural gas production increased 208% in the past 10 years, while oil production increased 160%—so has associated saline water production, increasing the need for economic and environmentally responsible disposal plans (figure 1) (DOGM, 2012). In fact, U.S. Bureau of Land Management (BLM) records indicate that up to 25,000 new wells have been proposed for drilling in the basin (figure 2) (U.S. BLM, 2012). Many Uinta Basin operators claim that petroleum production cannot reach its full potential until a suitable, long-term water disposal solution is determined.

Currently there are three main ways to dispose of produced saline water in the Uinta Basin: 1) treat and re-use the water, 2) place the water in an evaporation pond, or 3) re-inject the water underground. Treatment and re-use, while applicable in

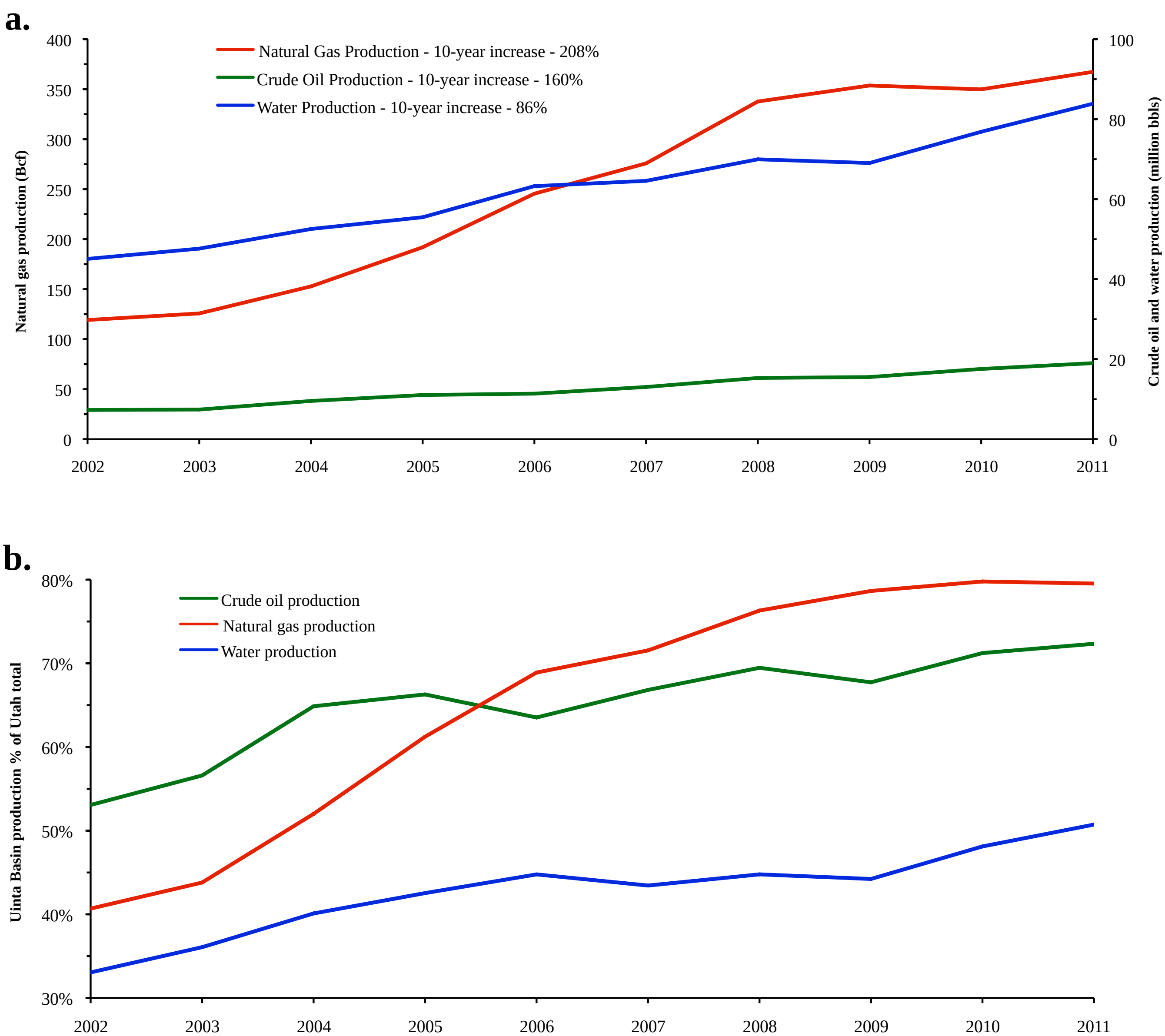


Figure 1. a. *Natural gas, crude oil, and water production in the Uinta Basin, Utah, 2002–2011 (DOGM, 2012).* ***b.*** *Percentage of Utah's total natural gas, crude oil, and water production from the Uinta Basin.*

some cases (Anadarko, 2010), is often uneconomic and typically more water is produced than can be re-used. Evaporation ponds are considered by many as a last resort since they pose several environmental risks (brine concentration, potential for shallow groundwater contamination, potential hazard to wildlife, and potential for increase in volatile organic compound and ozone emissions) and have limited capacities (Energy Dynamics Laboratory, 2012; NETL, 2012). The method preferred by most operators and regulators, as well as the method having the largest storage volume potential, is re-injection into deep underground saline aquifers (U.S. EPA, 2012).

Federal regulations dictate that saline water from oil and gas wells can only be injected into aquifers containing water having >10,000 mg/L total dissolved solids (TDS) salinity or are exempted under the Safe Drinking Water Act (U.S. EPA, 2012; U.S. NARA, 2012). This practice was implemented as a means to protect potential underground sources of drinking water, a priority in the arid Uinta Basin. Current water disposal wells are near capacity and permitting for new wells has been delayed because of insufficient technical data regarding potential disposal aquifers and questions concerning contamination of freshwater sources. Eastern Uinta Basin natural gas producers have identified the Birds Nest aquifer, located in the Parachute Creek Member of the Green River Formation, as one of the most promising reservoirs suitable for large-volume saline water disposal. Drilling companies indicate that the Birds Nest aquifer creates a zone of lost circulation when accessing deeper natural gas deposits, which is often cited as evidence for large storage volume potential. In fact, three petroleum companies have already commenced limited saline water disposal into the Birds Nest aquifer; Anadarko currently operates eight disposal wells (with one more proposed), EOG Resources operates nine disposal wells, and Questar operates one (with an additional well proposed) (table 1).

Our research focused on defining the Birds Nest aquifer's geologic characteristics (i.e., the origin of the aquifer, its

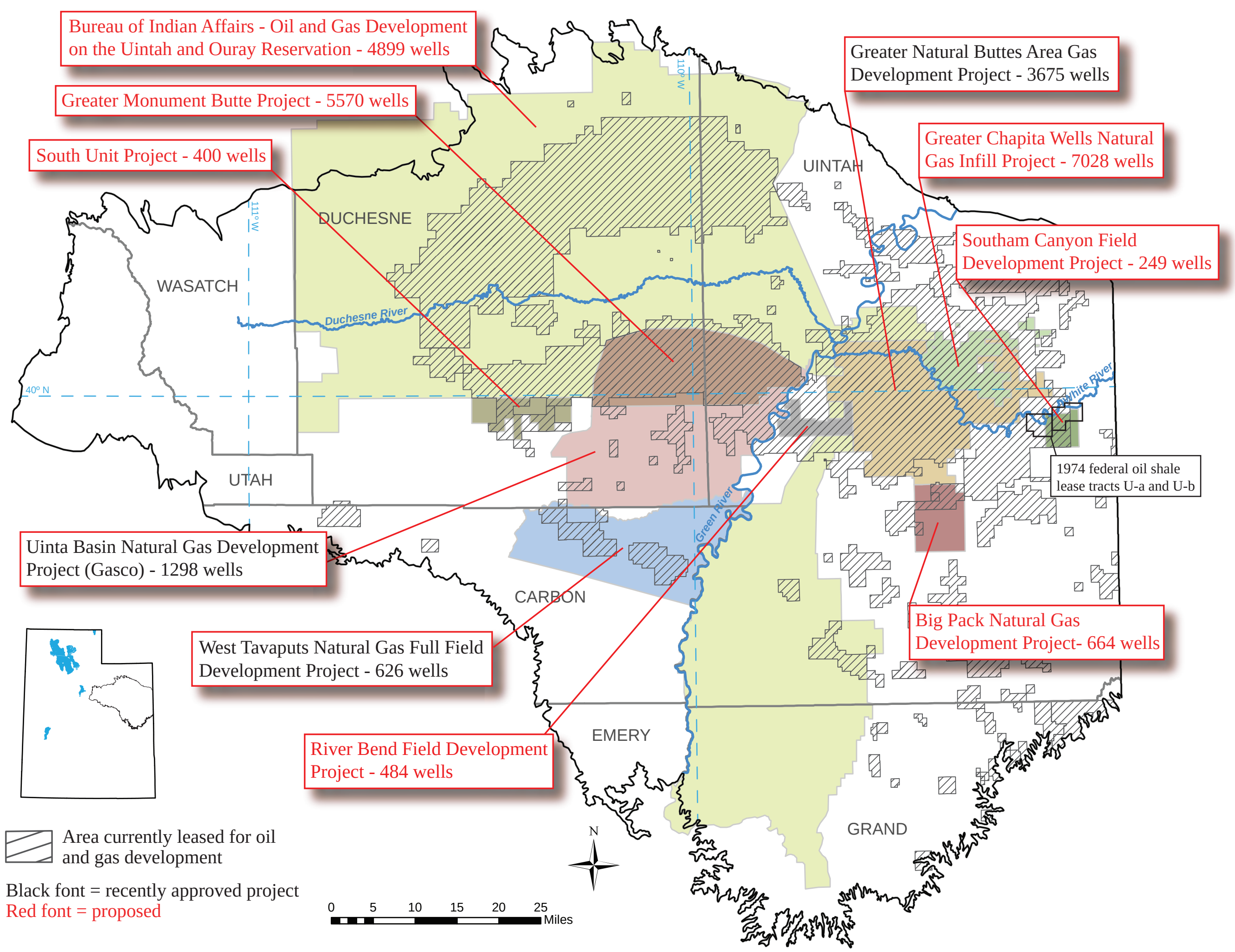


Figure 2. Proposed oil and gas drilling projects in the Uinta Basin comprise more than 25,000 new wells (U.S. BLM, 2012). This potential future drilling will greatly increase the amount of produced water needing proper disposal.

Table 1. *Active and proposed Birds Nest aquifer saline water disposal wells.*

API	Operator	Well Name	Status	Completion date	Twn	Rng	Sec	Mrd	UTM E	UTM N	Water Chemistry[1]	TD	Disposal Zone		Notes
			as of May 2012						NAD 83	NAD 83		ft	top - ft	base - ft	
4304737309	Questar	RWS 12 SWD 5-9-24	proposed		9S	24E	5	SL	649726	4436250	No	8105			current gas well
4304738875	Questar	NBE 12-10-9-23	active	29-Nov-2007	9S	23E	10	SL	643288	4434526	Yes	2070	1803	2070	
4304750290	EOG	Hoss 901-36	active	1-Apr-2009	8S	22E	36	SL	638083	4437416	Yes	2376			
4304750302	EOG	Hoss 903-36	active	2-Jul-2009	8S	22E	36	SL	637646	4437660	Yes	2150			
4304750304	EOG	Hoss 904-36	active	25-Jul-2009	8S	22E	36	SL	637074	4437408	Yes	2158	2143		
4304750303	EOG	Hoss 905-31	active	14-Sep-2009	8S	23E	31	SL	638759	4437381	Yes	2365	2094		
4304750300	EOG	Hoss 906-31	active	24-Sep-2009	8S	23E	31	SL	639426	443768	Yes	2365	2104		
4304750301	EOG	Hoss 907-31	active	6-Oct-2009	8S	23E	31	SL	639436	4437129	Yes	2345	2071		
4304733116	EOG	Chapita 550	active	25-Jun-2009	9S	23E	30	SL	639392	4430427	No[2]	5930	1620	1955	recompleted gas well, injection also above BN
4304738434	EOG	CWU SWD 2-29	active	8-Nov-2007	9S	23E	29	SL	640711	4430297	Yes	1940	1723	1830	
4304750806	EOG	Coyote SWD 1-16	active	1-Apr-2011	9S	23E	16	SL	642958	4433213	Yes	1970	1706	1964	
4304740254	Anadarko	NBU 921-34H	active	6-May-2011	9S	21E	34	SL	625402	4428106	Yes	1955	1641	1955	
4304736394	Anadarko	NBU 921-33J	active	2-Jun-2011	9S	21E	33	SL	623436	4427695	No	9400	1664	1957	recompleted gas well
4304740255	Anadarko	NBU 921-34L	active	15-Jan-2010	9S	21E	34	SL	624156	4427885	Yes	2260	1674	1932	recompleted gas well
4304736389	Anadarko	NBU 921-34K	active	5-Jun-2009	9S	21E	34	SL	624721	4427872	Yes	9650	1632	1960	recompleted gas well
4304731915	Anadarko	CIGE 114	active	12-Jun-2009	9S	21E	34	SL	625471	4427699	Yes	6150	1654	1959	recompleted gas well
4304740253	Anadarko	NBU 921-33F	active	20-Nov-2009	9S	21E	33	SL	622955	4428184	Yes	2260	1645	1970	
4304731996	Anadarko	NBU 159	active	9-Aug-1991	9S	21E	35	SL	626227	4427765	Yes	6049	1601	1927	
4304751396	Anadarko	NBU 921-35J	active	17-Nov-2011	9S	21E	35	SL	626821	4427616	Yes	1869	1533	1869	
4304736393	Anadarko	NBU 921-33I	proposed		9S	21E	33	SL	623762	4427746	No	9750	1662	1957	keeping as producing gas well for now

[1]Available in appendix B

[2]Original disposal was into formations above Birds Nest; later the permit was amended to include Birds Nest, so a Birds Nest specific water sample could not be collected.

thickness, areal extent, and outcrop exposure), defining the area having potential for saline water disposal, and analyzing the possible effects water disposal could have on a future oil shale industry. Except for a detailed analysis of the aquifer's water chemistry and an attempt to calculate the available storage space, determining the Birds Nest aquifer's other hydrogeologic characteristics was beyond the scope of this study.

PREVIOUS RESEARCH

Previous studies of the Birds Nest aquifer were limited to the area surrounding the 1974 federal oil shale lease tracts U-a and U-b, located mostly in T. 10 S., R. 24 E., Salt Lake Base Line and Meridian (SLBLM), on the far eastern side of the Uinta Basin (figure 2). Oil shale-related drilling within and surrounding these tracts provided limited subsurface data on the aquifer, but its overall areal extent was unknown. The first comprehensive study of the hydrology of the Birds Nest aquifer, within this limited area, was included in a U.S. Environmental Protection Agency (EPA) Environmental Baseline Report prepared for the White River Shale Project (U-a and U-b) (VTN, 1977). Following this report, Phillips (1979) detailed the hydrogeology of the Birds Nest aquifer surrounding the federal lease tracts, mainly using data from the VTN (1977) report supplemented with some outcrop examinations. Also in the mid-1970s, the U.S. Geological Survey (USGS) drilled six test wells south of the U-a and U-b tracts to investigate the shallow bedrock aquifers (Holmes, 1980). Only two of the six USGS wells penetrated the Birds Nest aquifer (with minimal water influx) and both were cased through this zone to perform aquifer testing on the underlying Douglas Creek aquifer. Lindskov and Kimball (1984) subsequently presented a summary of the extensive hydrologic investigations performed under the direction of the EPA and the USGS between 1974 and 1980 in the southeastern Uinta Basin, while Holmes and Kimball (1987) went one step further and generated various computer models simulating conditions and flows within the Birds Nest aquifer and underlying Douglas Creek aquifer, but again, the models were limited to the far eastern side of the Uinta Basin.

In the mid-1980s, the price of oil crashed and interest in developing oil shale greatly diminished. The federal U-a and U-b oil shale lease tracts reverted back to BLM ownership. The disinterest in developing an oil shale industry also stopped all research related to the Birds Nest aquifer. In 2001, the BLM commissioned the Dynamac Corporation to collect, organize, and present monitoring-well, groundwater-quality, and aquifer-characteristic data from the U-a and U-b tracts to facilitate well closure and abandonment measures (Dynamac, 2002). Dynamac located and sampled several old wells in the area. However, only two wells were found to be completed in the Birds Nest aquifer; other wells were completed in the alluvial aquifer or included other bedrock aquifers along with the Birds Nest. Data collected from the two wells completed in the Birds Nest were consistent with earlier reports of TDS concentrations.

Only in the past few years has there been resurgent interest in the Birds Nest aquifer. With the 2005 run-up in the price of oil, interest in oil shale development was renewed, and the BLM awarded a Research, Demonstration, and Development lease to the Oil Shale Exploration Company (which in 2011 sold the lease to Enefit American Oil) for the area surrounding the old White River mine project. As was the case with companies in the past, Enefit American Oil is keenly interested in how the Birds Nest aquifer might influence their oil shale development plans. Also, as natural gas production increases in the Uinta Basin, the search for suitable saline water disposal zones has increased the interest in the Birds Nest aquifer in the deeper part of the basin.

GEOLOGICAL CHARACTERIZATION

The Green River Formation is the record of an Eocene, continental interior, periodically terminal lake basin system that covered a significant area across northeastern Utah and western Colorado (Uinta-Piceance Basin respectively, Lake Uinta), and southwestern Wyoming (Greater Green River Basin, Lake Gosiute) (figure 3). In Utah, the lower Green River Formation, consisting of fluvial deltaic sands interbedded with lacustrine organic-rich muds, is one of the most important conventional oil and natural gas plays in the Uinta Basin, along with the stratigraphically lower Wasatch Formation and Mesaverde Group (figure 4) (Morgan, 2009a, 2009b). The upper Green River Formation's Parachute Creek Member, composed of alternating organic-rich ("R" zones) and organic-lean ("L" zones) marlstone (figure 4), hosts a vast, but mostly thermogenically immature, oil shale resource estimated at 1.32 trillion barrels in-place (USGS, 2010a) with approximately 77 billion barrels of oil as a potentially economic resource (Vanden Berg, 2008) (figure 5).

During deposition of the upper Green River Formation, Utah's Lake Uinta transitioned from a balanced-filled basin dominated by organic-rich, laminated marlstone, to an underfilled restricted basin (Carroll and Bohacs, 1999; Smith and others, 2008). During this time, as Lake Uinta began to shrink, the saline mineral nahcolite ($NaHCO_3$) formed within the deeper-lake sediments (depocenter in central Uintah County) as isolated crystals, nodules ranging up to one foot in diameter, and beds ranging from less than an inch to 1 to 2 feet thick. Post-deposition, the saline mineral shortite ($Na_2Ca_2(CO_3)_3$) was deposited in fracture zones several feet thick within the nahcolite-bearing interval (much of the shortite may now be replaced by calcite). More recently, the movement of fresher groundwater through the saline zone dissolved significant amounts of the saline minerals, creating the Birds Nest aquifer.

The Birds Nest aquifer is more similar to a fractured rock aquifer than it is to a traditional sandstone aquifer, and maintains unique advantages and challenges. The large macro-porosity created by the dissolution of large saline nodules within an otherwise impermeable oil shale creates significant space for water storage and thus defines the area of the Birds Nest aquifer suitable for saline water disposal (figure 6). The permeability of the aquifer is most likely the result of fracturing of the rock along structural weakness created from the growth of the saline minerals (figure 7). In addition, significant permeability is created as groundwater dissolves the shortite/calcite minerals deposited in a fracture-fill type texture (figure 8).

The Birds Nest aquifer is typically separated into two distinct zones within an overall saline zone in the upper Green River Formation (figure 4). The more extensive lower zone represents the first deposition of large saline nodules and is overlain by a thick sequence of organic-lean oil shale with only minor saline mineral deposition—mostly small crystals and shortite. A more areally restricted upper Birds Nest records a second period of large saline nodule deposition followed again by a sequence of organic-lean oil shale with only minor small saline crystals. The saline zone is overlain by saline-free lacustrine marlstone that predated the transition to the fluvial sands of the Uinta Formation. Radiating out from the basin's paleo-depocenter, the overall saline zone thins and contains much smaller saline mineral crystals (<1 inch) as compared to the large (up to 1 foot) nodules found near the basin's center. This transition is confirmed to the south where cores and outcrop exposures are present, and it is presumed that the same transition to small saline crystals exists to the north and west, but no cores exist to confirm this suspicion.

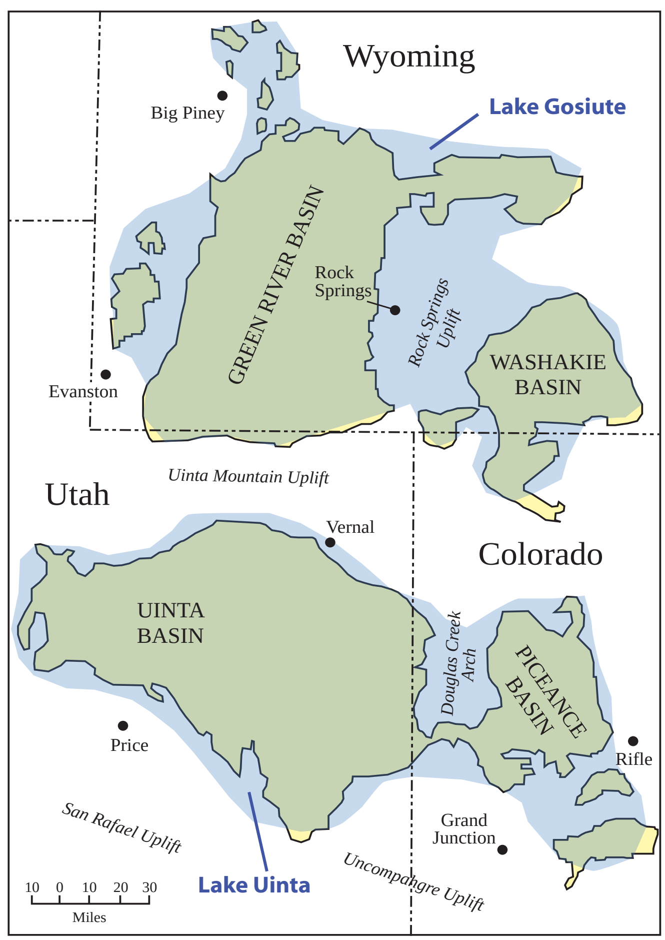


Figure 3. *Paleogeography of Eocene lake system, with modern basin margins in Utah, Colorado, and Wyoming.*

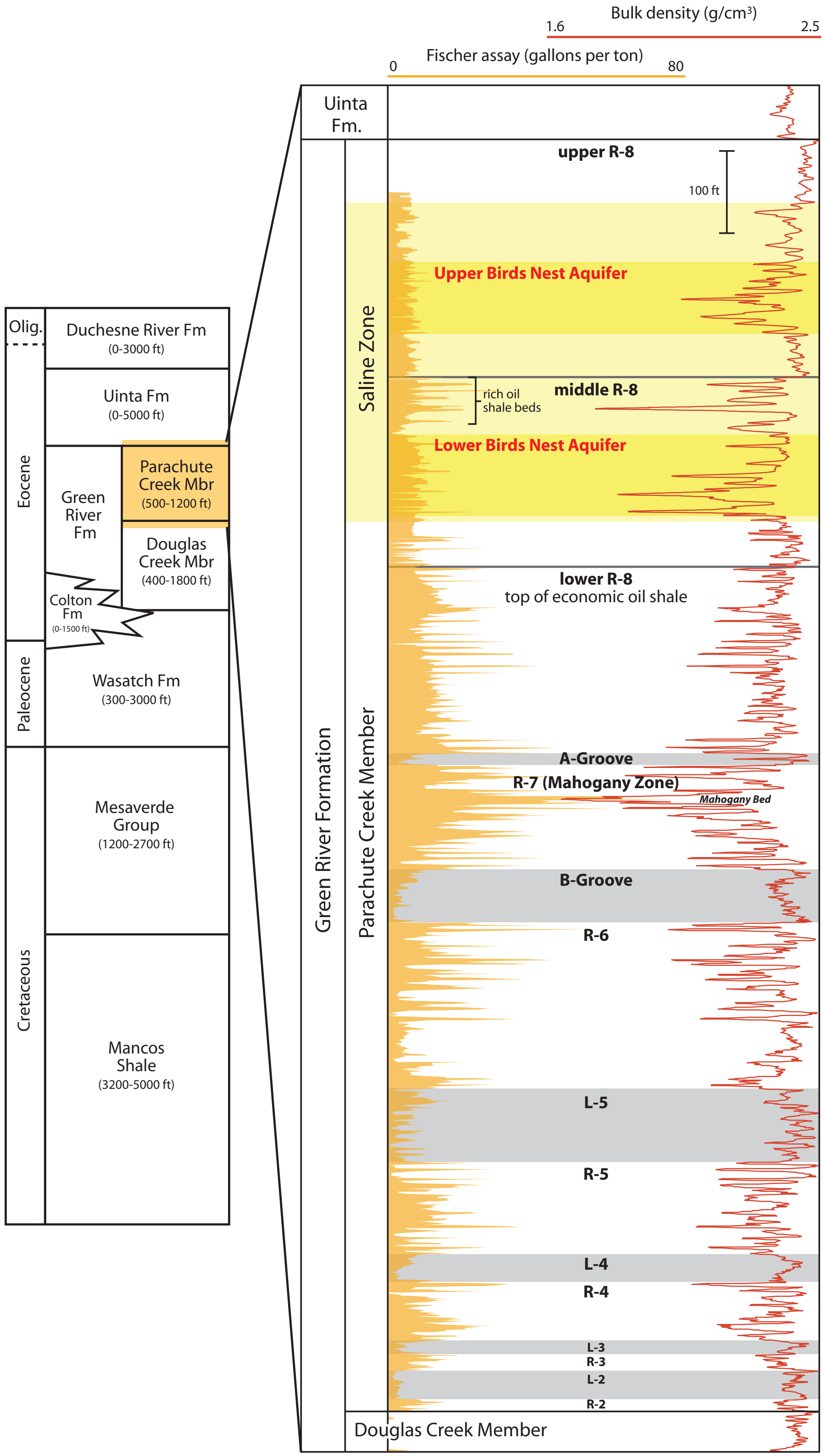


Figure 4. *General Upper Cretaceous through Oligocene stratigraphic column for the Uinta Basin (after Bradley, 1931; Cashion and Donnell, 1974; Hintze, 1988) and a composite section of the upper Green River Formation, highlighting the alternating rich and lean oil shale zones and stratigraphic position of the saline zone.*

The lateral and stratigraphic extent of the saline zone and the Birds Nest aquifer, as mapped on plate 1, was determined through the examination of core, outcrop, and geophysical log traces. The following sections describe each method in detail.

Core Evaluation

The most precise way of examining the Birds Nest aquifer at depth is through the examination of core. Thanks to the oil shale industry of the late 1970s and early 1980s, several oil shale cores were drilled, which captured all or part of the Birds Nest aquifer and/or saline zone (no Birds Nest core from conventional oil and gas wells exists since the target formations are far below the upper Green River Formation). Out of the 22 cores located, 21 were examined (the DP core was not examined due to its very close proximity to the X-13 core and its poor condition), and detailed core logs were generated with special attention made to the type and size of saline minerals present (plate 1, table 2). Each core log was then plotted with all available geophysical logs and Fischer assay oil shale data (plates 2–22) (Vanden Berg and others, 2006). Oil shale tops were picked for all horizons including the Mahogany zone, the richest and most prospective oil shale horizon, and the top of the Big Three rich oil shale beds, selected as the top of economic oil shale averaging at least 15 gallons of oil per ton of rock (figure 4, more detail in the "Birds Nest aquifer and oil shale" section below). For several of the cores, high-resolution photographs were taken of the entire saline zone/Birds Nest aquifer, as well as close-up photographs of saline minerals and other interesting structures.

Four cores (EX-1, Utah State 1, Coyote Wash 1, and P-4; plates 2, 3, 9, and 15), used to construct a 24 mile west-east cross section, were examined in much more detail as part of a separate study to help define the evolution of Lake Uinta (Birgenheier and Vanden Berg, 2011). The core logs from these wells display very detailed sedimentological information as well as information on sedimentary structures, textures, and preserved fossils.

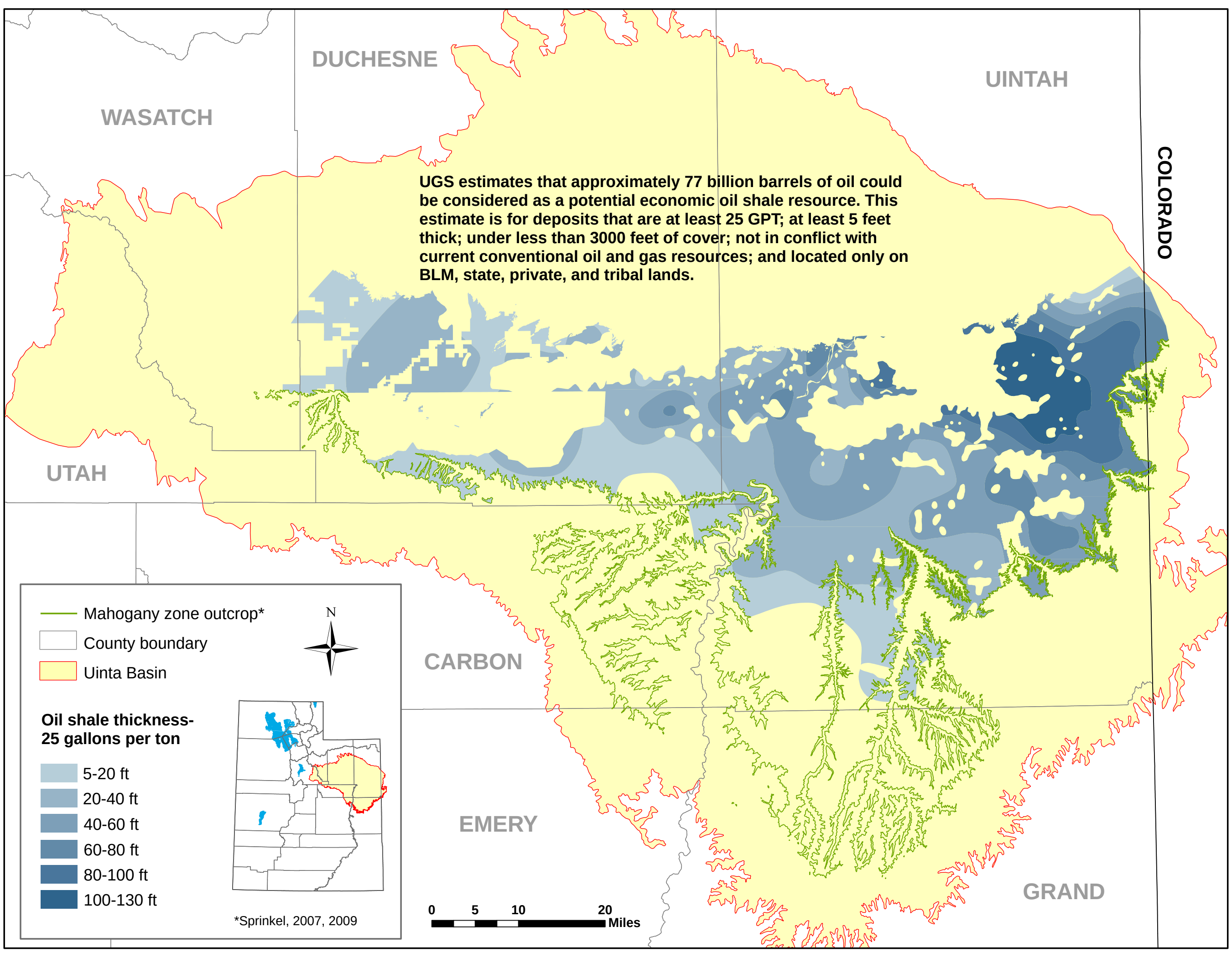


Figure 5. *Oil shale resource assessment in the Uinta Basin (from Vanden Berg, 2008).*

Figure 6. *Photographs of nahcolite nodules in core and outcrop.* ***a.*** *The Birds Nest aquifer in outcrop along Evacuation Creek, eastern Uinta Basin, Utah. The cavities were created by the dissolution of nahcolite nodules.* ***b.*** *The Birds Nest aquifer in the 42-34 core (1648–1671 ft). The slips of paper (red circles) represent 0.5- to 1.0-foot gaps in the core created from the dissolution of nahcolite nodules.* ***c.*** *Cavity created from the dissolution of a nahcolite nodule in the 13X-2 core (1528 ft).* ***d.*** *Intact nahcolite nodule in the Utah State 1 core (1825 ft).*

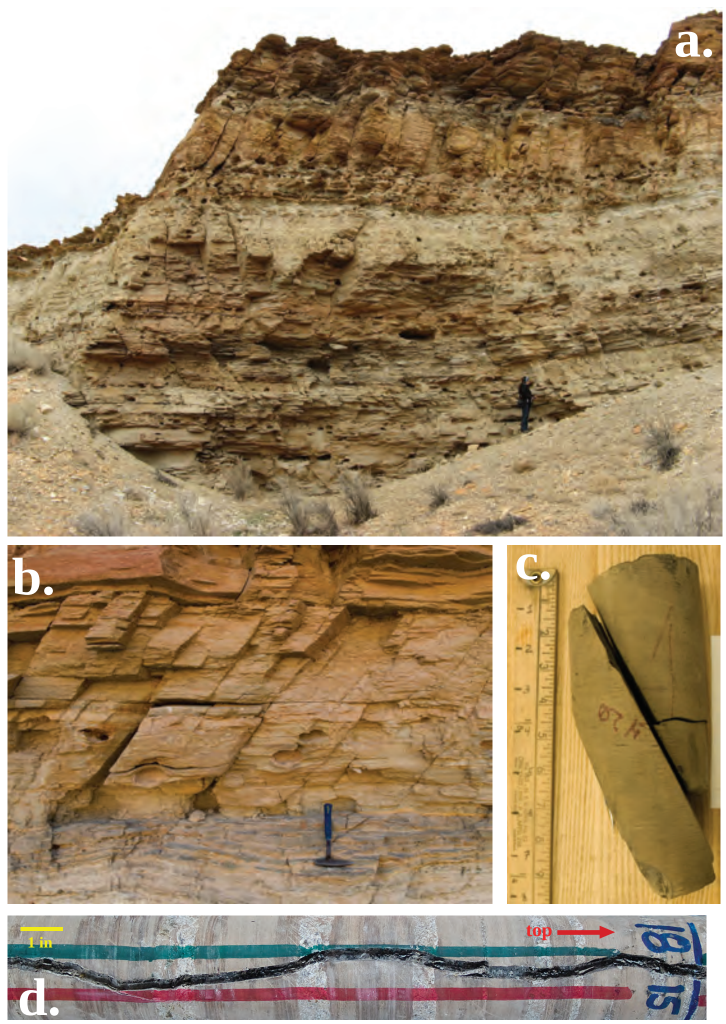


Figure 7. *Photographs of fractures within the Birds Nest aquifer.* ***a.*** *Extensive high-angle fracturing within the Birds Nest aquifer near Evacuation Creek, eastern Uinta Basin, Utah.* ***b.*** *High-angle fractures associated with dissolved saline nodules, near Watson, Utah.* ***c.*** *High-angle fracture in the P-1 core (420 ft)* ***d.*** *Near-vertical fracture filled with nahcolite in the 42-34 core (1815 ft).*

Comparing the cores to available geophysical logs revealed that the large to medium sized saline mineral nodules and the saline mineral beds are recorded as low-density spikes on the bulk density log (1.7 to 2.0 g/cm^3, compared to typical organic-lean oil shale with a density near 2.5 g/cm^3) (figure 9). However, smaller nodules as well as small saline mineral crystals had little to no effect on the bulk density reading. Therefore, for wells lacking core but having bulk density logs, the upper and lower Birds Nest could be picked, but the overall saline zone could not be defined. However, organic-rich oil shale also records low bulk density values (2.0 to 1.5 g/cm^3) and could be mistaken for saline minerals. Luckily, the organic-rich oil shale beds occur in regular stratigraphic horizons and create distinct, traceable patterns on the bulk density log. For example, six to seven thin organic-rich oil shale beds are located within the saline-zone interburden between the upper and lower Birds Nest aquifers and can easily be traced throughout the paleo-depocenter (figure 9). These beds, recorded as spikes to low density, might be confused with saline mineral nodules or beds if core and Fischer assay data were not available to confirm that they are in fact rich oil shale beds.

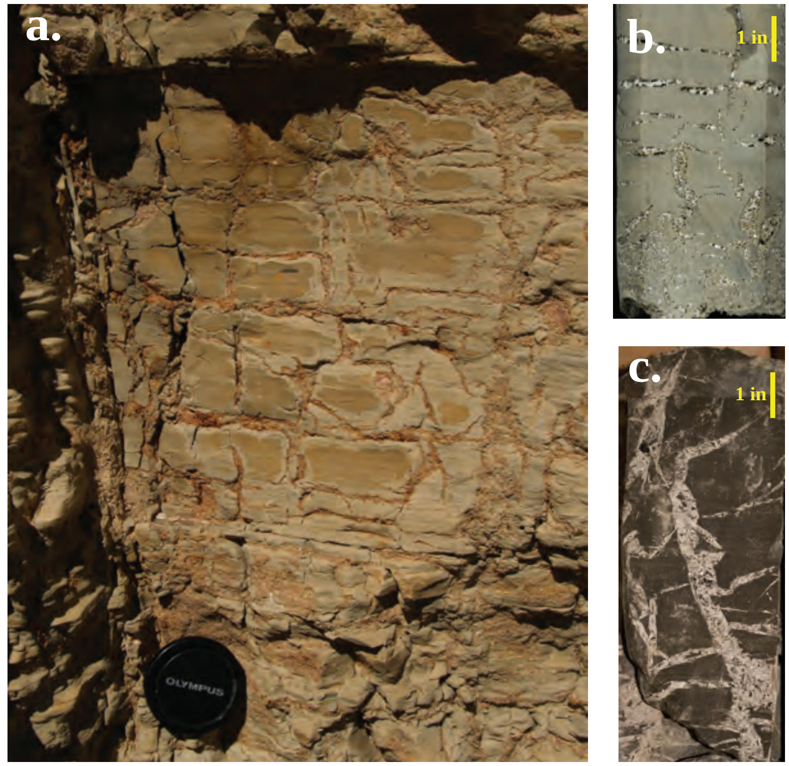


***Figure 8.** Photographs of shortite fracture fill within the Birds Nest aquifer.* ***a.** Saline-mineral (most likely shortite or calcite after shortite) fracture fill near Long Draw, southeastern Uinta Basin, Utah.* ***b.** Dissolved saline-mineral fracture fill in the P-4 core (365 ft).* ***c.** Intact saline-mineral fracture fill in the 13X-2 core (1580 ft).*

Depocenter Cores

Six cores were examined from the basin's paleo-depocenter: EX-1, Utah State 1, 42-34, 14X-34, 14-36, and 13X-2, of which only Utah State 1, 42-34, and 13X-2 capture the entire saline zone (figure 10, table 2, plates 2-7). The saline zone within the center of the basin is between 375 and 401 feet thick and contains both an upper and lower Birds Nest aquifer. The upper Birds Nest is between 87 and 99 feet thick and is primarily made up of large to medium nahcolite nodules within organic-lean oil shale. The lower Birds Nest is between 95 and 100 feet thick and contains large to medium nahcolite nodules as well as 1–2 foot thick nahcolite beds, again within a matrix of organic-lean oil shale. The saline zone interburden, the area between the upper and lower Birds Nest aquifers, is composed mostly of impermeable organic-lean oil shale with few to abundant small disseminated saline crystals (nahcolite, shortite, and possibly other saline mineral species). The interburden also contains a package of six to seven thin organic-rich oil shale beds which can be easily traced throughout the basin's paleo-depocenter. In a few wells (42-34, 14X-34, Utah State 1), large to medium nahcolite nodules were observed within the above-mentioned oil shale beds. These nodules seem to correlate to low-density spikes beyond that of the rich oil shale beds. Since they are only limited to a small lateral area (possibly the very center of the depocenter near T. 9 S., R. 21 E., SLBLM) and are separated stratigraphically by 20–30 feet, they are not included in the lower Birds Nest as defined in this study.

EX-1: The EX-1 well was drilled in 1969 by the Western Oil Shale Corporation and is the study's westernmost core capturing the saline zone and underlying rich oil shale beds (plate 2) (Smith and others, 1972). Drillers recovered 1202 feet of core from this well, starting in the middle of the saline zone and continuing to the R-4 rich oil shale zone. The core captures the lower Birds Nest aquifer at a depth of ~1870 to 1963 feet (93 feet thick)—the upper boundary is approximately located due to lack of a bulk density log through this interval, and the inability to pick a distinct boundary on core. The upper Birds Nest should be present in this well, but without core and/or a bulk density log through the upper part of the drill hole, the depth and thickness are unknown. The lower Birds Nest aquifer is characterized by organic-lean oil shale with large nahcolite nodules and relatively thick nahcolite beds (1–2 feet thick) near the base (represented by spikes to low density on the bulk density log and washouts recorded by the caliper log), with a gradual upward transition to smaller saline nodules. Only minor saline mineral dissolution is present in this core. The saline zone interburden is composed mainly of lean oil shale with few, relatively thin, silty beds. A zone of richer-oil shale beds is present from 1805–1847 feet, as seen on the Fischer assay oil yield log. The saline minerals within the saline zone interburden are dominated by smaller nahcolite crystals and shortite fracture fill. The top of the Big Three oil shale beds is at a depth of

Table 2. *Core capturing all or part of the Birds Nest aquifer.*

USGS #	Well Name	Operator	Area	Twn	Rng	Sec	Mrd	UTM E	UTM N	Cored interval		Saline zone		Upper Birds Nest aquifer		Lower Birds Nest aquifer		Big Three	Mahogany zone	Fischer assays	Geophysical logs			
								NAD 83	NAD 83	Top	Bottom	Top	Bottom	Top	Bottom	Top	Bottom	Top	Top		Density	Sonic	Resistivity	Gamma Ray
U043	EX-1	Western Oil Shale	Depocenter	9S	20E	36	SL	618562	4427091	1767	2969	na	1974	na	na	na	1963	2050	2267	y	y	y		y
U102	Utah State 1	TOSCO	Depocenter	9S	21E	26	SL	626967	4430197	1570	2600	1590	1965	1659	1746	1862	1960	2037	2274	y	y			y
U113	42-34	TOSCO	Depocenter	9S	21E	34	SL	625568	4428012	14	2683	1511	1912	1556	1655	1803	1903	1982	2210		y			y
U110	14X-34	Shell Oil Co.	Depocenter	9S	21E	34	SL	624255	4427363	1750	2597	na	1954	1618[1]	1712[1]	1846	1946	2026	2252	y	y			y
U108	14-36	Shell Oil Co.	Depocenter	9S	21E	36	SL	627444	4427386	1850	2508	na	1888	1577[1]	1671[1]	1786[1]	1881	1960	2186	y	y	y	y	y
U112	13X-2	TOSCO	Depocenter	10S	21E	2	SL	625850	4426165	120	2191	1408	1797	1476	1570	1690	1789	1872	2091		y		y	y
U045	Red Wash 1	USGS	Northeast depocenter	9S	22E	1	SL	637362	4436212	2160	2970	na	2267	2001[1]	2063[1]	2175	2261	2347	2599	y	y	y	y	y
U044	Coyote Wash 1	USGS	Northeast depocenter	9S	23E	22	SL	644096	4431654	1817	3460	na	1875	1610[1]	1658[1]	1772[1]	1865	1945	2191	y	y	y	y	y
U028	Corehole 2	National Farmer's Union	Eastside	9S	25E	32	SL	659784	4428684	30	560	57	188	--	--	103	180	265	476	y				
U056	P-1	White River Shale Co.	Eastside	10S	24E	12	SL	656732	4424894	74	1240	325	436	--	--	331	431	513	722	y	y	y	y	y
U057	P-2	White River Shale Co.	Eastside	10S	24E	17	SL	651084	4422804	94	1292	398	522	--	--	427	513	585	793	y	y		y	y
	DP[2]	White River Shale Co.	Eastside	10S	24E	22	SL	653858	4421249	5	1416	na	na	--	--	na	na	808	1009		y		y	y
U130	X-13	White River Shale Co.	Eastside	10S	24E	22	SL	654044	4421465	13	1125	630	728	--	--	649	720	na	998	y			y	
U058	P-3	White River Shale Co.	Eastside	10S	24E	26	SL	655414	4419858	70	1220	407	507	--	--	446	507	582	775	y	y	y	y	y
U059	P-4	White River Shale Co.	Eastside	10S	25E	19	SL	659365	4422017	214	1173	283	418	--	--	348	411	487	683	y	y	y	y	y
U029	Corehole 9	National Farmer's Union	Eastside	10S	25E	32	SL	659586	4418979	240	1123	250	340	--	--	272	338	417	603	y				
	Skyline 16	UGS	Eastside	11S	25E	10	SL	661445	4415109	20	1006	94	188	--	--	126	182	259	430		y		y	y
U086	Asphalt Wash 1	USGS	Southside	11S	24E	7	SL	647934	4415544	307	1364	na	322	--	--	--	--	392	553	y	y	y		y
U124	Corehole 10	National Farmer's Union	Southside	11S	24E	32	SL	649269	4408511	370	660	na	444	--	--	--	--	511	641	y				
U087	Suicide Canyon 1	Arco	Southside	12S	23E	36	SL	646039	4399044	104	576	na	188	--	--	--	--	285	431	y				
U055	CRU-1	USGS	Southside	12S	24E	3	SL	653097	4408125	14	498	104	239	--	--	--	--	308	435	y				
U080	SUB 12	U.S. ERDA-LERC	Southside	12S	24E	19	SL	647985	4402283	91	621	132	270	--	--	--	--	332	470	y				

[1]Depth picked off bulk density log

[2]Core not examined due to very close proximity to X-13 and poor core condition

na=not available; y=available in UGS OFR-469

Note: All depths in feet.

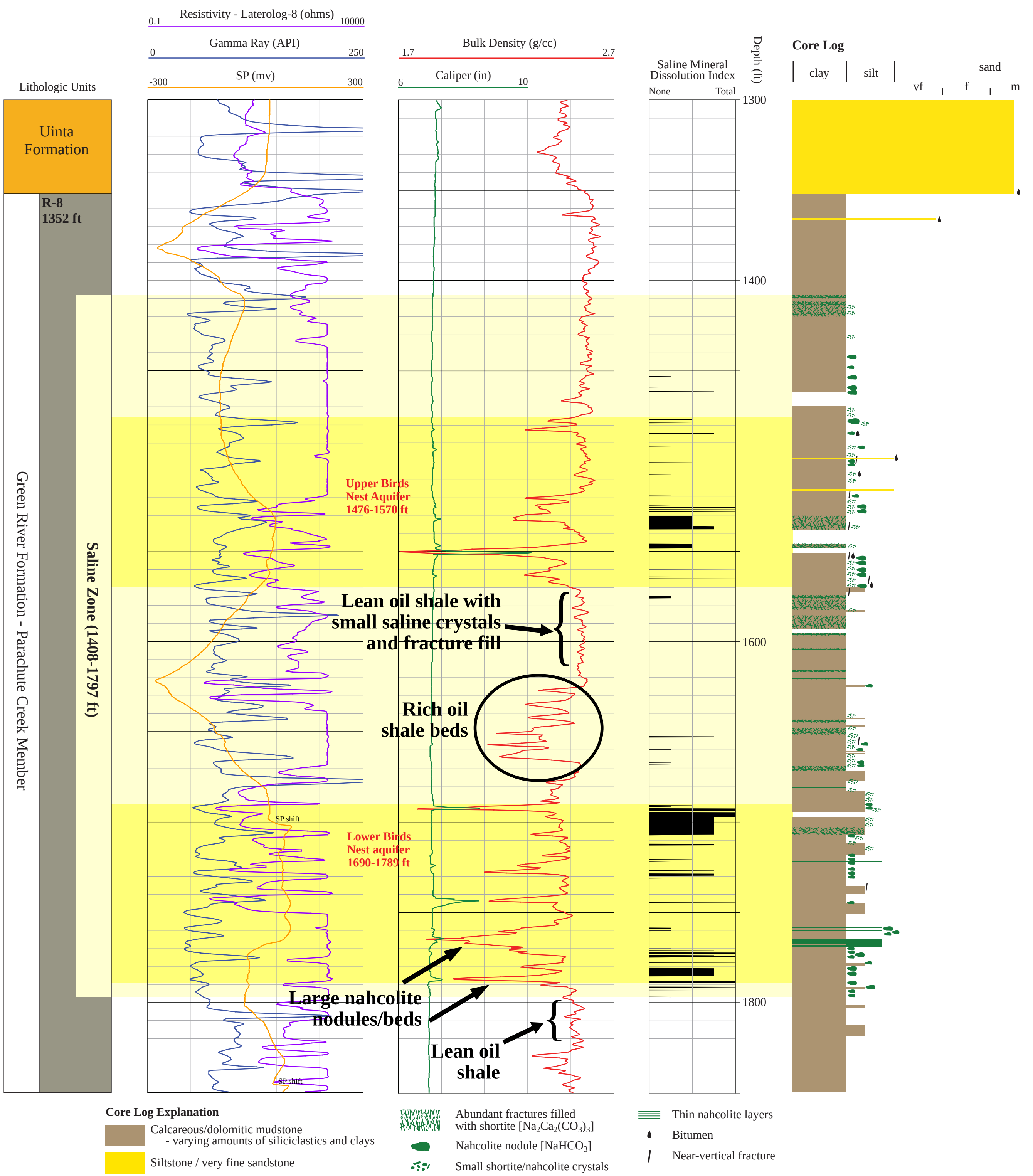


Figure 9. *Geophysical, core, and dissolution logs through the Birds Nest aquifer from the 13X-2 core located in the basin's paleo-depocenter. Notice the spikes to low density representing medium to large nahcolite nodules or beds. Smaller saline mineral crystals, saline mineral fracture fill, and small saline nodules are not recognized by the bulk density log, as seen in the zone between the upper and lower Birds Nest aquifers. The rich oil shale beds between the upper and lower Birds Nest are very consistent and can be traced throughout the basin.*

__Figure 10.__ Photographs of core within the saline zone from the basin's paleo-depocenter, yellow bars represent one inch. ***a.*** *Nahcolite beds, 13X-2, 1760–1769 ft.* ***b.*** *Partially dissolved shortite fracture fill, 13X-2, 1532 ft.* ***c.*** *Dissolution cavity lined with pyrite, 13X-2, 1774 ft.* ***d.*** *Nahcolite nodule coated with pyrite, EX-1, 1923 ft.* ***e.*** *Dissolution cavities, 13X-2, 1772 ft.* ***f.*** *Nahcolite nodule, notice the warped sediment beds, Utah State 1, 1825 ft.* ***g.*** *Partially dissolved small saline mineral crystals, 42-34, 1657 ft.* ***h.*** *Small saline mineral (shortite?) crystals, Utah State 1, 1814 ft.* ***i.*** *Cross-cutting shortite fracture fill, 42-34, 1813 ft.* ***j.*** *Shortite fracture fill, Utah State 1, 1753 ft.*

2050 feet and the top of the Mahogany zone is at a depth of 2267 feet, providing interburden interval thicknesses of 87 and 304 feet, respectively.

Utah State 1: The Utah State 1 well was drilled in 1974 by the TOSCO Development Corporation as part of a feasibility study for an underground oil shale mine in the area (plate 3). Drillers recovered 1030 feet of core, starting just above the saline zone and continuing down to the middle R-6. The 375-foot saline zone is between 1590 and 1965 feet deep, with the upper Birds Nest at 1659–1746 feet and the lower Birds Nest at 1862–1960 feet. Both Birds Nest intervals are characterized by large nahcolite nodules and individual nahcolite beds, both easily observed in the core and on the bulk density log. The top of the Big Three oil shale beds is at a depth of 2037 feet and the top of the Mahogany zone is at a depth of 2274 feet, providing interburden interval thicknesses of 77 and 314 feet, respectively. The Utah State 1 core displays no saline mineral dissolution, suggesting that an actual aquifer does not exist in this area. In short, we believe that a prominent gilsonite vein located just south of this well might play a role in limiting access to groundwater in the area. This topic is further discussed in the "Influence of Gilsonite Veins on Groundwater Movement" section.

42-34: The 42-34 well was drilled in 1981, also by the TOSCO Development Corporation, as part of a feasibility study for an underground oil shale mine in the area (plate 4). The well was cored from near the surface (14 feet) to a depth of 2683 feet, recovering 2669 feet of core. The core captures a large portion of the Uinta Formation along with the entire saline zone within the upper Green River Formation, and continues down to the L-5 lean oil shale zone. The 401-foot saline zone is between 1511 and 1912 feet deep, with the upper Birds Nest at 1556–1655 feet and the lower Birds Nest at 1803–1903 feet. Both intervals are characterized by large to medium nahcolite nodules within organic-lean oil shale with several minor thin silty beds (that could help increase permeability in the area). Significant saline mineral dissolution was observed in the core within both the upper and lower Birds Nest aquifers. The top of the Big Three oil shale beds is at a depth of 1982 feet and the top of the Mahogany zone is at a depth of 2210 feet, providing interburden interval thicknesses of 79 and 307 feet, respectively. This well is located very close to Anadarko's already permitted and active Birds Nest saline water disposal wells.

14X-34: The 14X-34 well was drilled by Shell Oil Company in 1964 to help characterize the oil shale resource in the area (plate 5). The well was cored from a depth of 1750 feet, about 50 feet below the upper Birds Nest, to 2597 feet, within the middle R-6 oil shale zone. Unfortunately, roughly every other box of core (3 feet of core per box) is missing, making useful observation difficult. Stratigraphic picks were made using a formation density log. The upper Birds Nest (picked solely using a formation density log) is located at depths of 1618–1712 feet and the lower Birds Nest (only partially verified with core) is located at 1846–1946 feet. Within the available core, saline mineral dissolution seems fairly extensive. The top of the Big Three oil shale beds is at a depth of 2026 feet and the top of the Mahogany zone is at a depth of 2252 feet, providing interburden interval thicknesses of 80 and 306 feet, respectively.

14-36: The 14-36 well was also drilled in 1964 by Shell Oil Company to help characterize the oil shale resource in the area (plate 6). The well was cored starting at a depth of 1850 feet, capturing only the lower 38 feet of the saline zone, down to 2508 feet at the base of the upper R-6 oil shale zone. Similar to the 14X-34 well, stratigraphic picks were made from a formation density log. The upper Birds Nest (picked solely using the formation density log) is located at depths of 1577–1671 feet and the lower Birds Nest (only the lower portion verified with core) is located at 1786–1881 feet. Significant saline mineral dissolution was present in the core. The top of the Big Three oil shale beds is at a depth of 1960 feet and the top of the Mahogany zone is at a depth of 2186 feet, providing interburden interval thicknesses of 79 and 305 feet, respectively.

13X-2: The 13X-2 well was drilled by the TOSCO Development Corporation in 1977 as part of a feasibility study for a possible underground oil shale mine (plate 7). Similar to the 42-34 well, 13X-2 was cored from near the surface (120 feet) to a depth of 2191 feet, recovering 2071 feet of core. The core captures a large portion of the Uinta Formation along with the entire saline zone within the upper Green River Formation, down to the base of the Mahogany zone. The 389-foot saline zone is between 1408 and 1797 feet deep, with the upper Birds Nest at 1476–1570 feet and the lower Birds Nest at 1690–1789 feet. Both intervals are characterized by large to medium nahcolite nodules within organic-lean oil shale, but only the lower interval contains beds of nahcolite. The top of the Big Three oil shale beds is at a depth of 1872 feet and the top of the Mahogany zone is at a depth of 2091 feet, providing interburden interval thicknesses of 83 and 302 feet, respectively. The excellent quality and completeness of this core made it possible to qualitatively rate the level of saline mineral dissolution on a scale of zero (no dissolution) to three (total dissolution). The generated dissolution log (displayed next to the core log) clearly identifies both the upper and lower Birds Nest aquifers within the overall saline zone. The bulk density log from this well was used as a reference when picking the upper and lower Birds Nest on logs from wells lacking core.

Northeast Depocenter Cores

Two cores were examined from the northeast side of the basin's paleo-depocenter, Red Wash 1 and Coyote Wash 1, neither of which captured the entire saline zone (table 2, plates 8 and 9). Based on bulk density logs, the upper Birds Nest in this area is between 40 and 60 feet thick, thinner than the basin center cores, whereas the lower Birds Nest is of similar thickness to the basin depocenter, between 85 and 100 feet thick. The lower interval is confirmed by the Red Wash 1 core to contain large to medium nahcolite nodules. The package of six to seven, thin, organic-rich oil shale beds within the saline zone interburden are still found in this area (correlatable using the bulk density log).

Red Wash 1: The Red Wash 1 well was drilled by the USGS in 1981, targeting the thickest and richest oil shale interval in the Uinta Basin (plate 8) (Scott and Pantea, 1982a). In addition, Red Wash 1 is the northernmost core capturing part of the saline zone. It is located close to EOG Resources already permitted and active Birds Nest saline water disposal wells. The Red Wash 1 core begins at a depth of 2160 feet, about 15 feet above the lower Birds Nest, and continues down to 2970 feet within the middle R-6. The upper Birds Nest, as measured from the bulk density log, is at depths of 2001–2063 feet, whereas the lower aquifer is located between 2175 and 2261 feet. The lower Birds Nest is characterized by medium to large nahcolite nodules within a matrix of lean oil shale, and displays only minor saline mineral dissolution. The top of the Big Three oil shale beds is at a depth of 2347 feet and the top of the Mahogany zone is at a depth of 2599 feet, providing interburden interval thicknesses of 86 and 338 feet, respectively.

Coyote Wash 1: The Coyote Wash 1 well was also drilled by the USGS in 1981 as a means to capture the richest and thickest section of oil shale in the Uinta Basin (plate 9) (Scott and Pantea, 1982b). It is one of the deepest oil shale cores available, capturing nearly the entire Parachute Creek Member of the upper Green River Formation (except the very top) as well as the upper portion of the Douglas Creek Member. The Coyote Wash 1 core begins at a depth of 1817 feet, about 50 feet above the base of the lower Birds Nest, and continues down to 3460 feet, within the Douglas Creek Member. The upper Birds Nest, as measured from the bulk density log, is at depths of 1610–1658 feet, whereas the lower aquifer is located between 1772 and 1865 feet. Unfortunately, about 25 feet of core is missing from the base of the lower Birds Nest, making accurate characterization difficult. The top of the Big Three oil shale beds is at a depth of 1945 feet and the top of the Mahogany zone is at a depth of 2191 feet, providing interburden interval thicknesses of 80 and 326 feet, respectively.

Eastern Basin Cores

Eight cores were examined from the east side of the basin's paleo-depocenter: Corehole 2, P-1, P-2, X-13, P-3, P-4, Corehole 9, and Skyline 16 (figure 11, table 2, plates 10–17). The saline zone on the eastern side of the basin is much closer to the surface and has significant outcrop exposures. Only the lower Birds Nest aquifer is present in this area, ranging in thickness from 54 to 100 feet. The overall saline zone ranges in thickness from 90 to 135 feet and is composed of large saline mineral nodules, smaller saline mineral crystals, and abundant zones of shortite fracture fill. Overlying the saline zone are deposits of volcaniclastic debris flow material (volcaniclastic matrix material with abundant mud rip-up clasts and organic debris). This material is similar to the volcaniclastic deposits of the Sand Butte bed overlying the Green River Formation lake sediments in the Greater Green River Basin in Wyoming and northern Piceance Basin in Colorado (labeled as part of the Uinta Formation in Colorado) (Chetel and Carroll, 2010). After Lake Gosiute was filled and disappeared, the volcaniclastic material, brought in by river systems from the north, started filling in the Piceance Basin. Periodically, an accumulation of volcaniclastic material on the Douglas Creek Arch catastrophically let loose and flowed into the eastern Uinta Basin. These debris flows might also represent an influx of fresh water, which created a localized freshening of the lake on the far eastern side of the basin, shutting off saline mineral deposition. This localized freshening resulted in a much thinner saline zone, and hence only the lower Birds Nest aquifer. Saline deposition continued near the center of the basin as seen by a thicker saline zone in the basin center cores.

The volcaniclastic material has very high porosity and permeability (observed characteristic, no measurements were made) and most likely acts as a localized aquifer that is probably in communication with the Birds Nest aquifer due to their close stratigraphic relationship. In addition, the volcaniclastic material replaced the deposition of the five to six thin, rich oil shale beds seen in the saline zone interburden closer to the basin's depocenter.

Corehole 2: The Corehole 2 well was drilled in 1958 by the National Farmer's Union as a means to characterize the oil shale resource in the area (plate 10). Corehole 2 is also the northernmost well on the eastern side of the basin having core containing the Birds Nest aquifer. The Corehole 2 core begins near the surface at a depth of 30 feet, about 25 feet above the top of the saline zone, and continues down to 560 feet, near the base of the Mahogany zone. The lower Birds Nest is at a depth of 103–180 feet and is characterized by medium to large nahcolite nodules and abundant large nahcolite crystals. Significant saline mineral dissolution is present in this core. The number and density of the large nahcolite nodules begins to decrease starting near this core's location and continuing northward, as observed from outcrop exposures near Corehole 2. The top of the Big Three oil shale beds is at a depth of 265 feet and the top of the Mahogany zone is at a depth of 476 feet, providing interburden interval thicknesses of 85 and 296 feet, respectively.

P-1: The P-1 well was one of several wells drilled in the mid-1970s by the White River Shale Company to characterize the oil shale resource on the old U-a and U-b federal oil shale lease tracts (plate 11). The P-1 core begins near the surface at a depth of 74 feet, within the Uinta Formation, and continues down to 1240 feet, in the L-4 lean oil shale zone. The lower Birds Nest is measured from depths of 331–431 feet and is overlain by volcaniclastic debris flow material. The Birds Nest aquifer is characterized by abundant large to medium nahcolite nodules, abundant smaller saline crystals, and significant high-angle fractures. Extensive saline mineral dissolution is present in the core. The top of the Big Three oil shale beds is at a depth of 513 feet and the top of the Mahogany zone is at a depth of 722 feet, providing interburden interval thicknesses of 82 and 291 feet, respectively.

P-2: The P-2 well is the westernmost well drilled by the White River Shale Company to characterize the oil shale resource on the old U-a and U-b federal oil shale lease tracts (plate 12). The P-2 core begins near the surface at a depth of 94 feet, within the Uinta Formation, and continues down to 1292 feet, near the base of the R-5 oil shale zone. The lower Birds Nest is measured at depths of 427–513 feet and is overlain by relatively thin volcaniclastic debris flow material; the P-2 well is near the western extent of the debris flows. The aquifer is characterized by abundant large to medium nahcolite nodules, abundant smaller saline crystals, and significant high-angle

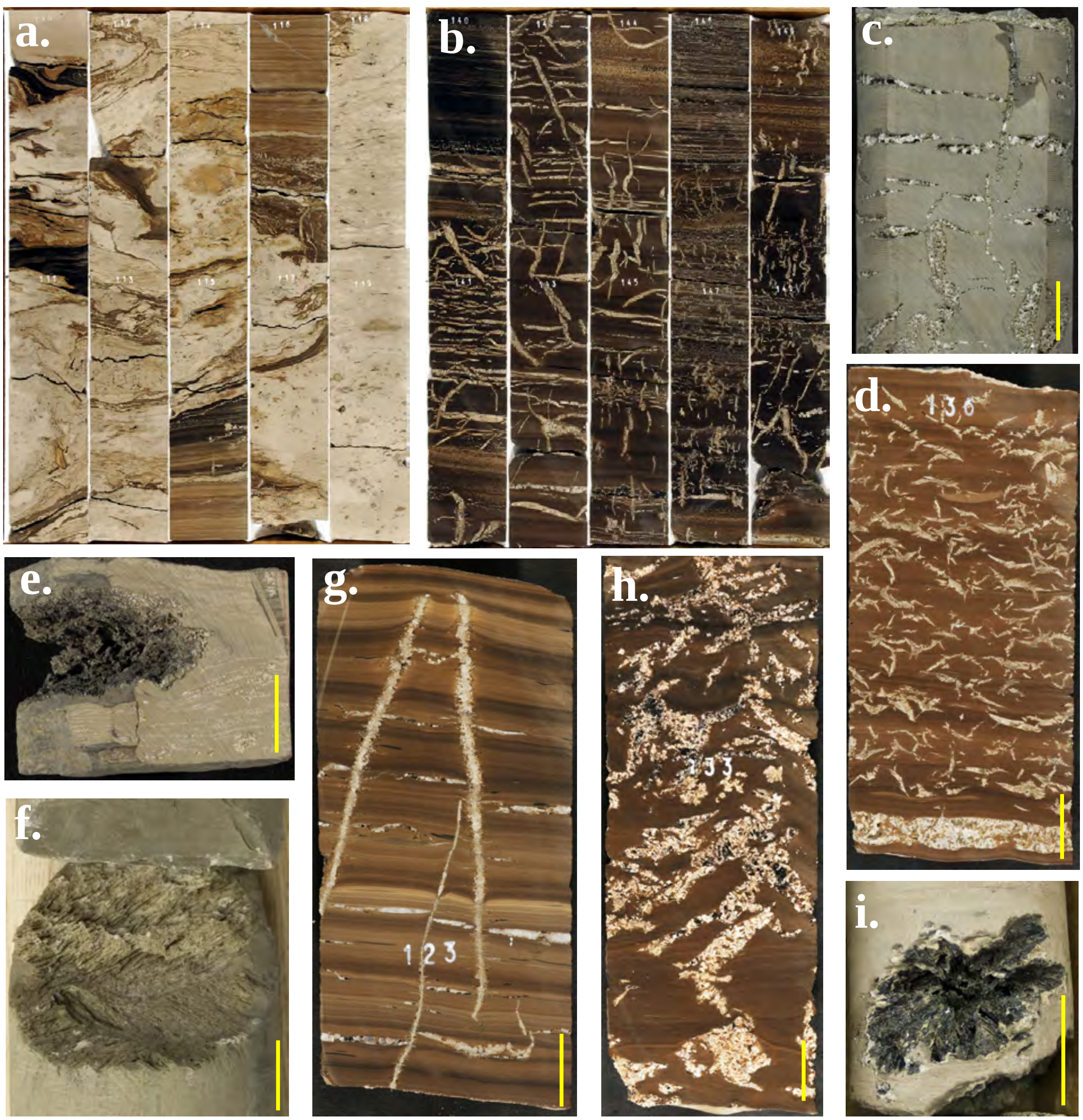


Figure 11. *Photographs of core within the saline zone from the basin's eastern margin, yellow bars represent one inch.* ***a.*** *Volcaniclastic debris flow ("Horsebench" Ss.), Skyline 16, 110–120 ft.* ***b.*** *Shortite fracture fill, Skyline 16, 140–150 ft.* ***c.*** *Partially dissolved shortite fracture fill, P-4, 365 ft.* ***d.*** *Saline mineral crystals (shortite?), Skyline 16, 136 ft.* ***e.*** *Dissolution cavity, P-4, 354 ft.* ***f.*** *Dissolution cavity, P-1, 324 ft.* ***g.*** *Partially dissolved shortite fracture fill, Skyline 16, 123 ft.* ***h.*** *Partially dissolved shortite fracture fill with inclusions of black tar (possibly gilsonite), Skyline 16, 133 ft.* ***i.*** *Dissolution cavity lined with black tar (possibly gilsonite), X-13, 710 ft.*

fractures. Significant dissolution of the saline minerals is represented by numerous borehole widenings recorded on the caliper log and gaps of missing or rubbly core. The top of the Big Three oil shale beds is at a depth of 585 feet and the top of the Mahogany zone is at a depth of 793 feet, providing interburden interval thicknesses of 72 and 280 feet, respectively.

X-13: The X-13 well was drilled in 1976 by the White River Shale Company at the site of the White River underground oil shale mine (plate 13). The X-13 core begins near the surface at a depth of 13 feet, within the Uinta Formation, and continues down to 1125 feet, within the B-groove. This core, despite not being slabbed, was in excellent condition and provided an exceptional view of the Birds Nest aquifer and surrounding rocks. The lower Birds Nest is measured from 649 to 720 feet and is overlain by 20–30 feet of volcaniclastic material. The Birds Nest aquifer is characterized by abundant large to medium nahcolite nodules, abundant smaller saline crystals, and significant high-angle fractures. Significant saline mineral dissolution is present in the core, but a complete assessment is difficult since the core is not slabbed (it is difficult to tell if the saline mineral dissolution is the result of groundwater or drilling fluids). The top of the Big Three oil shale beds is unknown (no bulk density log or Fischer assays were run through this interval) but the top of the Mahogany zone is at a depth of 998 feet, providing an interburden interval thickness of 278 feet.

P-3: The P-3 well was also drilled in 1974 by the White River Shale Company (plate 14). The P-3 core begins near the surface at a depth of 70 feet, within the Uinta Formation, and continues down to 1220 feet, within the R-5 oil shale zone. The lower Birds Nest is measured from 446 to 507 feet and is overlain by 15–20 feet of volcaniclastic material. The Birds Nest aquifer is characterized by abundant large to medium nahcolite nodules and abundant smaller saline crystals; both display signs of saline mineral dissolution. The top of the Big Three oil shale beds is at a depth of 582 feet and the top of the Mahogany zone is at a depth of 775 feet, providing interburden interval thicknesses of 75 and 268 feet, respectively.

P-4: Similarly, the P-4 well was drilled in 1974 by the White River Shale Company (plate 15). The P-4 core begins at a depth of 214 feet, below the Uinta Formation but above the saline zone, and continues down to 1173 feet, within the L-5 lean oil shale zone. The lower Birds Nest is measured between 348 and 411 feet and is overlain by two units of volcaniclastic material: the lower unit is about 20 feet thick and the upper unit is about 15 feet thick. The Birds Nest aquifer is characterized by abundant, mostly dissolved, large to medium nahcolite nodules and abundant small saline crystals. The top of the Big Three oil shale beds is at a depth of 487 feet and the top of the Mahogany zone is at a depth of 683 feet, providing interburden interval thicknesses of 76 and 272 feet, respectively.

Corehole 9: The Corehole 9 well was drilled in 1959 by the National Farmer's Union as a means to characterize the oil shale resource in the area (plate 16). The Corehole 9 core begins at a depth of 240 feet, about 10 feet above the top of the saline zone, and continues down to 1123 feet, within the R-4 oil shale zone. The lower Birds Nest is between 272 and 338 feet and is overlain by volcaniclastic material of unknown thickness. The Birds Nest aquifer is characterized by partially dissolved medium to large nahcolite nodules and abundant nahcolite crystals. The top of the Big Three oil shale beds is at a depth of 417 feet and the top of the Mahogany zone is at a depth of 603 feet, providing interburden interval thicknesses of 79 and 265 feet, respectively.

Skyline 16: The Skyline 16 well was drilled in 2010 through collaboration between the Utah Geological Survey and the University of Utah's Institute for Clean and Secure Energy (plate 17). The main goal of the drilling was to recover core through the entire Parachute Creek Member, including the saline zone and the underlying rich oil shale units. This well is located near the southern boundary of the large saline nodule zone, which defines the area of the Birds Nest aquifer possibly suitable for saline water disposal. The Skyline 16 core begins at a depth of 20 feet, near the top of the Green River Formation, and continues down to 1006 feet, within the top of the Douglas Creek Member. The lower Birds Nest is thinner in this area and lies between 126 and 182 feet. The volcaniclastic material occurs in two beds: a lower, thinner bed within the top of the saline zone and an upper, thicker bed above the saline zone. The Birds Nest aquifer is characterized by partially dissolved medium to large nahcolite nodules and abundant nahcolite crystals. The top of the Big Three oil shale beds is at a depth of 259 feet and the top of the Mahogany zone is at a depth of 430 feet, providing interburden interval thicknesses of 77 and 248 feet, respectively.

Southern Basin Cores

Five cores were examined from south of the defined large-saline-nodule Birds Nest aquifer: Asphalt Wash 1, Corehole 10, Suicide Canyon 1, CRU-1, and SUB 12 (figure 12, table 2, plates 18–22). The saline zone in this area averages about 130 feet thick, but is composed entirely of small saline mineral crystals or shortite fracture fill, displaying varying amounts of dissolution; no large saline mineral nodules or beds exist. The same transition to small saline crystals presumably exists to the north and west, but no cores or outcrop are available to confirm this suspicion and bulk density logs do not pick up the signature from the smaller saline crystals. Groundwater may still flow through the saline zone in this area, but the saline zone lacks the large void space needed for significant volumes of saline water disposal.

Asphalt Wash 1: The Asphalt Wash 1 well was drilled in 1976 by the USGS to help characterize the oil shale in the area (plate 18). The core starts at a depth of 307 feet, very near the base of the saline zone, and continues down to 1364 feet, well into the Douglas Creek Member of the Green River Formation. The core only captures about 15 feet near the base of the saline zone (which extends to 322 feet) and is characterized by abundant small saline mineral crystals.

Corehole 10: The Corehole 10 well was drilled in 1960 by the National Farmer's Union to help characterize the oil shale in the area (plate 19). The core starts at a depth of 370 feet, about midway through the saline zone, and continues down to 660 feet, at the top of the Mahogany zone. The core only captures about 74 feet near the base of the saline zone (which extends to 444 feet) and is characterized by abundant partially dissolved small saline mineral crystals and shortite fracture fill.

Suicide Canyon 1: The Suicide Canyon 1 well was drilled in 1965 by ARCO to help characterize the oil shale in the area (plate 20). The core starts at a depth of 104 feet, which is within the saline zone, and continues down to 576 feet, near the base of the Mahogany zone. The core captures 84 feet of the base of the saline zone (which extends to 218 feet) and is characterized by abundant partially dissolved small saline mineral crystals.

CRU-1: The CRU-1 well was drilled in 1976 by the USGS to help characterize the oil shale in the area (plate 21) (Keighin, 1982). This is one of two cores near the southern outcrop that capture the entire saline zone. The core starts near the surface at a depth of 14 feet, above the saline zone but below the Uinta Formation, and continues down to 498 feet, near the base of the Mahogany zone. The saline zone is 135 feet thick and extends from 104 to 239 feet. The zone is characterized

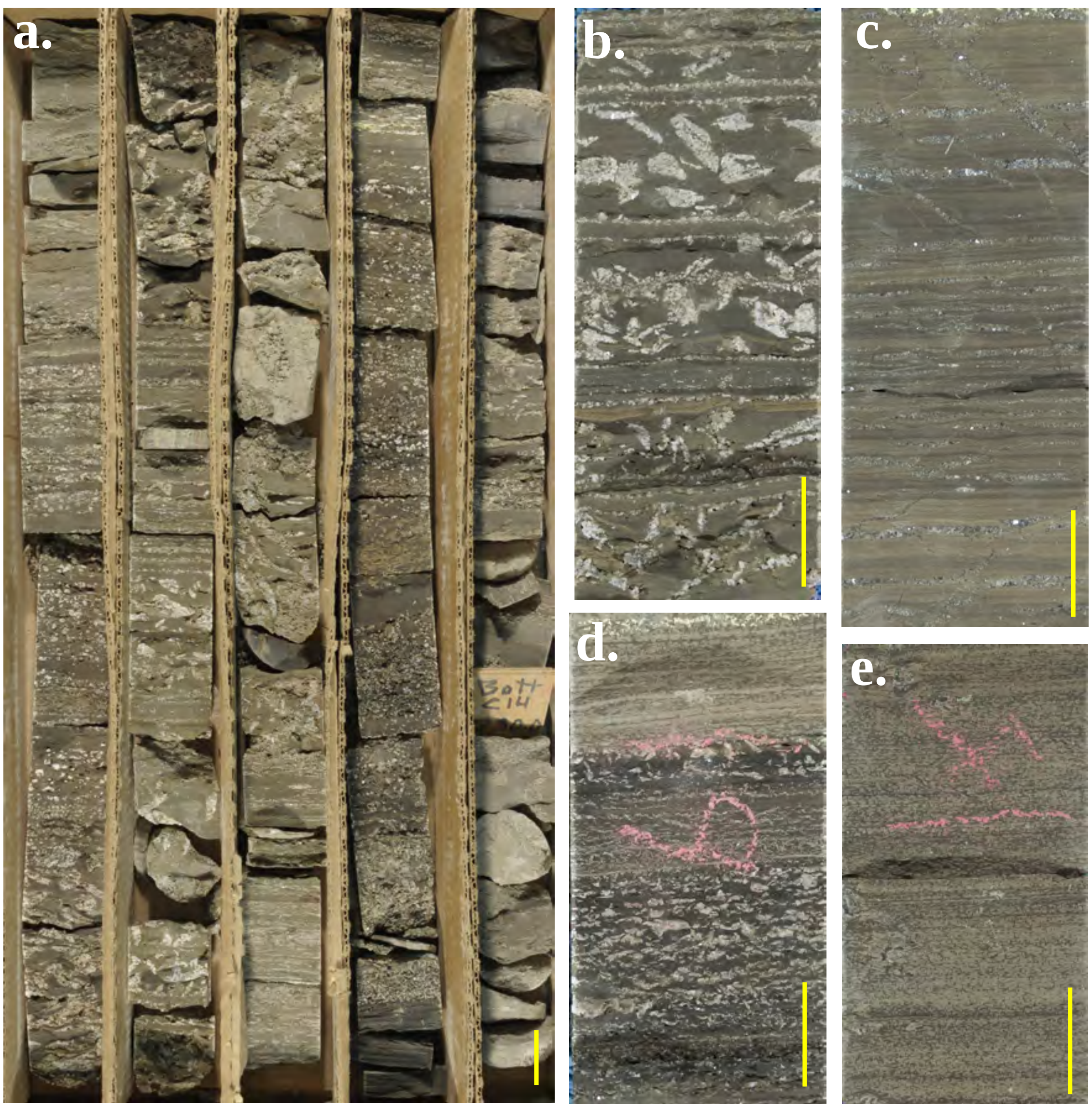


Figure 12. *Photographs of core within the saline zone from the basin's southern margin, yellow bars represent one inch.* ***a.*** *Partially dissolved medium to small saline mineral crystals, SUB-12, 221–231 ft.* ***b.*** *Partially dissolved medium saline mineral crystals, CRU-1, 197 ft.* ***c.*** *Thin saline mineral layers (shortite?), CRU-1, 105 ft.* ***d.*** *Partially dissolved small saline mineral crystals, CRU-1, 177 ft.* ***e.*** *Very small saline mineral crystals, CRU-1, 170 ft.*

by abundant partially dissolved small saline mineral crystals and zones of shortite fracture fill. In addition, the five to six thin rich oil shale beds seen near the center of the basin above the lower Birds Nest aquifer are clearly visible in the Fischer assay log from this well.

South Uinta Basin 12 (SUB-12): The SUB-12 well was the last in a series of 12 wells drilled by the U.S. Energy Research and Development Agency–Laramie Energy Research Center (ERDA-LERC) from 1975 to 1977 near the southern oil shale outcrop (plate 22) (Vanden Berg and others, 2006; only the core and Fischer assay data exist, no other information on this drilling program is available). The SUB-12 well cored from 91 feet to 621 feet, capturing the entire saline zone and extending down to the deltaic sands below the R-6 oil shale zone. The saline zone is 138 feet thick and extends from 132 to 270 feet. The zone is characterized by abundant partially dissolved small saline mineral crystals and zones of shortite fracture fill. In addition, the five to six thin rich oil shale beds seen near the center of the basin above the lower Birds Nest aquifer are clearly visible in the Fischer assay log from this well.

Outcrop Evaluation

Rock layers in the southern Uinta Basin generally dip 1 to 4 degrees to the northwest, resulting in extensive upper Green River Formation outcrops along the eastern and southern flanks of the basin (Sprinkel, 2007, 2009). Plate 1 displays the rich Mahogany oil shale zone outcrop as a thin green line and the approximate saline zone outcrop as a thin brown line. The saline zone outcrop was estimated from the mapped "Horsebench Sandstone Bed" outcrop exposure (Sprinkel, 2007, 2009). This "sandstone" is not actually the Horsebench, as defined in the southwestern Uinta Basin, but represents the volcaniclastic material discussed in the previous section that sits directly on top of the saline zone. The outcrop line was edited to only include areas having observable saline minerals, mainly on the eastern side of the basin. In most cases, only cavities left behind by total dissolution of nahcolite nodules are present along outcrop, whereas smaller saline mineral crystals show varying degrees of dissolution. Four stratigraphic sections were measured (Cowboy, Watson, Long Draw, and Bitter Creek) and general observations were recorded from several other outcrop locations in order to help define the extent of the saline zone and the Birds Nest aquifer (plates 23–26).

Figure 13. *Photographs from the Cowboy measured section.* ***a.*** *The Cowboy section exposed along the White River.* ***b.*** *Dissolution cavity within the Cowboy section.* ***c.*** *Shortite fracture fill within the Cowboy section.*

Measured Sections

Cowboy section: The Cowboy section was measured along the White River, just east of Cowboy Canyon (near the termination of the Cowboy gilsonite vein) (figure 13, plate 23). This was the northernmost outcrop section examined in detail as saline zone exposures farther to the north are obscured by sloping topography. The saline zone exposed in this section is about 113 feet thick and dominated by small saline mineral crystals with zones of medium to large saline nodules. The lower Birds Nest is estimated at 63 feet thick; however, the tell-tale large nahcolite nodules usually found below the lowest occurrence of volcaniclastic material are typically covered in this area. In addition, unlike the other outcrop areas farther south, significant large nahcolite nodules exist above the lowest volcaniclastic flow, providing evidence that the volcaniclastic material may be part of the overall Birds Nest aquifer system.

Watson section: The Watson section was measured from outcrop along the Kings Well road near Evacuation Creek (figure 14, plate 24). This section marks the southernmost extent of the large saline nodules on the eastern side of the basin, before the transition to only small saline mineral crystals a short distance farther south. The overall saline zone is estimated to reach about 93 feet thick and is dominated by small saline mineral crystals and shortite fracture fill. The large nahcolite nodules only occur in three distinct layers (about 12 feet thick overall) directly below the lowest occurrence of volcaniclastic material.

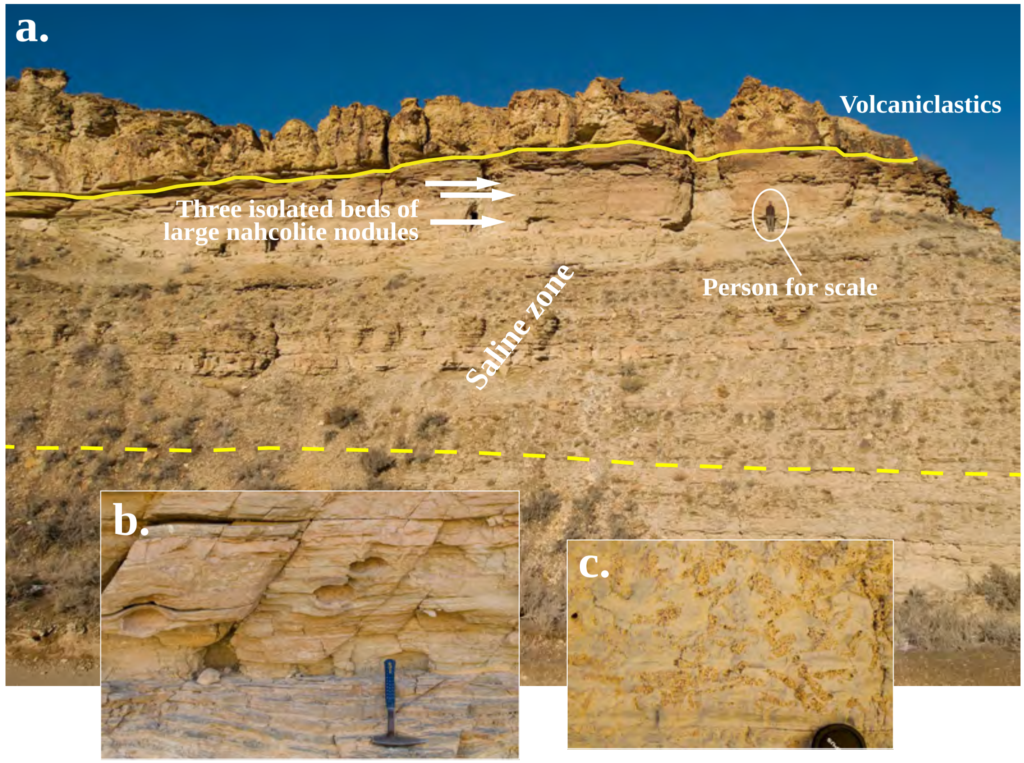


Figure 14. *Photographs from the Watson measured section.* ***a.*** *The Watson section displays the southern extent of the large nahcolite nodules which occur in only three isolated beds.* ***b.*** *Dissolution cavities within the Watson section. Note the high-angle fractures.* ***c.*** *Partially dissolved shortite fracture fill within the Watson section.*

Long Draw section: The Long Draw section was measured near the northern end of Long Draw (plate 25). The saline zone is estimated at about 90 feet thick (additional saline minerals might be found in unexposed rocks below the base of the measured section) and is dominated by small saline mineral crystals and shortite fracture fill. In addition, no volcaniclastic material was found exposed at this site, which helped define the southern extent of the debris flows.

Bitter Creek section: The Bitter Creek section was measured along the Kings Well road on the west side of Bitter Creek (figure 15, plate 26). The saline zone is estimated at about 110 feet thick (as with the Long Draw section, additional saline minerals might be found in unexposed rocks below the base of the measured section) and is dominated by small saline mineral crystals and shortite fracture fill. This exposure is believed to be near the southwesternmost extent of the overall saline zone dominated by small saline mineral crystals.

Additional Outcrop Observations

Despite the lack of good outcrop exposure, the northern extent of the large nahcolite nodule zone appears to be just north of the White River, as observed across the border in Colorado (section 14, T. 1 N., R. 104 W., northern extent observation point on plate 1). The limited outcrop in this area contains sparse, small to medium nahcolite nodules, but the thickness of the overall unit could not be determined (figure 16).

Upper Green River Formation outcrops along the northern portion of Evacuation Creek, near its intersection with the White River, are the type localities for the Birds Nest aquifer (figure 17). The cliffs along the creek expose numerous cavities left behind from the dissolution of large nahcolite nodules. In fact, the name "Birds Nest" comes from the fact that mud swallows like to nest in the empty nahcolite nodule cavities along the edge of the creek (Cashion, 1967). This area is also thought to be one of the main recharge sources for the Birds Nest aquifer (Holmes and Kimball, 1987). As water passes over the exposed Birds Nest aquifer along Evacuation Creek and the White River, it enters the unit and flows northwest, down the dip of the beds. This concept is further discussed in the "Birds Nest Water Chemistry" section. A measured section was not completed at this location due to the availability of several cores in the area.

Near the old townsite of Watson, Evacuation Creek once again cuts into the saline zone of the upper Green River Formation. Extensive exposures are present along this transect, which display the decreasing abundance of the large nahcolite cavities from north to south (North Watson observation point south to the Watson measured section).

The final observation point was made in Buck Canyon off the Seep Ridge road in section 36, T. 12 S., R. 21E., SLBLM. The

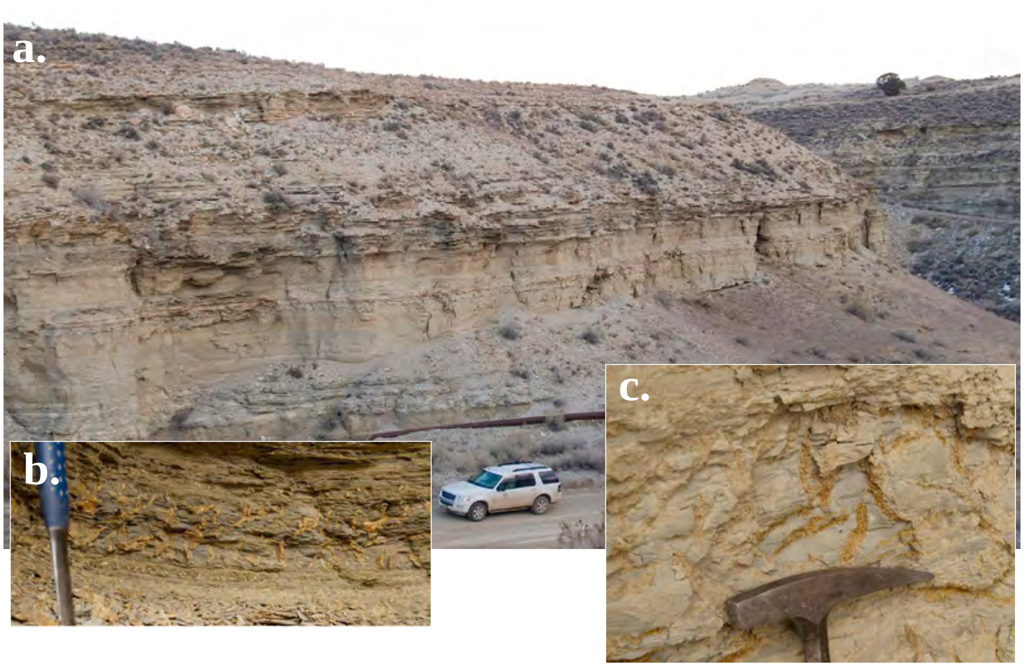


Figure 15. *Photographs from the Bitter Creek measured section.* ***a.*** *The Bitter Creek section was measured through the saline zone on the southern margin of the basin where only small saline mineral crystals are present.* ***b*** *and* ***c.*** *Shortite fracture fill within the Bitter Creek section.*

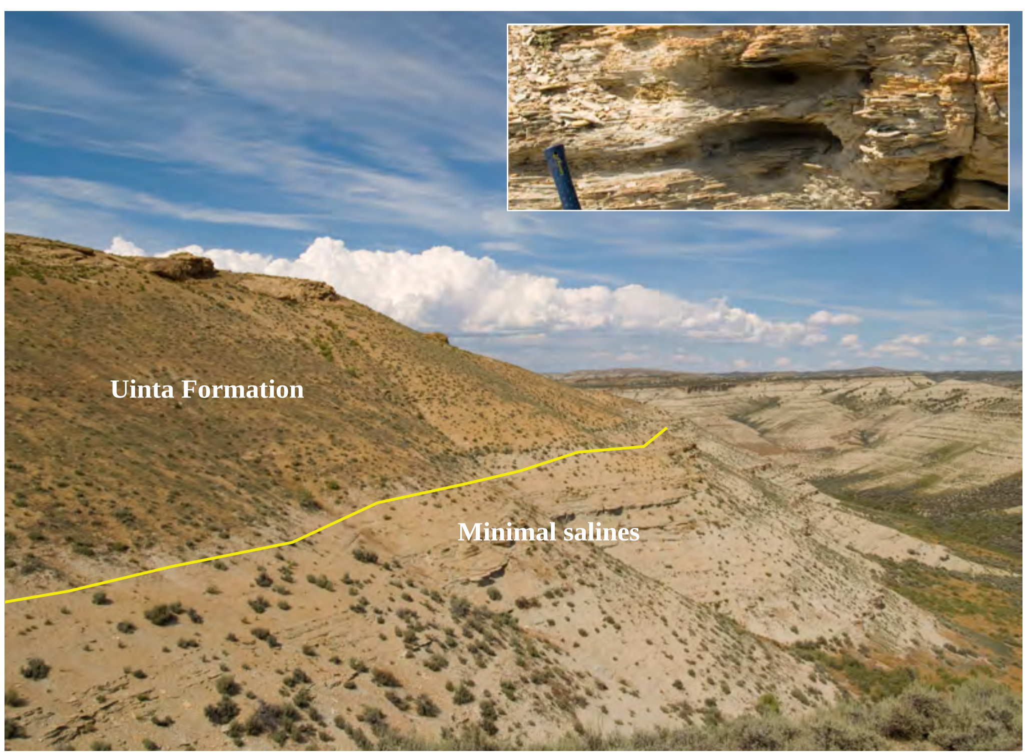


Figure 16. *Photographs of Birds Nest outcrop near its northern extent (see plate 1), characterized by abundant small saline mineral crystals with an occasional larger nodule (represented by the presence of dissolution cavities, inset).*

saline zone in this area is not present, possibly the result of being too far from the basin's paleo-depocenter. A few thin beds were found that contain minor small saline mineral crystals, but these are only negligible occurrences compared to the abundant saline minerals found at sections as close as Bitter Creek. These field observations helped define the extent of the small saline crystal area show in yellow on plate 1.

Regional Cross Sections

With only a limited number of cores capturing the Birds Nest aquifer and saline zone, a method was needed to make use of the thousands of oil and gas wells in the eastern Uinta Basin that have been drilled through this interval. Comparing the detailed core logs to geophysical logs revealed that the presence of large saline mineral nodules and beds were recorded on the bulk density log as low-density spikes (1.7–2.0 g/cm^3 as compared to ~2.5 g/cm^3 for typical organic-lean oil shale). It was also recognized that bulk density logs do not record the presence of small saline mineral crystals or shortite fracture fill. Only one other log seemed to record the presence of the saline minerals—the caliper log, used to measure the diameter of the borehole, often recorded larger hole widths in places where large saline mineral cavities were encountered.

Despite the fact that a bulk density log cannot be used to characterize the entire saline zone (both large nodules and smaller crystals), these logs proved useful in mapping the lateral extent of the area containing large saline nodules and thus the area having enough storage for possible saline water disposal. The first step in the mapping process was to create five regional cross sections, three north-south and two east-west, covering the expected extent of the Birds Nest aquifer (plate 1, plates 27–31). Bulk density, caliper, and gamma ray logs were plotted verses depth for each well and scaled vertically to reflect depth below surface (in some cases Fischer assay oil yield data were plotted when a bulk density log was not available for wells with core). To make the sections shorter, the horizontal distance between wells was set to a uniform value instead of scaling to the true horizontal distance between the wells. The position of the overall saline zone was estimated from the core data, and the upper and lower Birds Nest aquifers were picked based on the presence of low-density spikes on bulk density logs. In addition to the saline zone, the underlying rich and lean oil shale units (lower R-8, A-Groove, Mahogany Zone, B-Groove, R-6, L-5, R-5, L-4, and R-4) were highlighted, again using the bulk density log to designate their boundaries (rich oil shale is less dense than lean oil shale). The five to six rich oil shale beds present within the saline zone interburden are also noted on the cross sections.

Cross Section Descriptions

A–A′ – North-south: The A–A′ north-south cross section is composed of 13 wells and cuts through the middle of the basin's paleo-depocenter, passing near Anadarko's active Birds Nest saline water disposal wells (plate 27). The saline zone in the southern wells is near the surface and dips to nearly 4000 feet below the surface in the northernmost wells. Only the seven middle wells record the presence of large saline nodules within the saline zone; the bulk density signal disappears in the southernmost three wells and in the northernmost three

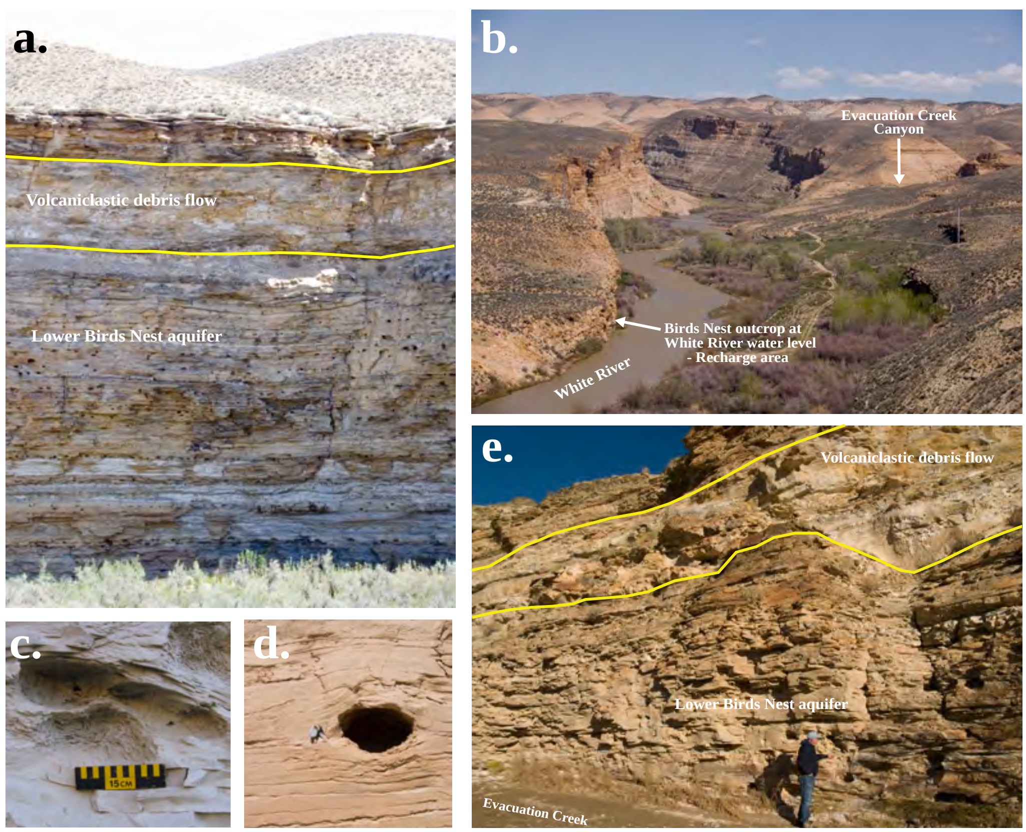


Figure 17. *Photographs of Birds Nest outcrop along Evacuation Creek and the White River.* ***a.*** *Outcrop of the lower Birds Nest aquifer along Evacuation Creek.* ***b.*** *Outcrop of the lower Birds Nest aquifer along the White River.* ***c*** *and* ***d.*** *Dissolution cavities; notice how the nodule growth warped and fractured the surrounding sediments (keys for scale in photo d).* ***e.*** *Outcrop of the lower Birds Nest aquifer along Evacuation Creek.*

wells. In addition, the signature of the oil shale beds begins to disappear in the northernmost wells.

B–B′ – East-west: The B–B′ east-west cross section is composed of 13 wells and also cuts through the middle of the basin's paleo-depocenter (plate 28). The saline zone starts near the surface in the eastern wells and dips to about 2700 feet below the surface in the westernmost wells before disappearing. Six wells record the presence of large saline nodules within the saline zone in both an upper and lower zone, while the eastern five wells only record the presence of the lower Birds Nest, due to the presence of the volcaniclastic debris flow material (discussed in an earlier section). All oil shale units were mapped through the entire cross section.

C–C′ – North-south: The C–C′ north-south cross section is composed of nine wells and cuts through the western portion of the basin's paleo-depocenter (plate 29). The saline zone in the southern wells is about 1000 feet below the surface and dips to over 4000 feet in the northernmost wells before disappearing. Only the four center wells record the presence of large saline nodules in both an upper and lower Birds Nest; the bulk density signal disappears in the southernmost three wells and the northernmost two wells. In addition, the usual signature of the oil shale beds begins to disappear in the northernmost wells.

D–D′ – East-west: The D–D′ east-west cross section is composed of nine wells and cuts through the northern portion of the basin's paleo-depocenter (plate 30). The western four wells record the presence of large saline nodules within the saline zone in both an upper and lower zone, while the central well only records the presence of the lower Birds Nest. The saline zone signature, as well as the oil shale signature, is lost in the eastern four wells.

E–E′ – North-south: The E–E′ north-south cross section is composed of 11 wells and hugs the eastern side of the basin near the outcrop exposure (plate 31). The southern eight wells all have core available from the saline zone, of which the southern three wells contain no large saline mineral nodules. The northern three wells also lack the density log signature of large saline nodules. Also displayed on the cross section is the north-south extent of the volcaniclastic material, which occurs in one or two distinct beds/flows. The typical oil shale log signature again disappears in the northernmost wells, but can be traced easily through the central and southern wells.

Examination of Additional Wells

The creation of the five regional cross sections allowed the overall extent of the Birds Nest aquifer to be roughly defined. To better define the boundaries in areas away from the cross section traces, additional bulk density logs were examined from hundreds of oil and gas wells. While this area has been extensively drilled for natural gas and crude oil, found stratigraphically below the Birds Nest, one limiting factor on the utility of this well data is whether the oil and gas operator logged the upper part of the borehole through the Birds Nest aquifer. Typically, the upper ~3000 feet of the well including the Birds Nest was cased and not logged. Despite this limitation, logs from 322 wells (including all cores and cross section wells) were examined and tops were picked for the upper and lower Birds Nest aquifers in the 217 wells which lay within the extent of the aquifer (plate 1, appendix A). Tops for the oil shale horizons were also picked in all examined wells. Well data coverage is fairly uniform across the study area, except in the northwest corner (T. 3 S., R. 1 W., R. 1 E., and R. 2 E.). This area has not seen extensive oil and gas drilling compared to areas farther south and east, and thus the aquifer boundaries are not as well defined.

Isopach Maps

After defining the areal extent of the Birds Nest aquifer, the tops database could be used to create isopach maps of the upper and lower aquifers, as well as the interburden between the aquifers. The upper surface of each aquifer was also subtracted from a digital elevation model of the area to create overburden contours.

Upper Birds Nest Aquifer Isopach

The upper Birds Nest aquifer, as defined by 150 wells, covers 410 square miles and averages 79 feet thick (figure 18). The aquifer is thickest near its center (between 100 and 110 feet thick) and gradually thins toward its edges (between 33 and 40 feet thick) defining the bowl-like structure of the ancient lake's depocenter. The upper Birds Nest ranges in depth from about 1000 feet in the southeast to about 4000 feet in the northwest.

Lower Birds Nest Aquifer Isopach

The lower Birds Nest aquifer, as defined by 217 wells, covers 719 square miles and averages 84 feet thick (figure 19). The lower aquifer has the shape of an elongated oval and is thickest in the center (between 100 and 110 feet thick) and gradually thins toward the north and south (between 33 and 40 feet thick). The lower Birds Nest is exposed at the surface on the eastern side of the basin and deepens northwestward to just over 4000 feet in the northwest.

Aquifer Interburden Isopach

The upper and lower Birds Nest aquifers are separated by a 100- to 210-foot-thick sequence, thickening to the west, of organic-lean oil shale that contains only limited saline mineral deposits (figure 20). The upper and lower aquifers are probably not hydraulically connected through this thick package of impermeable oil shale, unless extensive fractures or cross-cutting gilsonite veins are present.

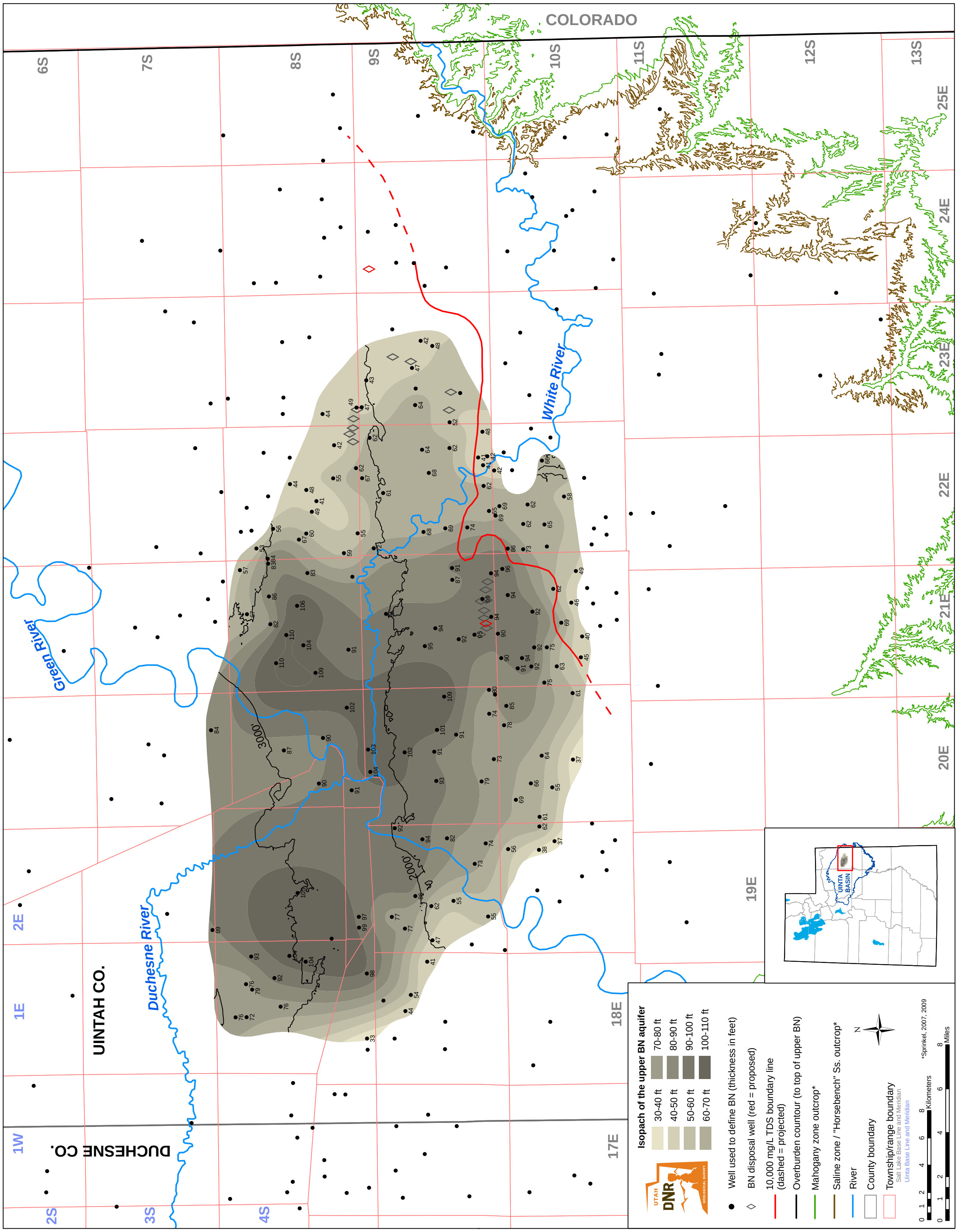


Figure 18. The upper Birds Nest aquifer thickness.

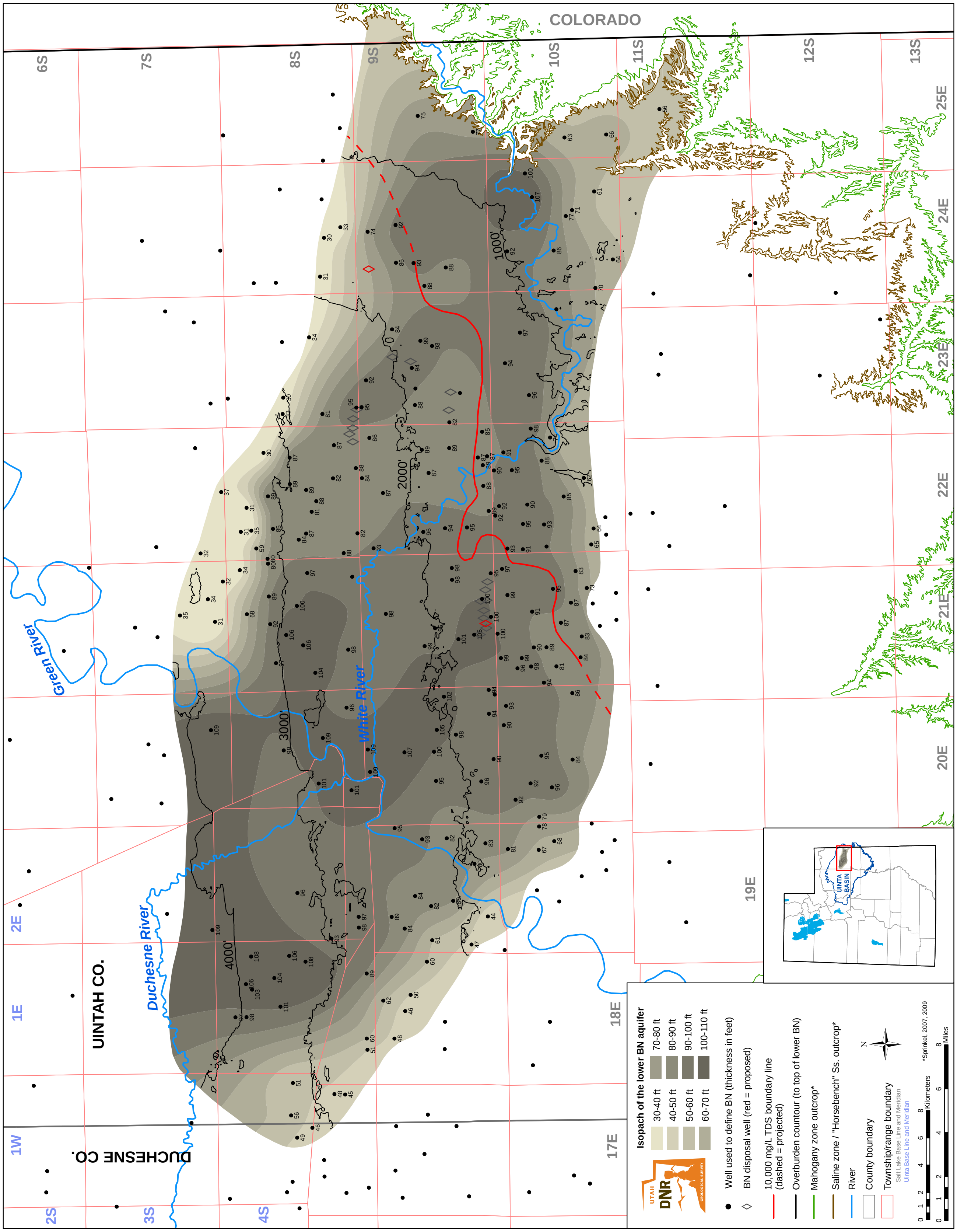


Figure 19. The lower Birds Nest aquifer thickness.

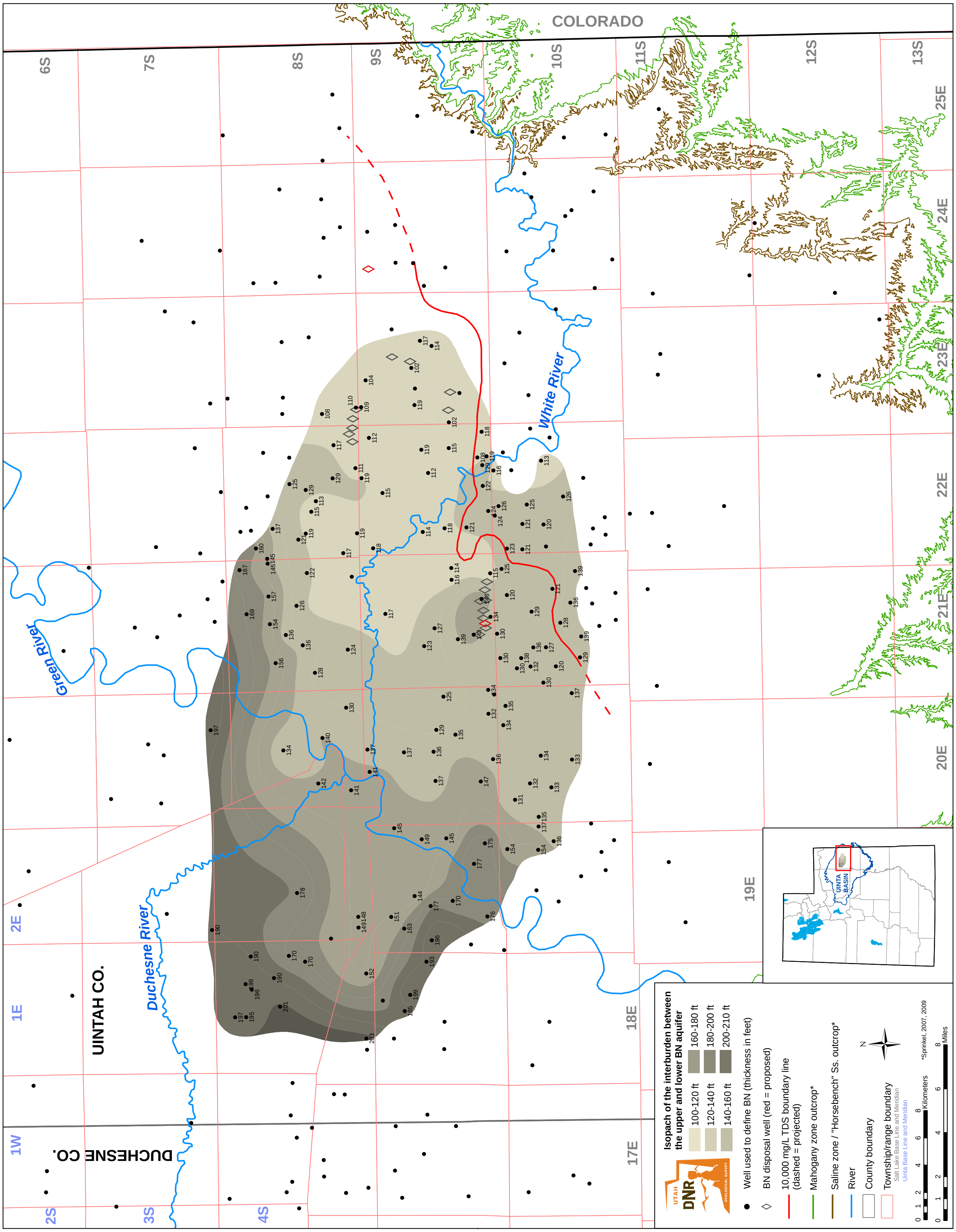


Figure 20. Thickness of the interburden between the upper and lower Birds Nest aquifer.

BIRDS NEST WATER CHEMISTRY

Regulations stipulate that underground saline water disposal can only occur within aquifers that already have water averaging more than 10,000 mg/L TDS or are exempted under the Safe Drinking Water Act (U.S. EPA, 2012). Therefore, it is important to define areas within the Birds Nest aquifer that meet this critical criterion to identify areas suitable for large-scale saline water disposal. A database of Birds Nest water chemistry was compiled containing 208 analyses from 161 wells. Water analyses from 155 of these wells were utilized in an effort to identify areas where Birds Nest aquifer salinities exceeded 10,000 mg/L TDS (appendix B, figures 21 and 22).

The Birds Nest aquifer water samples were collected through one of two methods:

1. The first method involves collecting isolated and stabilized water samples directly from the Birds Nest aquifer. This was accomplished by selectively completing only the Birds Nest interval (either through perforations or in an openhole completion) and producing water until a stabilized sample was obtained. This is a requirement of the UIC (Underground Injection Control) permitting and approval process for all saline water disposal wells. This method produces the most accurate and representative samples of Birds Nest aquifer water. Locations where isolated and stabilized Birds Nest water data were collected are identified by red circles in figures 21 and 22.

2. The second method involves collecting water samples from open wellbores after the surface interval of the well is drilled with a shallow air-rig and prior to running surface casing, but before the deep production drilling rig is moved to the location (Sean Kelly, Anadarko, personal communication, 2012). This is accomplished by circulating a water sample to the surface with compressed air after the well has penetrated the Birds Nest interval. Caution is needed when using the air-rig data since the water is collected from an open borehole after drilling into the Birds Nest interval (and as such the sample is not isolated). Consequently, these samples are subject to dilution with fresher water from sources above the Birds Nest aquifer (fresher water from overlying Uinta Formation aquifer sands or alluvial sources). The air-rig samples have proven to be diluted when compared to isolated representative samples obtained later from the same well and should be considered only as the potential minimum TDS level for water sourced from the Birds Nest aquifer. Locations where air-rig Birds Nest water data were collected are identified by black circles on figures 21 and 22.

Birds Nest aquifer salinities are assumed to be in excess of 10,000 mg/L where the air-rig samples have TDS values in excess of 10,000 mg/L despite any potential dilution from shallow water sources. Additionally, it is possible that isolated, stabilized and representative Birds Nest aquifer water will have TDS values in excess of 10,000 mg/L in areas where air-rig data presently indicate that TDS levels are less than 10,000 mg/L.

Using the water chemistry database compiled during this study, it was possible to draw a line on the map representing the southeast to northwest transition of 10,000 mg/L TDS water within the Birds Nest aquifer (figure 21). Chemistry of water to the northwest of the boundary (averaging >10,000 mg/L TDS and as high as 100,000 mg/L TDS) is distinct from that in the southeast (averaging <10,000 mg/L TDS and down to near 1000 mg/L TDS). The observed variations in Birds Nest aquifer salinity are most likely due to differing amounts of saline mineral dissolution. Areas where Birds Nest aquifer TDS values are <10,000 mg/L are located near and immediately down-dip from areas of aquifer recharge such as Evacuation Creek, the White River, and outcrops to the east and south. In these areas, continuous freshwater recharge and flushing over time have likely removed all of the original natural saline minerals. Areas where the Birds Nest aquifer salinity is known to exceed 10,000 mg/L TDS are located away from active aquifer recharge and flushing, so the original saline minerals are still present and undergoing active dissolution.

Since no aquifer exemptions have been sought in this area, saline water disposal may take place only in the area where the Birds Nest aquifer TDS is known to exceed 10,000 mg/L. This likely eliminates southern and eastern potions of the aquifer from consideration as a saline water disposal zone. However, isolated and stabilized representative samples of the Birds Nest aquifer would need to be collected before eliminating the saline water disposal potential of this entire area. The area available for saline water disposal within the upper Birds Nest is approximately 360 square miles and the area available for saline water disposal in the lower Birds Nest is 499 square miles based on the presently known area with Birds Nest aquifer salinity in excess of 10,000 mg/L TDS (figures 22–24). This possible disposal area is centered under the Greater Natural Buttes natural gas field, the largest natural gas field in Utah, making the Birds Nest aquifer attractive as a saline water disposal zone (figure 25).

APPROXIMATE BIRDS NEST PORE VOLUME CALCULATIONS

We attempted to calculate the volume of pore space within the upper and lower Birds Nest aquifer that might be available for saline water disposal. However, the unique pore structure of this aquifer makes a volume calculation difficult; the best that can be determined is a gross estimate of the available stor-

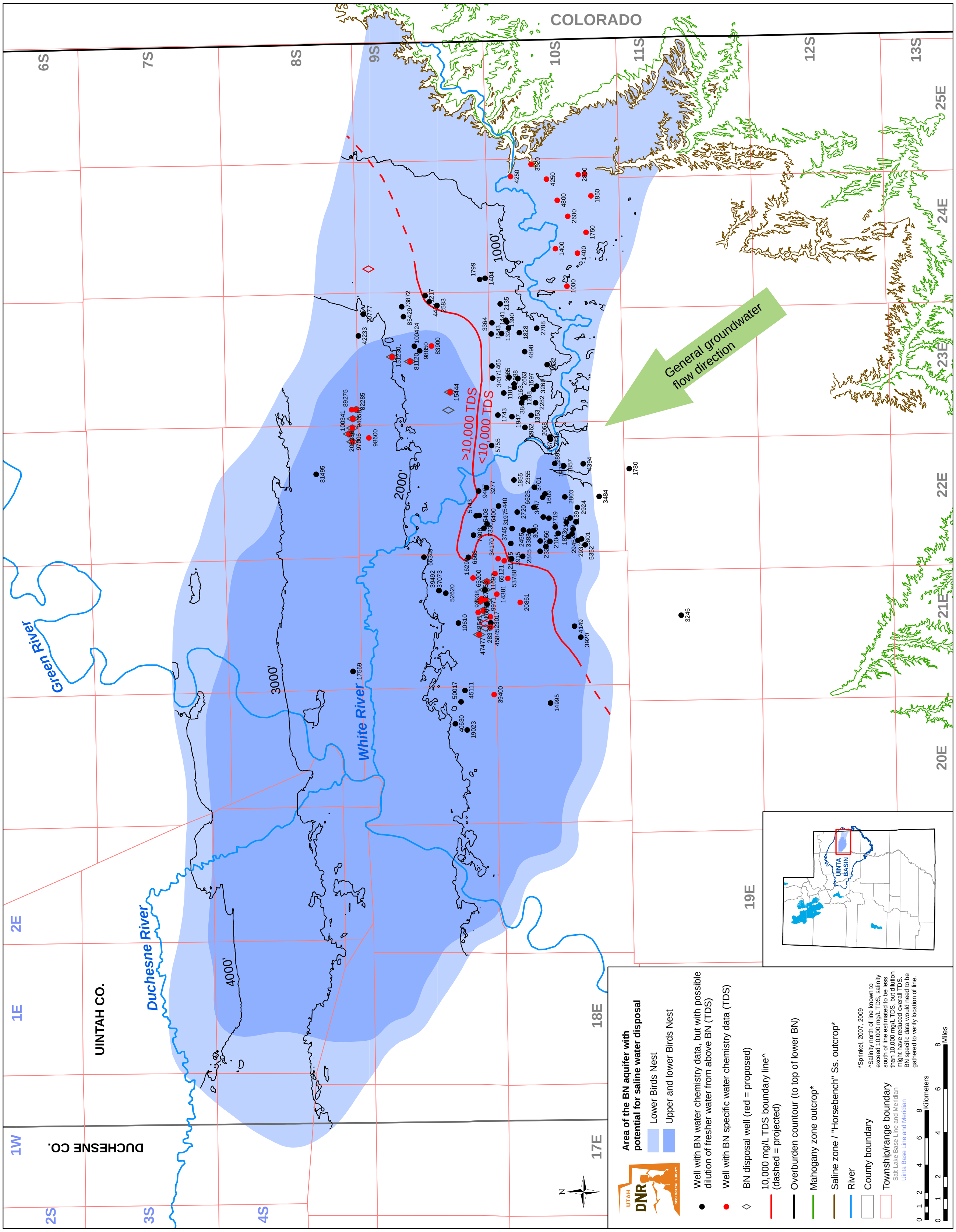


Figure 21. The Birds Nest aquifer's water chemistry.

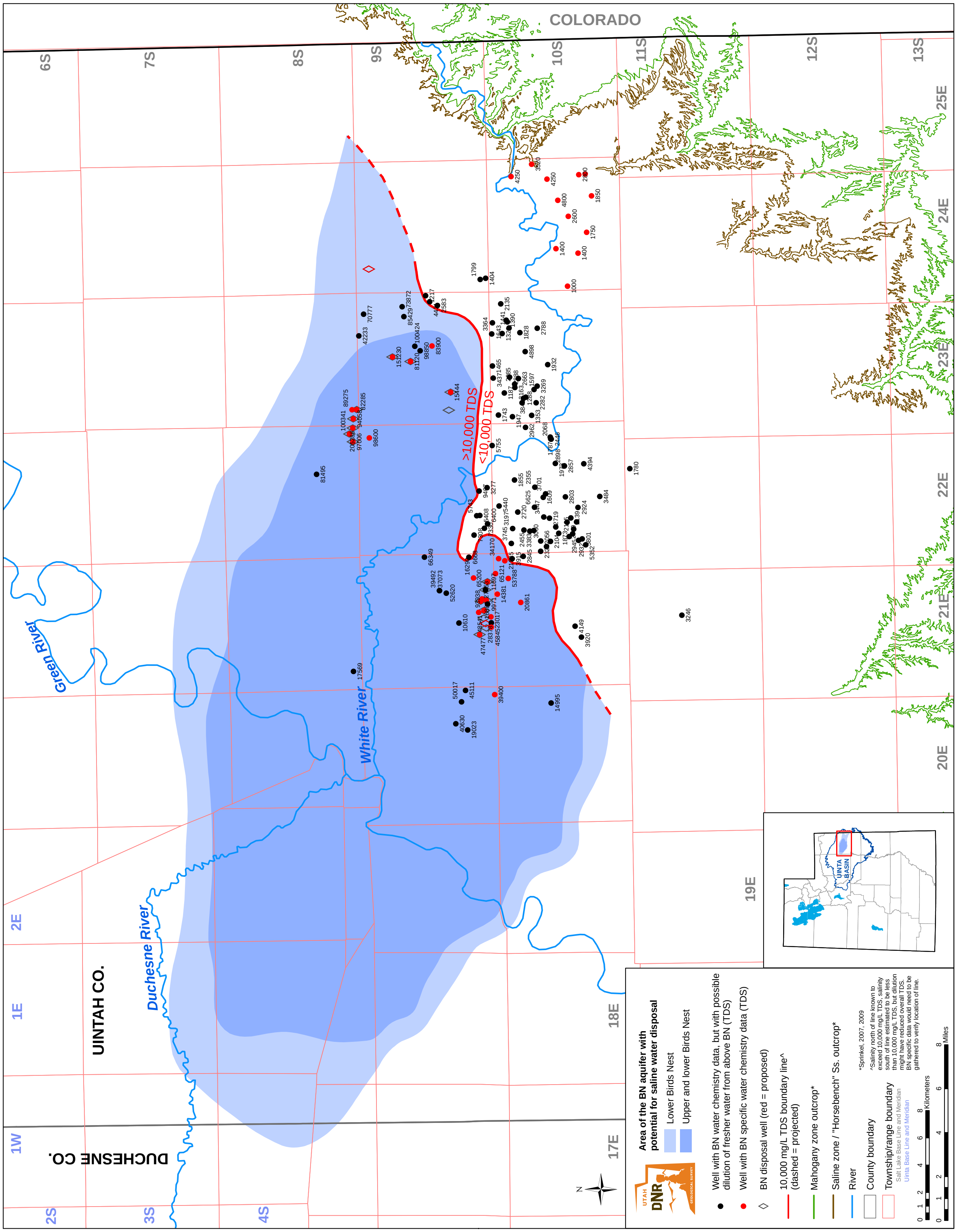


Figure 22. Area of the Birds Nest aquifer with potential for saline water disposal.

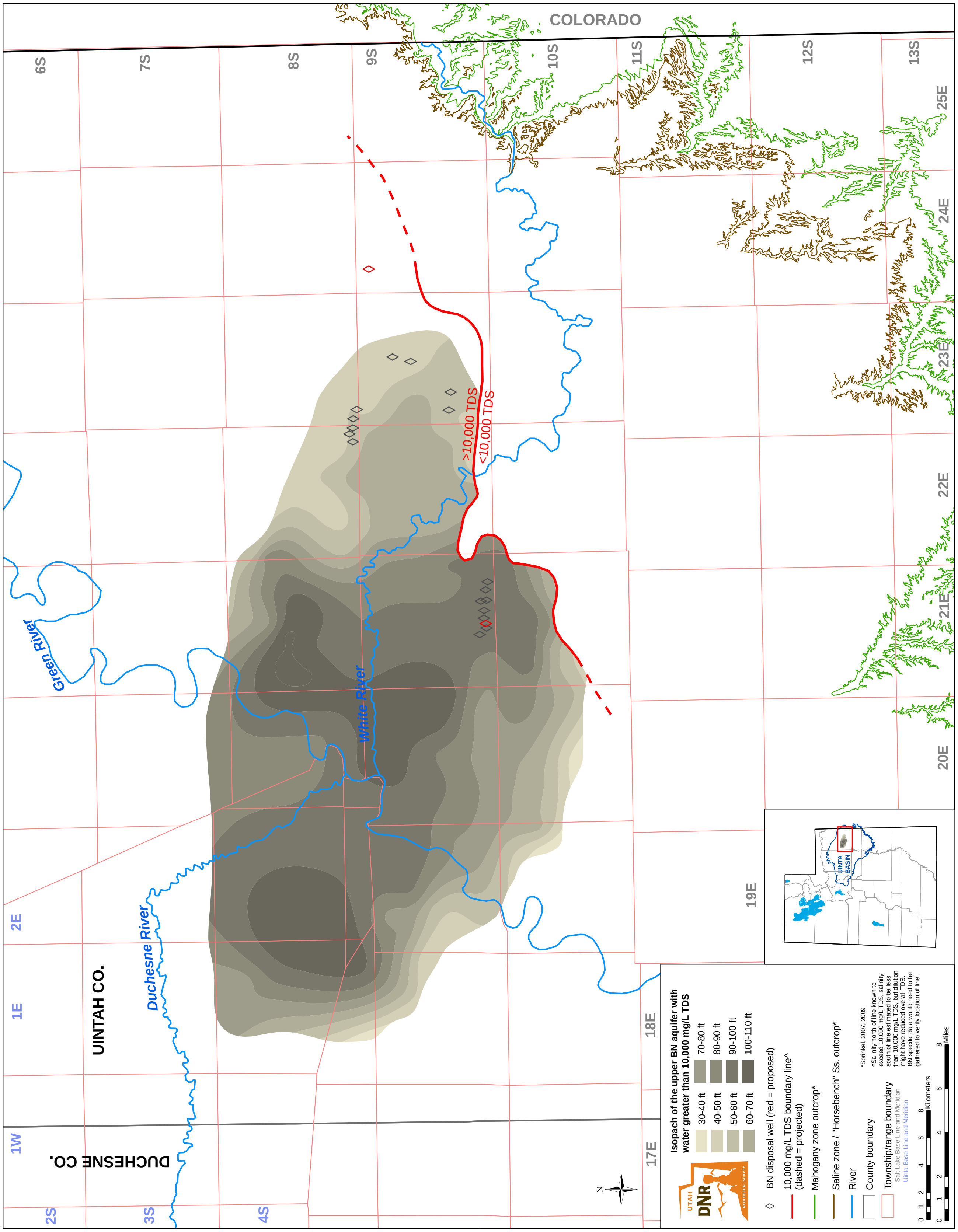


Figure 23. Thickness of the upper Birds Nest aquifer where there is potential for saline water disposal.

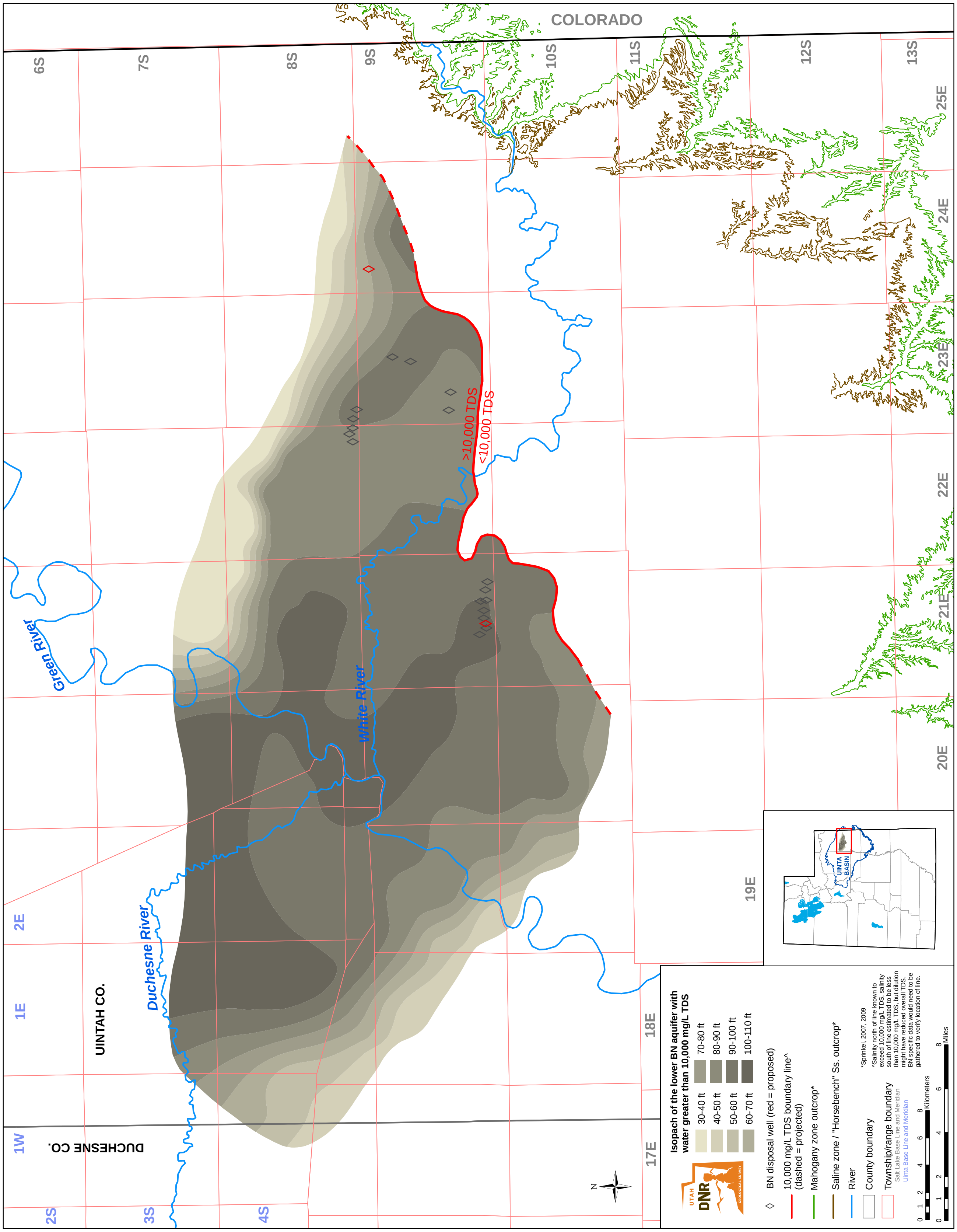


Figure 24. Thickness of the lower Birds Nest aquifer where there is potential for saline water disposal.

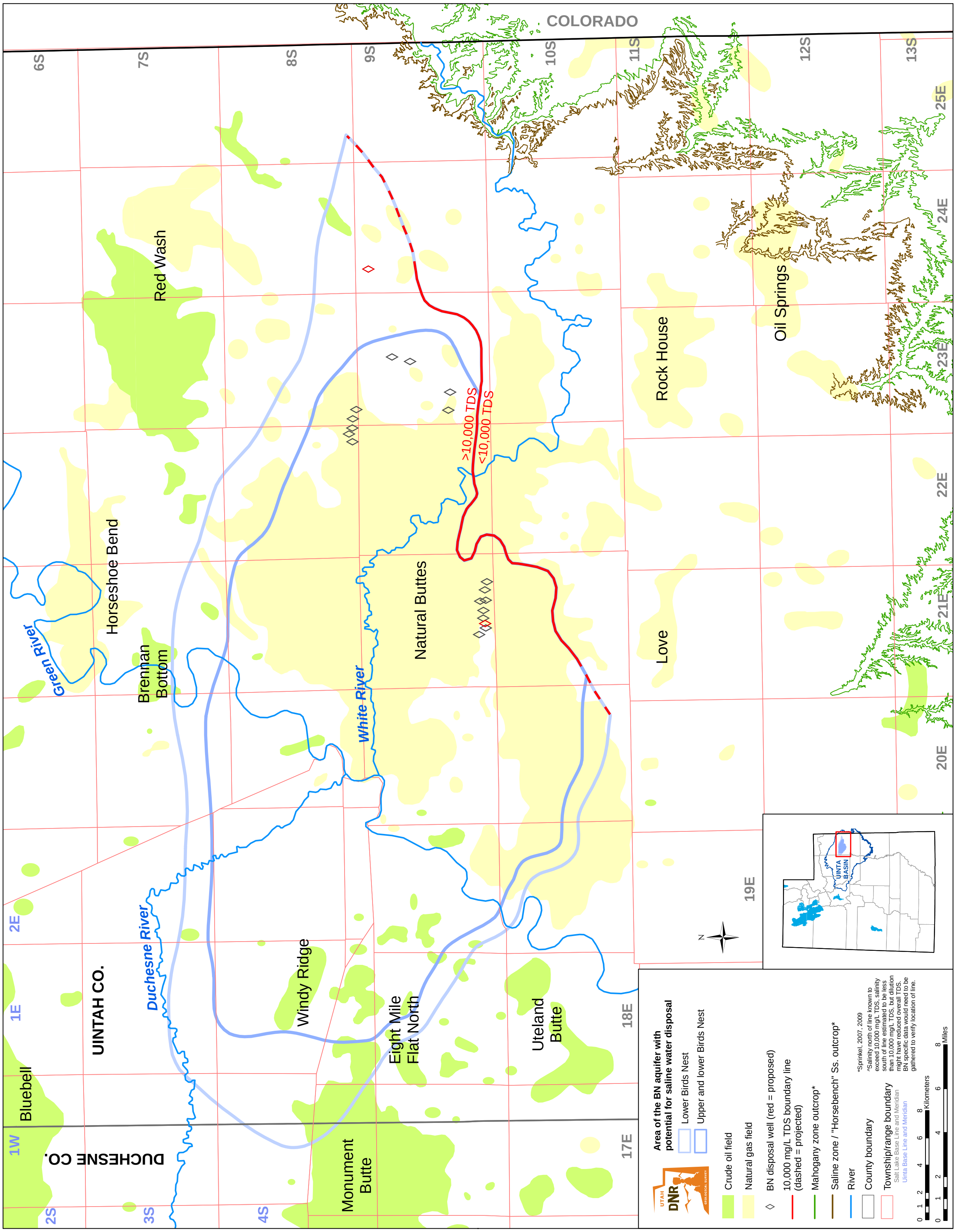


Figure 25. Area of the Birds Nest aquifer with potential for saline water disposal and its proximity to major producing oil and gas fields.

age space. We examined a representative outcrop to approximately estimate the vuggy-porosity of the hollow cavities left behind after saline mineral dissolution, as core typically provides too narrow a window (cores often miss nodules, giving the appearance of less vuggy-porosity). In addition, operators drilling through this aquifer commonly report very little water present in the Birds Nest, meaning most of the space is available for disposal. In fact, some drilling reports indicate that the Birds Nest is a zone of lost circulation where drilling fluids are lost.

A photograph was taken of the lower Birds Nest aquifer outcrop along Evacuation Creek. Using GIS techniques, each open cavity on the photograph was "mapped" and the total area of open cavities was calculated and compared to the total area of the rock surface (figure 26). This information was then used to estimate an overall average macro-porosity of 2.5%. In many cases, nodules occur in discrete beds or groups, with estimated macro-porosities as high as 10.5% and 3.5%, respectively.

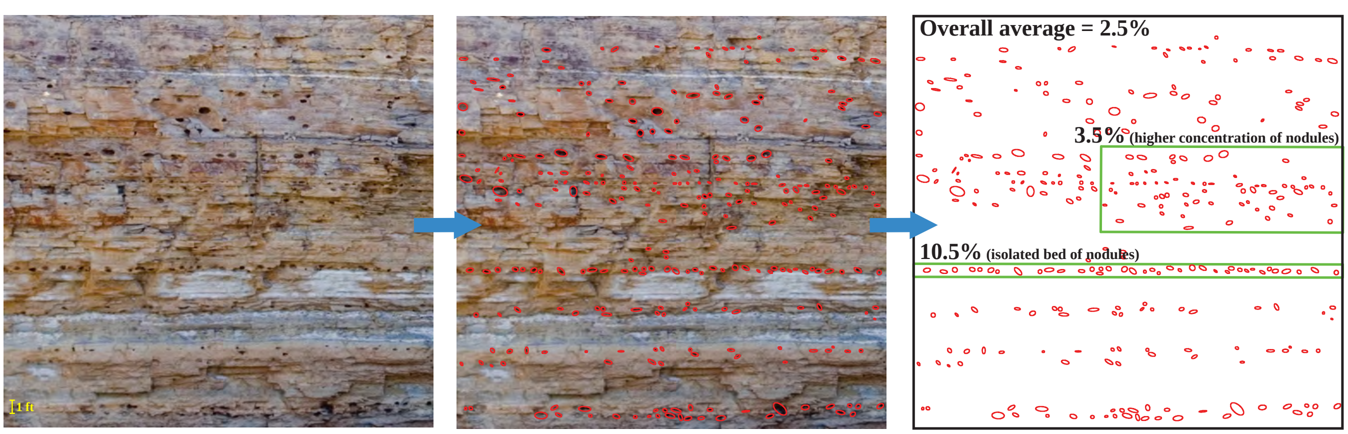
The upper Birds Nest aquifer, where current water quality is known to exceed 10,000 mg/L TDS, covers an area of 384 square miles. The average mean thickness of the upper Birds Nest over this area is 80 feet, which results in a calculated total rock volume of 860 billion cubic feet. After applying the overall average vuggy-porosity of 2.5%, as calculated from outcrop, the estimated storage volume totals 21 billion cubic feet or 493,000 acre-feet. The lower Birds Nest aquifer, where current water quality is known to exceed 10,000 mg/L TDS, covers an area of 533 square miles. The average mean thickness of the lower Birds Nest aquifer over this area is 85 feet, which results in a calculated total rock volume of 1260 billion cubic feet. After applying the overall average vuggy-porosity of 2.5%, the estimated storage volume totals 32 billion cubic feet or 724,000 acre-feet.

Several significant unknown parameters reduce the accuracy of the volumetric estimates provided above. These unknown parameters include: 1) The estimated storage area is calculated for only the areas of the Birds Nest aquifer where salinities are presently known to exceed 10,000 mg/L TDS, 2) these volumetric calculations do not take into account fracture porosity or micro-porosity, which are highly variable, difficult to quantify, and potentially significant, and 3) these volumetric calculations do not take into account the possible large areas where no or partial saline mineral dissolution has taken place, thus reducing the macro-porosity. Again, these areas are hard to quantify because a density log reacts similarly to an intact saline nodule verses one that has been dissolved away. A caliper log is somewhat more useful, recording widening of the borehole that could be related to saline mineral dissolution, but often, the drilling process causes some dissolution of the saline nodules, giving the false impression of groundwater-induced dissolution. Some drilling reports can be used to determine if the drilling company encountered lost circulation (a sign of natural dissolution), but reading through thousands of drilling reports is cumbersome and beyond the scope of this project.

In many places, the fracture porosity might be more important than the vuggy macro-porosity. Near EOG Resource's disposal wells, TDS measurements from Birds Nest specific water range from 80,000 mg/L up to 200,000 mg/L (figure 21). With the existing water at or near saline saturation, active dissolution of saline minerals might be limited, suggesting that the available space for disposed water could lie within the fracture network. In fact, the Red Wash 1 core (plate 8), near EOG Resource's disposal wells, shows only limited dissolution of the saline minerals.

INFLUENCE OF GILSONITE VEINS ON GROUNDWATER MOVEMENT

Gilsonite is a solid hydrocarbon that forms a swarm of subparallel, northwest-trending, near-vertical, laterally and vertically extensive veins in the Uinta Basin, but mostly on the eastern side in Uintah County (plate 1) (Boden and Tripp, 2012). Gilsonite is thought to be sourced from the rich oil



Evacuation Creek outcrop　　Red circles = dissolution cavities　　Macro-porosity estimations based on outcrop

Figure 26. *Method used on Evacuation Creek Birds Nest outcrop to estimate an overall average macro-porosity.*

shale units of the upper Green River Formation. Overpressuring produced during periods of hydrocarbon generation and expulsion deep in the Uinta Basin hydraulically fractured the overlying strata, expelling large quantities of hydrothermal water. Subsequently, thick, liquid gilsonite was expelled, forcing open most, but maybe not all, existing fractures. The gilsonite veins can extend up to the surface cross-cutting the Birds Nest aquifer, as seen near the surface on the eastern side of the Cowboy vein (figure 27). Questions remain as to how these veins might affect groundwater movement through the Birds Nest aquifer—i.e., whether they act as barriers to flow or whether they create vertical and/or horizontal pathways for water transmission. The concern is that disposed saline water might use a gilsonite vein or associated fractures to travel into deeper aquifers that might not contain water with >10,000 mg/L TDS, or, if the aquifer becomes overpressured, saline water could travel upward into freshwater aquifers. Also, vertical movement of saline water downward could affect development of underlying oil shale deposits.

Hood and Fields (1978) indicated that gilsonite veins and associated fractures near Roosevelt, Utah, tend to trend through potentiometric-contour anomalies as well as trend through points of abnormally high transmissivity and anomalies in the chemical quality of groundwater. They went on to state that upward leakage of saline waters, which are characteristic of the deeper Tertiary section, is possible where fractures are not filled with impermeable material. However, where gilsonite is present, it presumably can act as a barrier to groundwater movement. Similarly, Holmes and Kimball (1987) suggested that fractures related to a gilsonite vein transmit water from the Birds Nest aquifer upward through the Uinta Formation and the overlying alluvial aquifer to a spring emitting in the downstream reaches of Bitter Creek.

Anadarko indicates that the Birds Nest aquifer in the location of their disposal wells is underpressured (Sean Kelly, Anadarko, personal communication, 2012). Initial stabilized water levels in wells penetrating the Birds Nest were at an approximate average of 300 feet below ground surface. This results in a calculated Birds Nest aquifer gradient of 0.35 psi/ft. The aquifers in the shallower Uinta Formation and the reservoirs in the deeper Green River Formation are normally pressured with gradients of 0.43 psi/ft and fluid levels typically at the surface. This is important because it demonstrates that the Birds Nest, at least in this area, is isolated and not in hydrodynamic communication with shallower and deeper zones, despite the proximity to gilsonite veins, creating a situation suitable for saline water disposal.

The assessment below provides additional anecdotal evidence for both cases, barrier and conduit, depending on the type of gilsonite in the vein, vein thickness, and abundance of associated fractures. Unfortunately, little is known about the gilsonite veins and fractures at depth in the areas suitable for saline water disposal; only surface expressions of the veins are easily mapped and accessed.

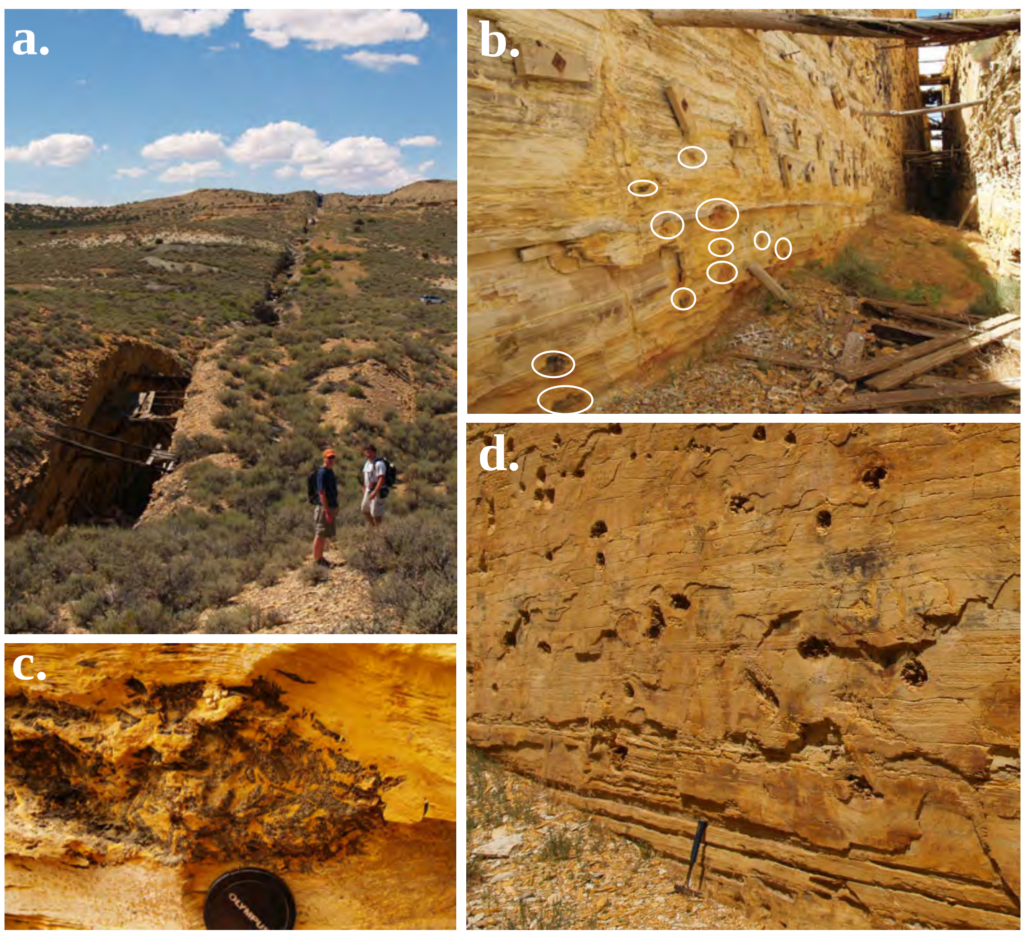


Figure 27. *Photographs of the mined-out Cowboy gilsonite vein cross-cutting the Birds Nest aquifer.* ***a.*** *Cowboy gilsonite vein.* ***b.*** *Wall of mined-out Cowboy vein showing large nahcolite nodules of the lower Birds Nest aquifer (white circles).* ***c.*** *Nahcolite nodule replaced with gilsonite within the wall of the Cowboy vein.* ***d.*** *Wall of mined-out Cowboy vein showing large nahcolite nodules.*

Basin Depocenter Cores—Evidence for Gilsonite as a Barrier to Groundwater Flow

Near the basin's paleo-depocenter, several cores exist that recovered the entire saline zone. Most of these cores show significant saline mineral dissolution (e.g., 13X-2). In fact, Anadarko has begun disposing saline water into the Birds Nest in this area. However, there is one well (Utah State 1) with core slightly to the north that shows no sign of saline mineral dissolution. This core is separated from the southern cores by a gilsonite vein, as mapped by its surface expression (figure 28). Water within the aquifer generally recharges from areas along outcrop in the east and south, particularly where the White River and Evacuation Creek pass over the outcrop, and travels down-dip to the northwest. Water within the Birds Nest has dissolved the saline minerals to the south of the vein, but the gilsonite vein seems to stop water from reaching the area on its northern side, creating a possible zone of no saline mineral dissolution with unknown extent. Similar areas of no dissolution are assumed to exist, especially on the northern sides of known gilsonite veins, but it is difficult to identify these areas without core.

Gilsonite Mine Tour—Evidence for Gilsonite as Both a Barrier and Conduit

The senior author toured two mines in different gilsonite veins, each roughly 3 feet thick, to assess how groundwater interacts with the veins. The first mine, within the Bonanza vein and at a mining depth of 630 feet, contained highly fractured gilsonite that easily transmitted water through the vein (figure 29). The second mine, within the Independent vein,

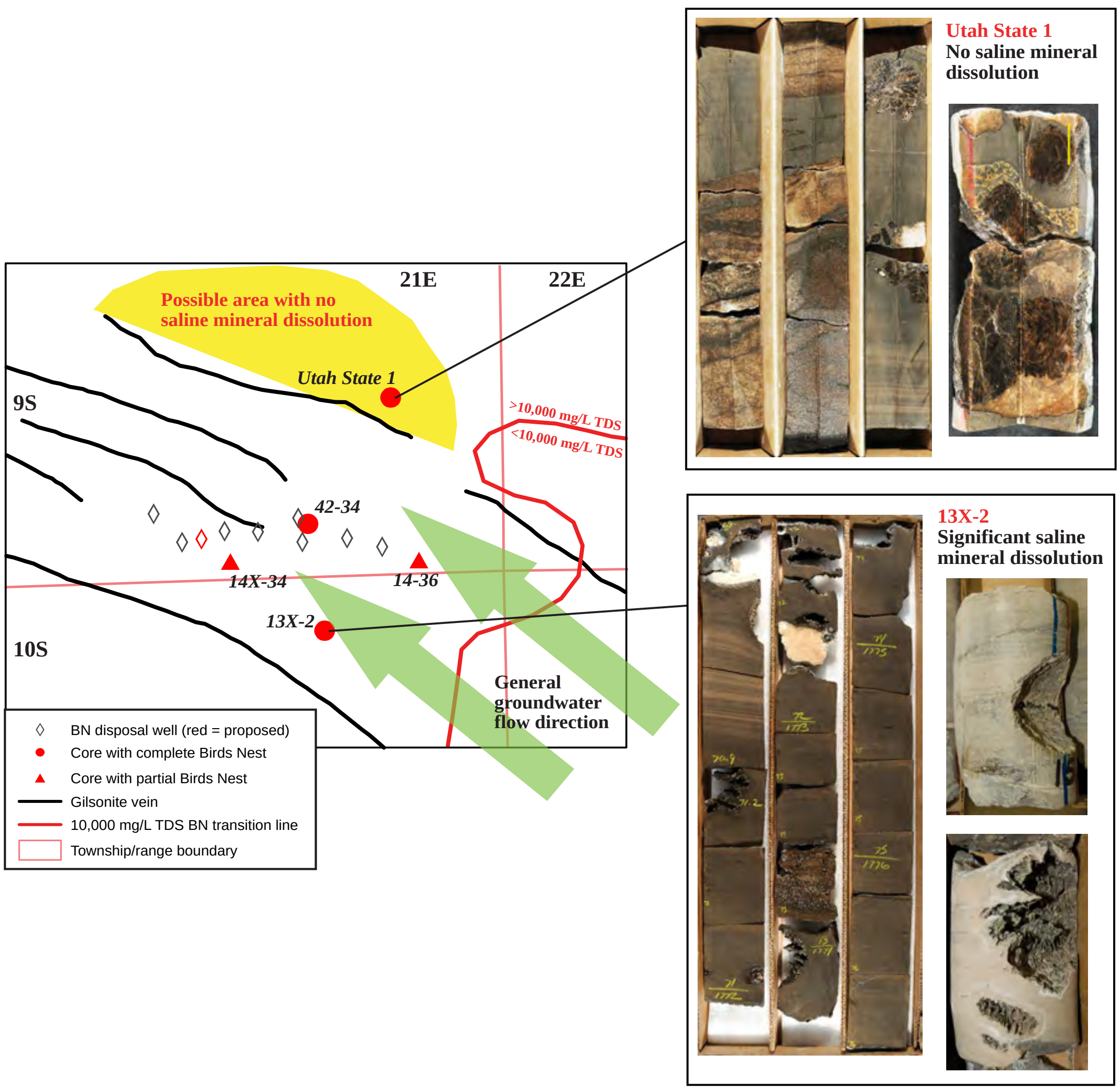


Figure 28. *Evidence for basin-center gilsonite veins acting as barriers to groundwater flow. Saline minerals in the 13X-2 core have experienced significant dissolution and are near Anadarko's Birds Nest saline water disposal wells. Saline minerals in the Utah State 1 core show no signs of dissolution. The two wells are separated by a gilsonite vein which could be preventing groundwater from reaching the area north of the vein.*

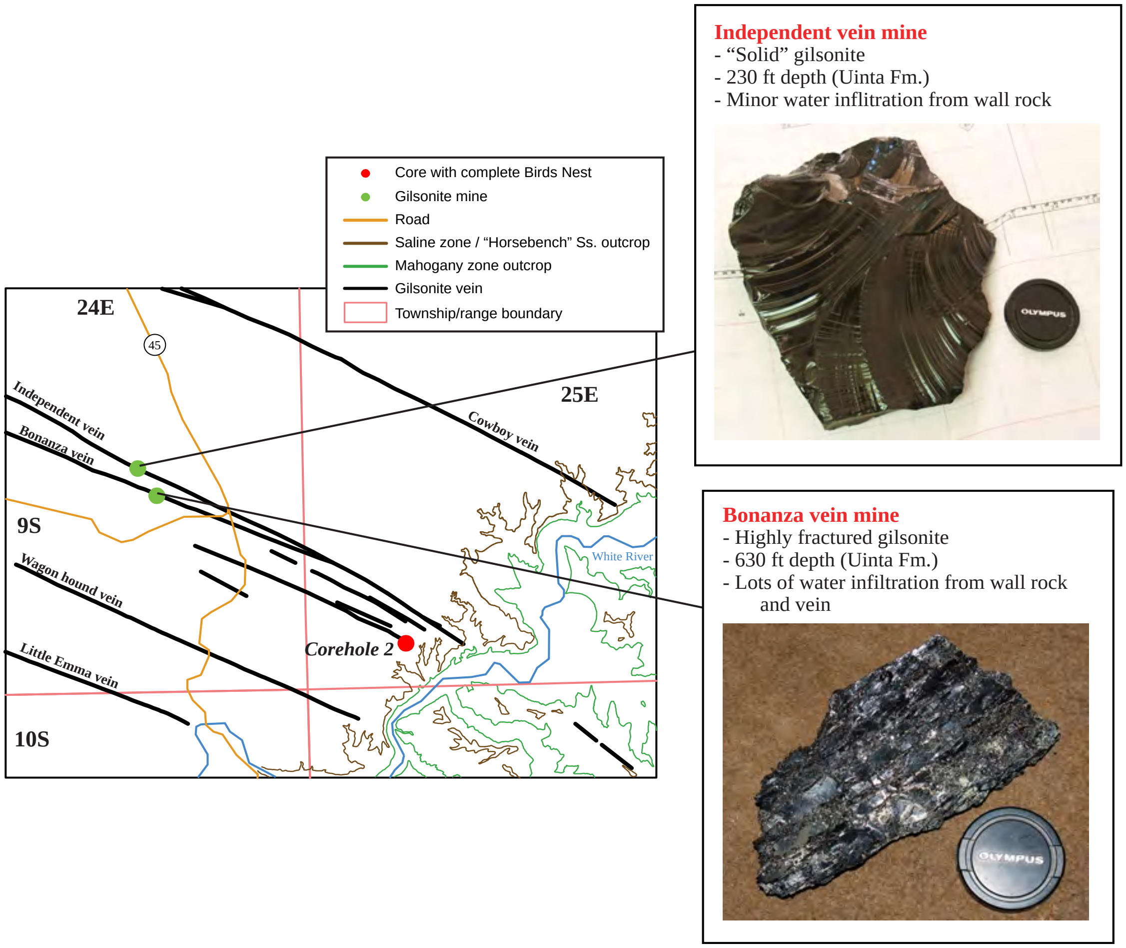


Figure 29. *Examples of gilsonite veins acting as both barriers to groundwater flow and conduits from gilsonite mine tour. Different kinds of gilsonite can be found in two different veins/mines; the solid gilsonite found in the Independent vein mine could act as a significant barrier to groundwater flow, whereas the fractured gilsonite of the Bonanza vein mine easily transmitted water through the vein.*

and at a mining depth of 230 feet, contained a variety of gilsonite called "select" that is solid and transmitted no water. These observations suggest that gilsonite veins could act as both barriers or conduits for water depending on the type of gilsonite in the vein. However, gilsonite type at depth is nearly impossible to determine in the absence of a mine.

Kings Well Groundwater Analysis—Evidence for Gilsonite as a Groundwater Conduit

Water from the Kings well, which is completed in a shallow bedrock aquifer, has elevated nitrate levels, as seen in seasonal water chemistry analyses performed by the Utah Geological Survey (figure 30) (Wallace, 2012). This might be expected from alluvial aquifers in an area with significant agriculture (near Ouray, Utah, in central Uintah County), but not in a bedrock aquifer from an area with no farmland. The Kings well does supply water to grazing stock. Waste (which is high in nitrate) from the stock congregating around the well might be percolating down the gilsonite vein and into the bedrock aquifer.

Course of Evacuation Creek—Evidence for Gilsonite Veins Influencing Water Flow

Near the intersection of State Route 45 and the Dragon road, Evacuation Creek generally flows north before taking an abrupt 90-degree turn to the east. Upon close inspection, it was determined that the path of the creek was influenced by a thin gilsonite vein (<2 inches thick) and associated fracture zone (figure 31). While this has only indirect relevance to underground conditions, it at least suggests that gilsonite veins can influence water flows. In addition, it demonstrates that in some cases, a specific gilsonite vein might not be as important as the vein's associated vertical fractures, which may or may not contain gilsonite. The case could be made that this fracture system could prove more influential on the movement of groundwater than the actual gilsonite veins.

BIRDS NEST AQUIFER AND OIL SHALE

Utah's oil shale is a carbonate mudstone deposited in a large ancient lake system that contains abundant organic matter

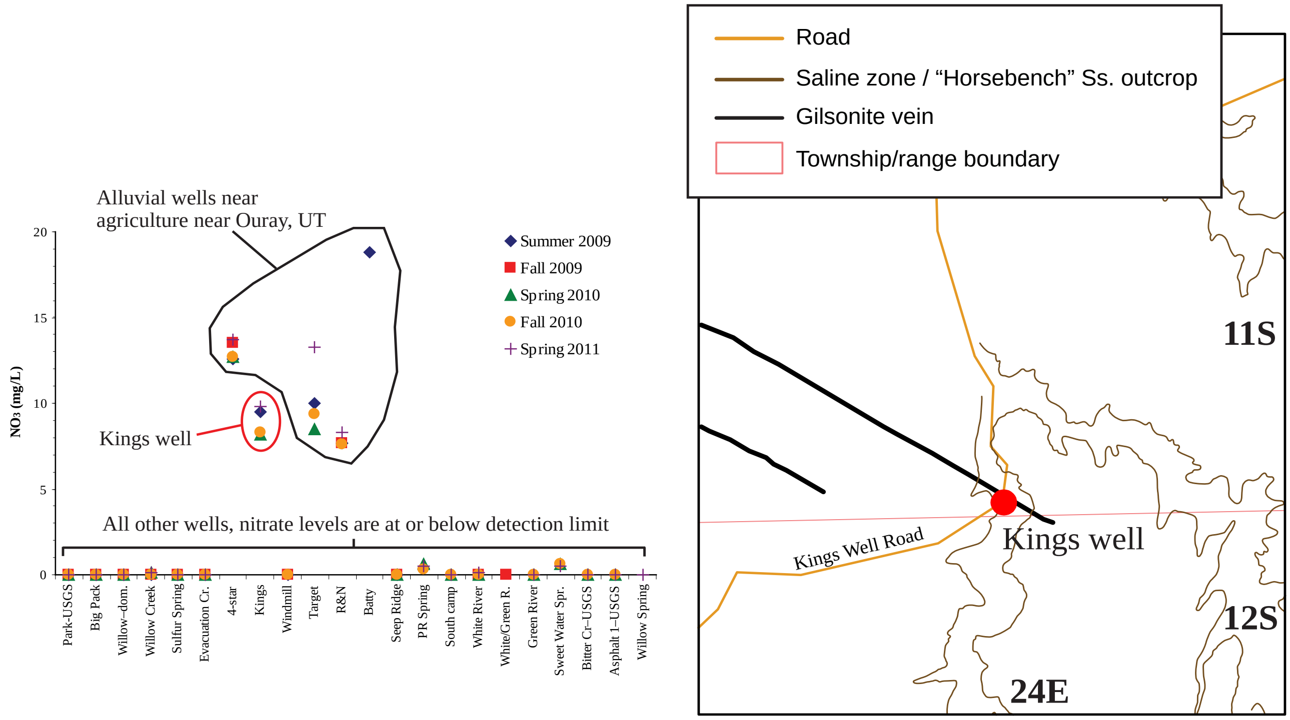


Figure 30. *Possible evidence for water traveling vertically along a gilsonite vein into a shallow bedrock aquifer. Seasonal nitrate levels from surface water and shallow wells in Uintah County mostly record concentrations below the detection limit, except for a cluster of wells near Ouray, Utah, where there is significant nearby agriculture, and the Kings well, which is next to a gilsonite vein. The Kings well is used to water stock; waste from the stock congregating near the well could be percolating down the gilsonite vein into the bedrock aquifer.*

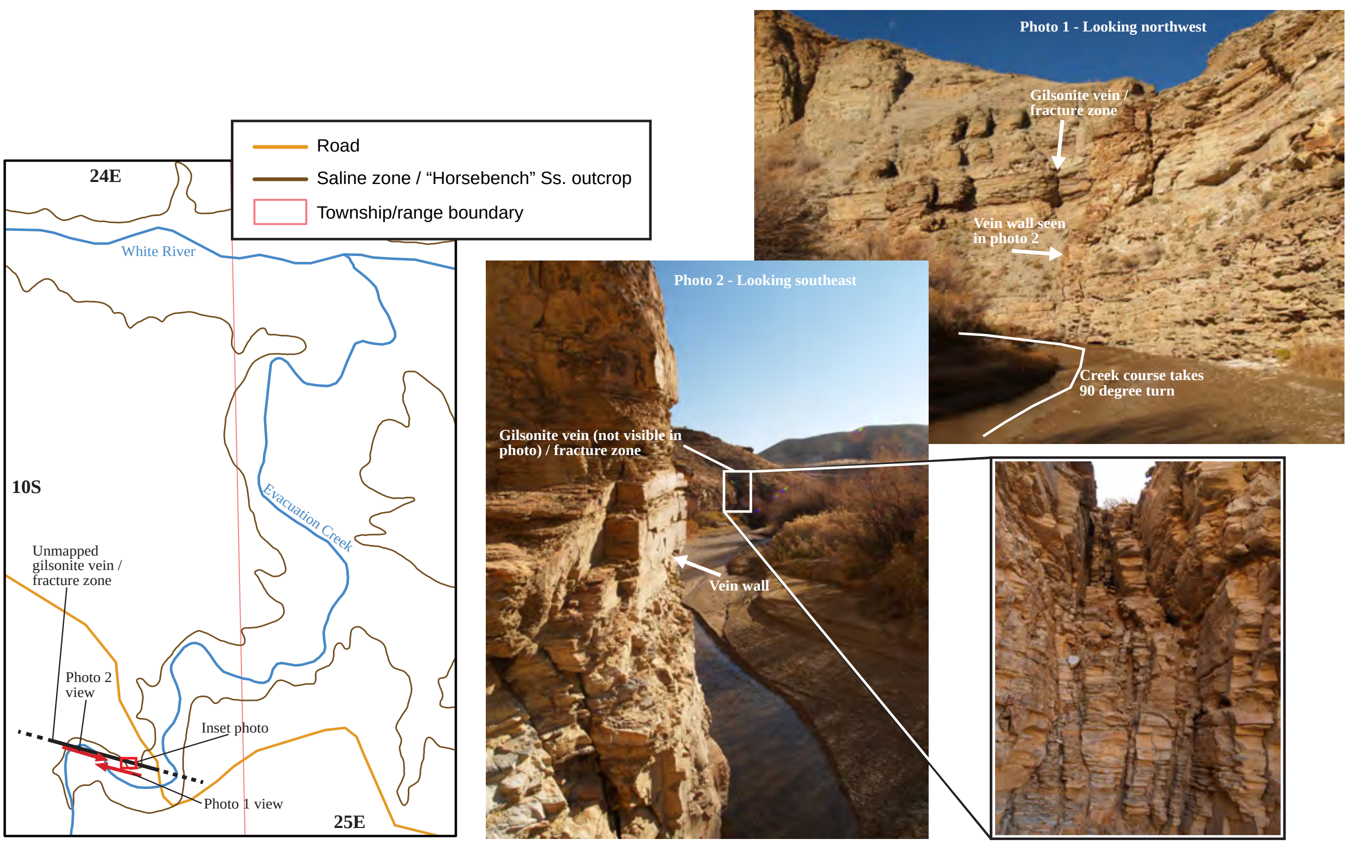


Figure 31. *Evidence along Evacuation Creek that gilsonite veins and their associated fractures influence the course of surface water flow.*

derived mostly from algae or cyanobacteria. It is considered a thermogenically immature source rock, meaning it has not experienced temperatures or pressures high enough to geologically convert the organic matter, called kerogen, into conventional oil and/or natural gas (except maybe in the deepest parts of the Uinta Basin to the northwest). However, several companies are working on technologies to artificially convert oil shale's kerogen into petroleum products using two basic methods: 1) surface/underground mining and surface retort (including modified *in-situ* capsule retorts), and 2) *in-situ* heating (heating the oil shale within the ground via wells) and recovery. The Utah oil shale deposit is more conducive to mining and surface retort since the richest oil shale zones are relatively thin (a sequence of oil shale averaging 25 gallons of oil per ton of rock [gpt] is between 70 and 120 feet thick) and accessible along extensive outcrops (figure 32). In contrast, the Colorado oil shale deposit, in the Piceance Basin, is better suited to *in-situ* recovery with a much thicker organic-rich sequence (a 25 gpt zone more than 1000 feet thick) under 1000 to 2000 feet of cover (USGS, 2010b). Detailed descriptions of the various oil shale conversion technologies and the companies looking to employ them can be found in the INTEK, Inc. report "Secure Fuels from Domestic Resources: Profiles of Companies Engaged in Domestic Oil Shale and Tar Sands Resource and Technology Development, 5th Edition," prepared for the U.S. Department of Energy, Office of Petroleum Reserves, Naval Petroleum and Oil Shale Reserves (INTEK, 2011).

The upper Green River Formation in the Uinta Basin hosts one of the largest deposits of oil shale in the world—as stated above, estimated in-place resources total 1.32 trillion barrels of oil (USGS, 2010a) with approximately 77 billion barrels as a potential economic resource (Vanden Berg, 2008) (figure 5). Nearly the entire upper Green River Formation consists of alternating organic-rich and lean oil shale, with the richest and the most prospective horizon being the Mahogany zone (figure 4). This zone represents a time when the ancient lake was at its highest level. After Mahogany-zone time, the lake began to shrink, at times becoming a restricted basin with high-salinity water. It was at this time that saline minerals were deposited in the lake bed sediments along with organic-lean oil shale. The fact that the extent of the Birds Nest aquifer is coincident with and lies a short distance above the Uinta Basin's most prospective oil shale horizon raises questions as to what impacts large-scale saline water disposal into this zone might have on potential future oil shale development (figure 32).

Utah's oil shale deposit is divided into alternating organic rich and lean zones, with potentially economic oil shale generally limited to deposits averaging at least 15 gpt. The Birds Nest aquifer lies within the relatively lean upper to middle R-8 zones, stratigraphically above the potentially economic oil shale horizons (figure 4). In order to relate the Birds Nest aquifer to potential economic oil shale zones below, two thicknesses of interburden were calculated and mapped using the data in appendix A: the thickness between the base of the lower Birds Nest aquifer and the top of the Mahogany oil shale zone, and the thickness between the base of the lower Birds Nest and the top of the defined economic oil shale, picked at the top of the lower R-8 (defined by Big Three oil shale beds) (figure 4). The top of the economic oil shale was selected at the top of the lower R-8 since this is the stratigraphically highest zone averaging roughly 15 gpt. Above this, in the middle R-8, the oil shale grade drops below 10 gpt, then becomes even leaner in the upper R-8. The interburden between the Mahogany zone and the lower Birds Nest aquifer ranges from 240 feet thick in the south to 430 feet thick in the north (figure 33). The interburden between the lower R-8 and the lower Birds Nest mostly ranges from 70 to 90 feet thick, except in the northeast, where the interburden reaches 180 feet thick (figure 34).

As stated above, the richest oil shale zone in Utah is the Mahogany zone, in which individual oil shale beds have Fischer assay values of up to 80 gallons of oil per ton of rock. The Mahogany zone as a whole averages between 20 and 25 gpt, is between 60 and 120 feet thick, and crops out along the eastern and southern flanks of the basin. Currently, all companies in Utah looking to develop an oil shale industry are focused on the near-surface extent of the Mahogany zone, and they plan to develop a surface/underground mine and surface retort or employ surface modified *in-situ* technologies (figure 32). Saline water disposal into the Birds Nest aquifer should not adversely affect any company looking to develop oil shale near outcrop. Since disposal may only take place north of the 10,000 mg/L TDS boundary (as mapped on plate 1 and figure 21), active disposal will be several miles northwest and downdip of the near-surface oil shale.

Impacts of saline water disposal into the Birds Nest aquifer on future oil shale development will depend on two main factors: 1) the value of leaner deposits, and 2) the possible vertical connectivity of oil shale deposits. As stated above, the Birds Nest aquifer lies within relatively lean oil shale rocks. Most likely, advances in in-situ technologies that might exploit leaner deposits will limit the recovery zone to the lower R-8 and below (leaving 70–90 feet of impermeable oil shale between the retort zone and the aquifer), purposely avoiding the Birds Nest aquifer and problems associated with retorting shale within a zone filled with water and saline minerals. Therefore, the lean oil shale within the Birds Nest has little to no economic value. In addition, if technologies advance to the point where deep underground mines prove economic (oil prices would also need to be favorably high), the mines would still be centered on the Mahogany zone, roughly 1500–3000 feet deep in the area where disposal can take place, with about 300 feet of impermeable oil shale between the mining horizon and the aquifer. In fact, in the early 1980s, substantial research was conducted on a proposed mine within the Mahogany zone, accessed via a proposed ~2000-foot shaft, very near the area where Anadarko currently has active Birds Nest saline water disposal operations (TOSCO Development Corp., 1982) (figure 32). This mine was never developed due to the crash in oil prices in the mid-1980s.

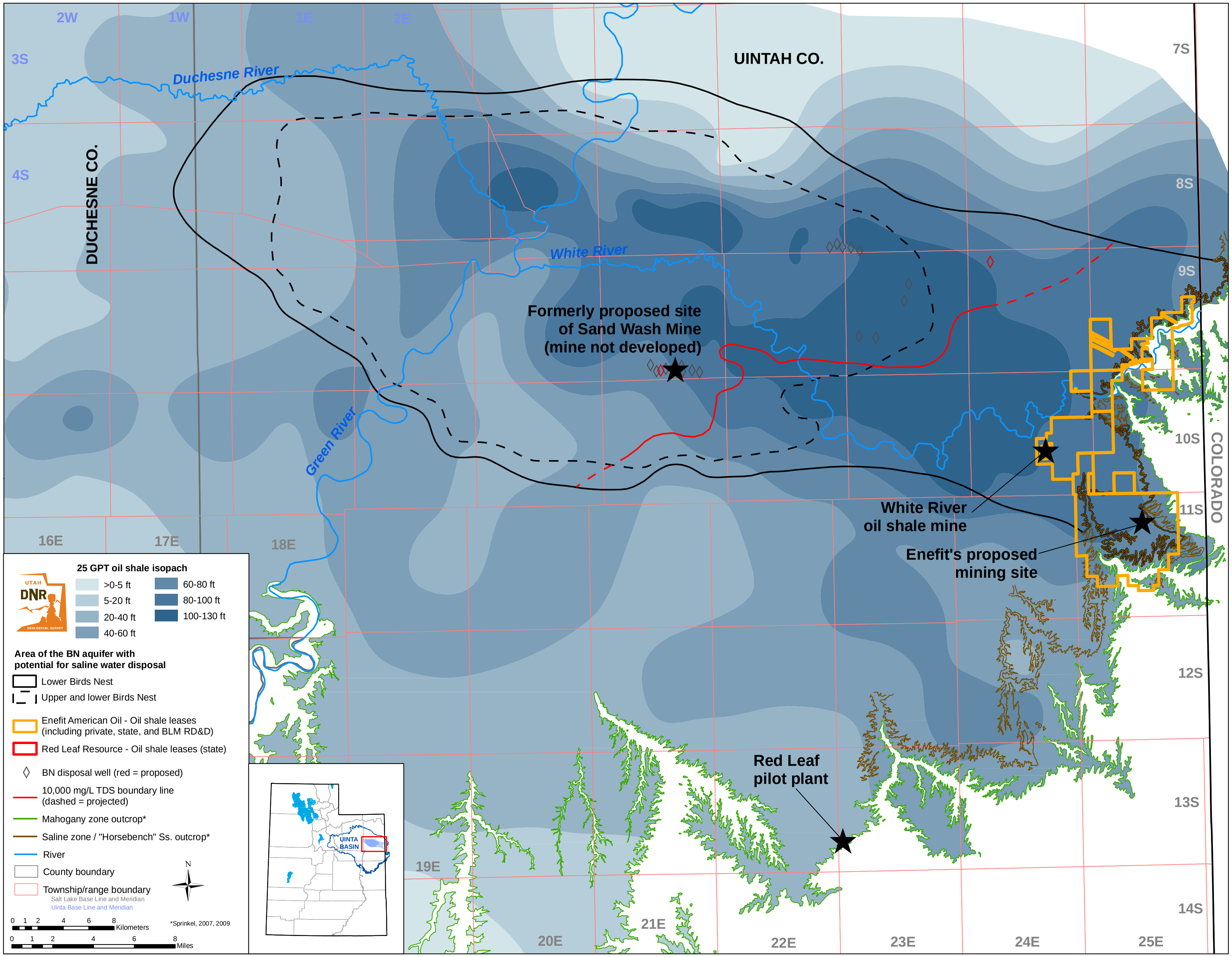


Figure 32. *Area of the Birds Nest aquifer and its coincidence with the 25 GPT oil shale zone.*

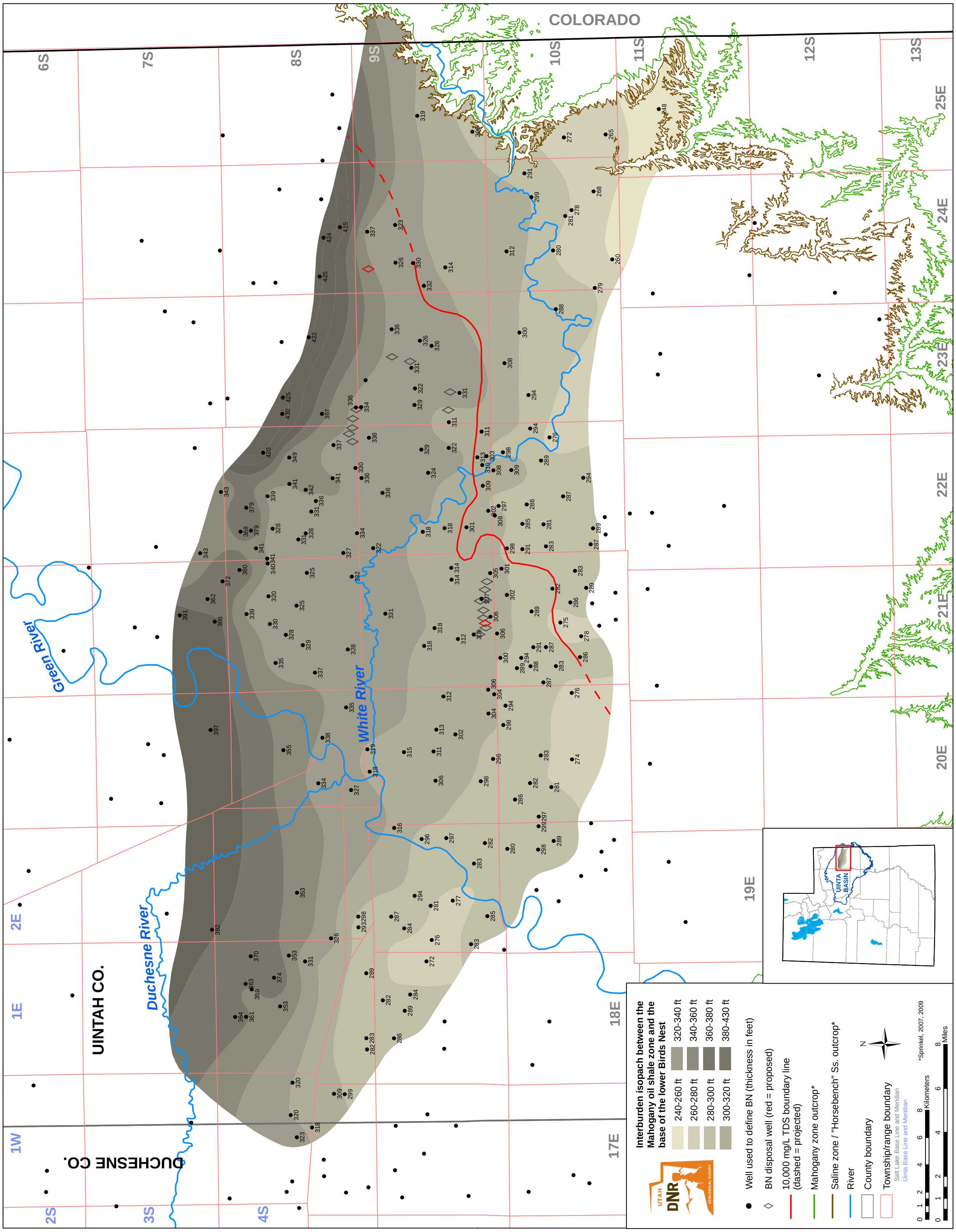


Figure 33. Thickness of the interburden between the base of the lower Birds Nest aquifer and the top of the Mahogany zone.

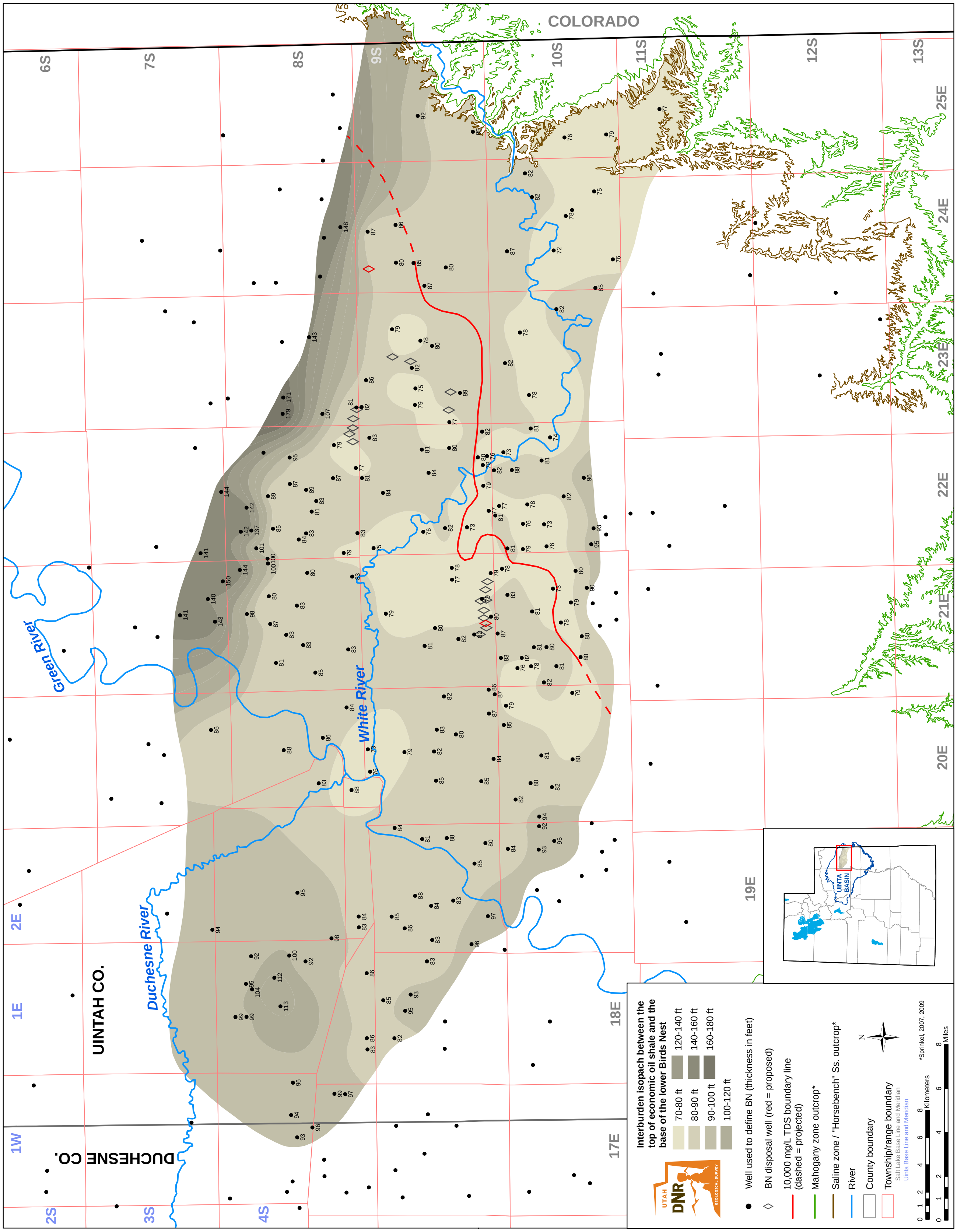


Figure 34. Thickness of the interburden between the base of the lower Birds Nest aquifer and the top of the economic oil shale.

If future economics prove favorable for either *in-situ* technologies or deep underground mine development, the most pressing question will be whether water in the Birds Nest aquifer can migrate vertically through thick sequences of impermeable oil shale by way of fractures or gilsonite veins, contaminating operations stratigraphically below the Birds Nest aquifer. Any kind of water infiltration into the mining horizon could greatly affect the economics of such marginal deposits. The likelihood of such a scenario is remote but possible, and will only increase as saline water disposal increases. Future research should look to address the issue of vertical migration of water in the upper Green River Formation.

SUMMARY AND CONCLUSIONS

The Birds Nest aquifer has significant potential as a large-scale saline water disposal zone for several reasons:

1. The aquifer currently contains highly saline water, much higher than the required 10,000 mg/L TDS, in areas generally north of T. 10 S., SLBLM.
2. The aquifer contains a large amount of potential storage space (in excess of 1.2 million acre-feet) due to the dissolution of saline minerals and natural fracturing.
3. The aquifer is relatively shallow, reducing drilling expense.
4. The aquifer is close to several producing natural gas fields and overlies the Greater Natural Buttes field, the largest natural gas field in Utah.
5. Saline water disposal would take place within lean oil shale deposits that have little to no current economic potential.
6. Organic-rich, economic oil shale deposits lie between 70 feet (for *in-situ* recovery) and 300 feet (for deep underground mining) below the aquifer.

Nevertheless, disposal into the Birds Nest aquifer poses several unique challenges and risks:

1. Potentially large areas with no saline mineral dissolution exist, thus reducing overall storage potential.
2. The aquifer is relatively shallow, with non-saline water (<10,000 mg/L TDS) both above and, in some instances, below the unit.
3. It is currently unclear where the water within the Birds Nest aquifer eventually goes: is the water pooling in areas down-dip, or is the water migrating vertically through the section?
4. Cross-cutting gilsonite veins and associated fractures have the potential to transmit water vertically through the section, posing risks to “fresh” water aquifers stratigraphically below (or above if the Birds Nest aquifer becomes pressurized).
5. The extent of the Birds Nest aquifer is coincident with the richest oil shale in the Uinta Basin.
6. Vertical transmission of water from the Birds Nest aquifer could adversely affect development of underlying organic-rich oil shale deposits.
7. Additional monitoring wells would be helpful in gaining a better understanding of the hydrology of the Birds Nest aquifer, while tracer studies might be helpful in understanding the flow direction and rate of groundwater movement.

ACKNOWLEDGMENTS

This project was generously funded by the U.S. Department of Energy, National Energy Technology Laboratory under project code NT0005671. Additional funding was provided by the Utah Geological Survey. Special thanks to our DOE project officers Traci Rodosta, Virginia Weyland, and Skip Pratt.

Special thanks go to Sean Kelly at Anadarko Petroleum Corporation who provided excellent background information on the Birds Nest aquifer and a detailed review of this report, as well as providing water chemistry data, digital well logs, and various maps. In addition, Anadarko paid to have two critical Birds Nest cores slabbed for easier examination. EOG Resources and Questar also provided water chemistry data. Thanks also to David Keighley, from the University of New Brunswick, for his detailed review. Thanks to Chuck Tinsley, Tricia Pfeiffer, and other EPA Region 8 staff for their help with data collection. Thanks to the staff of the U.S. Geological Survey and Utah Geological Survey Core Research Centers for finding and setting out several Birds Nest cores. Acknowledgment also goes to Utah Geological Survey employees David Tabet, Mike Hylland, Robert Ressetar, Kimm Harty, and Rick Allis for their detailed review and insightful comments.

REFERENCES

Anadarko Petroleum Corporation, 2010, ACTS—Anadarko Completion Transport System: Online, presentation at the Utah Energy Forum, July 2010, http://www.energy.utah.gov/government/docs/forum/july2010/bradmilleranadarko.pdf, accessed May 31, 2012.

Birgenheier, L.P., and Vanden Berg, M.D., 2011, Core-based integrated sedimentologic, stratigraphic, and geochemical analysis of the oil shale bearing Green River Formation, Uinta Basin, Utah: DOE Topical Report, award no. DE-FE0001243, p. 1–30.

Boden, T., and Tripp, B.T., 2012, Gilsonite veins of the Uinta Basin, Utah: Utah Geological Survey Special Study 141, compact disk.

Bradley, W.H., 1931, Origin and microfossils of the oil shale of the Green River Formation, southeastern Uinta Basin, Utah and Colorado: U.S. Geological Survey Professional Paper 168, 58 p.

Carroll, A.R., and Bohacs, K.M., 1999, Stratigraphic classification of ancient lakes—balancing tectonics and climatic controls: Geology, v. 27, p. 99–102.

Cashion, W.B., 1967, Geology and fuel resources of the Green River Formation, southeastern Uinta Basin, Utah and Colorado: U.S. Geological Survey Professional Paper 548, 48 p.

Cashion, W.B., and Donnell, J.R., 1974, Revision of nomenclature of the upper part of the Green River Formation, Piceance Creek Basin, Colorado, and eastern Uinta Basin, Utah: U.S. Geological Survey Bulletin 1394-G, 9 p.

Chetel, L.M., and Carroll, A.R., 2010, Terminal infill of Eocene Lake Gosiute, Wyoming, U.S.A.: Journal of Sedimentary Research, v. 80, p. 492–514.

DOGM (Utah Division of Oil, Gas, and Mining), 2012, Utah oil, natural gas, and water production data: Online, http://oilgas.ogm.utah.gov/Statistics/Statistics.cfm, accessed May 18, 2012.

Dynamac Corporation, 2002, Well sampling and analyses report, Bird's-nest aquifer, White River oil shale reserve, Uintah County, Utah, 32 p., 7 appendices.

Energy Dynamics Laboratory–Utah State University, 2012, Uintah Basin winter ozone and air quality study—March 2012 update: Online, http://rd.usu.edu/files/uploads/report_ozone_2012_03.pdf, assessed May 31, 2012.

Hintze, L.F., 1988, Geologic history of Utah: Brigham Young University Geology Studies Special Publication 7, 202 p.

Holmes, W.F., 1980, Results of test drilling for ground water in the southeastern Uinta Basin, Utah and Colorado: U.S. Geological Survey Water-Resource Investigation 80-951, 89 p. 6 plates.

Holmes, W.F., and Kimball, B.A., 1987, Ground water in the southeastern Uinta Basin, Utah and Colorado: U.S. Geological Survey Water-Supply Paper 2248, 47 p., 1 plate.

Hood, J.W., and Fields, F.K., 1978, Water resources of the northern Uinta Basin area, Utah and Colorado, with special emphasis on ground-water supply: Utah Department of Natural Resources Technical Publication No. 62, 66 p.

INTEK, Inc., 2011, Secure fuels from domestic resources—Profiles of companies engaged in domestic oil shale and tar sands resource and technology development, 5th Edition: Online, http://www.unconventionalfuels.org/publications/reports/SecureFuelsReport2011.pdf, accessed March 31, 2012.

Keighin, C.W., 1982, Characteristics and description of cores from the USGS core hole CRU-1, Parachute Creek Member, Green River Formation, east-central Uinta Basin, Utah: U.S. Geological Survey Open-File Report 82-0528, 44 p.

Lindskov, K.L., and Kimball, B.A., 1984, Water resources and potential hydrologic effects of oil-shale development in the southeastern Uinta Basin, Utah and Colorado: U.S. Geological Survey Professional Paper 1307, 31 p.

Morgan, C.D., 2009a, Conventional northern Uinta Basin play, *in* Chidsey, T.C., Jr., editor, Major oil plays in Utah and vicinity: U.S. Department of Energy, National Energy Technology Laboratory, final report, DOE award no. DE-FC26-02NT15133, p. 7-1 to 7-10.

Morgan, C.D., 2009b, Conventional southern Uinta Basin play, *in* Chidsey, T.C., Jr., editor, Major oil plays in Utah and vicinity: U.S. Department of Energy, National Energy Technology Laboratory, final report, DOE award no. DE-FC26-02NT15133, p. 8-1 to 8-11.

NETL (National Energy Technology Laboratory), 2012, Produced water management technology descriptions—Fact Sheet—Evaporation: Online, http://www.netl.doe.gov/technologies/pwmis/techdesc/evap/index.html, accessed May 31, 2012.

Phillips, F.M., 1979, Hydrogeology of the Bird's Nest aquifer, Uintah County, Utah: Tucson, University of Arizona, M.S. thesis, 165 p.

Scott, R.W., and Pantea, M.P., 1982a, Results of USGS oil-shale core drilling in the eastern Uinta Basin—Red Wash-1 drill hole: U.S. Geological Survey Open-File Report 82-965, 41 p.

Scott, R.W., and Pantea, M.P., 1982b, Results of USGS oil-shale core drilling in the eastern Uinta Basin, Utah—Coyote Wash-1 drill hole: U.S. Geological Survey Open-File Report 82-966, 58 p.

Smith, J.W., Trudell, L.G., and Robb, W.A., 1972, Oil yields and characteristics of Green River Formation oil shales at WOSCO EX-1, Uintah County, Utah: U.S. Bureau of Mines Report of Investigation 7693, 145 p.

Smith, M.R., Carroll, A.R., and Singer, B.S., 2008, Synoptic reconstruction of a major ancient lake system—Eocene Green River Formation, western United States: Geological Society of America Bulletin, v. 120, no. 1/2, p. 54–84.

Sprinkel, D.A., 2007, Interim geologic map of the Vernal 30′ x 60′ quadrangle, Uintah and Duchesne Counties, Utah, and Moffat and Rio Blanco Counties, Colorado: Utah Geological Survey Open-File Report 506DM, scale 1:100,000, compact disk.

Sprinkel, D.A., 2009, Interim geologic map of the Seep Ridge 30′ x 60′ quadrangle, Uintah, Duchesne, and Carbon Counties, Utah, and Garfield and Rio Blanco Counties, Colorado: Utah Geological Survey Open-File Report 549, scale 1:100,000, compact disk.

TOSCO Development Corporation, 1982, Sand Wash shale oil project—project description: technical report, 23.2–3 p.

U.S. BLM (Bureau of Land Management), 2012, Environmental Notification Bulletin Board: Online, https://www.blm.gov/ut/enbb/, accessed May 31, 2012.

U.S. EPA (Environmental Protection Agency), 2012, Underground Injection Control Program: Online, http://water.epa.gov/type/groundwater/uic/, accessed May 31, 2012.

USGS (U.S. Geological Survey) Oil Shale Assessment Team, 2010a, Oil shale resources of the Uinta Basin, Utah and Colorado: U.S. Geological Survey Digital Data Series DDS-69-BB, compact disk.

USGS (U.S. Geological Survey) Oil Shale Assessment Team, 2010b, Oil shale and nahcolite resources of the Piceance Basin, Colorado: U.S. Geological Survey Digital Data Series DDS-69-Y, compact disk.

U.S. NARA (National Archives and Records Administration), 2012, Title 40—Protection of Environment, Chapter I—Environmental Protection Agency, Subchapter D—Water Programs, Parts 144-147: Online, http://ecfr.gpoaccess.gov, accessed May 31, 2012.

Vanden Berg, M.D., 2008, Basin-wide evaluation of the uppermost Green River Formation's oil-shale resource, Uinta Basin, Utah and Colorado: Utah Geological Survey Special Study 129, compact disk.

Vanden Berg, M.D., Dyni, J.R., and Tabet, D.E., 2006, Utah oil shale database: Utah Geological Survey Open-File Report 469, compact disk.

VTN Colorado, Inc., 1977, Final environmental baseline report—Federal prototype oil shale leasing program tracts Ua and Ub, Utah: White River Shale Project.

Wallace, J., 2012, Baseline water quality for selected sites in the southeastern Uinta Basin, Utah: Utah Geological Survey Open-File Report 595, compact disk.

APPENDICES

APPENDIX A

BIRDS NEST AQUIFER AND OIL SHALE TOPS DATABASE

on CD: Appendix A - Tops database.xls

APPENDIX B

BIRDS NEST AQUIFER WATER CHEMISTRY DATABASE

on CD: Appendix B - Birds Nest water chemistry.xls