Preliminary Studies of Geothermal Resources—Northern Great Salt Lake Region, Utah

Robert E. Blackett, Mark L. Gwynn, Christian L. Hardwick, and Richard G. Allis

Utah Geological Survey

Keywords

Utah, Great Salt Lake, Box Elder County, geothermal, heat flow, thermal gradient, bottom-hole temperature

ABSTRACT

The northeastern Basin and Range Province surrounding Great Salt Lake of northern Utah has relatively high heat flow (> 100 mW/m^2) and other characteristics suggesting geothermal resource potential. Deep Neogene sedimentary basins, observed in wildcat oil/gas wells and geophysical surveys, underlying the main north and south arms of Great Salt Lake are separated into two troughs that include Gunnison Bay (north basin/trough) and Gilbert Bay (south basin/trough). Gravity data also suggests similar deep Neogene basins underlying Bear River Bay and the northern Wasatch Front, although deep drilling data are lacking in these areas. Beneath Gunnison Bay, more than 3 km of low-thermal-conductivity sediments and volcaniclastic deposits overlie Paleozoic and Precambrian carbonate, silicic, and metamorphic stratigraphic sequences that are known to have primary and secondary permeability elsewhere in the Great Basin. The thick basin-fill deposits within a region of high heat flow provide conditions for high (> 200°C) temperatures at depths between 3 and 4 km below the basin fill and within the Paleozoic and Precambrian rocks. Young volcanic rocks in the region include basalts, ranging in age between 2.2 Ma and about 28 ka, and rhyolite dated at about 2.1 Ma. Quaternary faults within and around Great Salt Lake, currently under investigation, likely contribute to fracturing within basement rock units, helping enhance permeability. The major thermal springs of the region all issue from fractured Paleozoic carbonate or Precambrian metamorphic rocks, equivalent to units projected beneath the thick basin-fill deposits in this region. Future development of geothermal resources in deep basins beneath Great Salt Lake may be challenging from technical, economic, and environmental perspectives, however, similar geologic conditions may exist beneath Bear River Bay and the northern Wasatch Front regions where development potential may be more attractive.

Introduction

Purpose and Scope

This paper describes the beginning of an effort to extend recent geothermal potential studies of deep sedimentary basins in

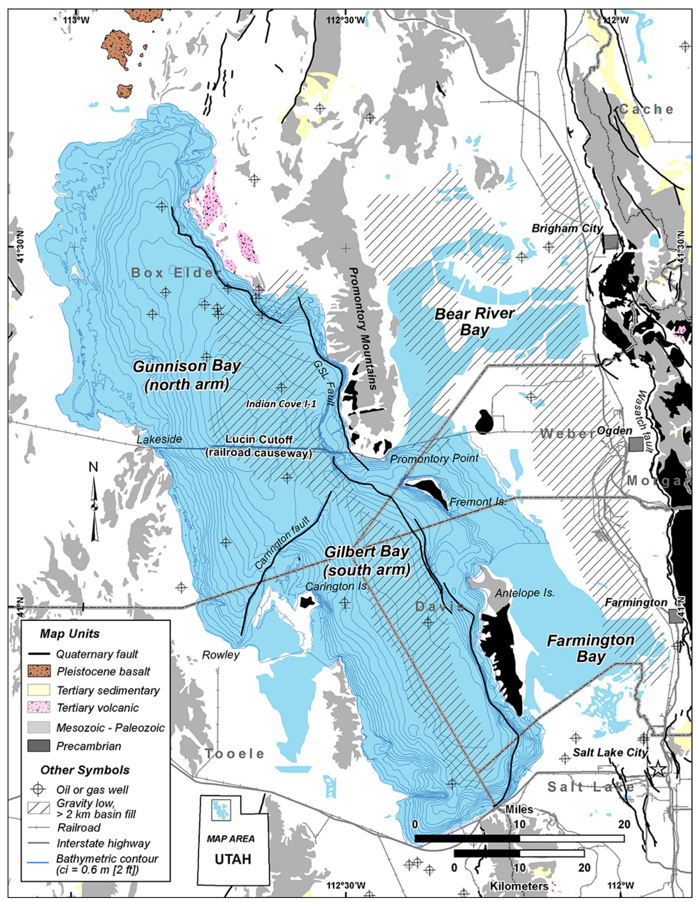


Figure 1. Great Salt Lake and surrounding region of northern Utah showing general geology and possible deep basins (gravity lows) with respect to Gunnison (north arm) and Gilbert (south arm) Bays. Hatch pattern depicts projected deep sedimentary basins from Saltus and Jachens (1995). Well symbols indicate oil/gas wells used in determining corrected bottom-hole temperatures and heat flow (Edwards, 2013).

west-central Utah (Sevier-Black Rock Desert), and northeastern Nevada (Marys River Basin and Steptoe Valley) into northern Utah (Allis and others, 2011, 2012). Deep Neogene basins in the northeastern Basin and Range high-heat-flow province suggest the possibility of large-volume geothermal resources beneath these basins in the region of Great Salt Lake (GSL) and the northern Wasatch Front. Potential geothermal reservoirs may exist within pre-Cenozoic (mostly Paleozoic and Precambrian), sub-horizontal bedrock formations underlying thick Neogene, fine-grained sediments that have characteristic low thermal conductivity. The thick "basin-fill" sedimentary section yields high thermal gradients where low thermal conductivity is combined with high heat flow. Below this sedimentary section at 3–4 km depth, temperatures within the pre-Cenozoic bedrock are known to exceed 200°C. The sub-horizontal "reservoir rocks," characterized as part of continued research, may eventually prove viable for development of large-volume geothermal resources.

Although deep sedimentary basins are present throughout the GSL region, this paper focuses primarily on the northern basin of GSL extending northward from the Lucin Cutoff, a railroad causeway connecting Promontory Point with Lakeside (figure 1). This part of GSL is known as the northern arm or Gunnison Bay. We discuss Quaternary volcano-tectonics, thermal water sources, oil and gas exploration wells and related bottom-hole temperature (BHT) data, and past geothermal exploration for this area. These geothermal-related elements are evaluated to suggest the presence of deep Cenozoic sedimentary basins and the potential for high-temperature (>150°C) geothermal reservoirs in bedrock units beneath the sediment-filled basins.

Land Management in GSL Region

Land ownership and management surrounding GSL comprises many private stakeholders, federal agencies, and state agencies. Lands extending eastward from the north and south arms of GSL are mostly private holdings comprised of rural agriculture lands near GSL to the urban corridor of the Wasatch Front where roughly eighty percent of the population of Utah (~ 2.9 million people) resides. U.S. Fish and Wildlife Service, Utah Division of Wildlife Resources, and the Utah Division of Forestry, Fire & State Lands (FFSL) are responsible for management of wetland areas mostly in and around Bear River Bay. Utah State Parks manages Antelope Island and Willard Bay State Parks. West of GSL are mainly public lands managed through the U.S. Bureau of Land Management (BLM), military lands of the Utah Test & Training Range, and scattered tracts managed through the Utah School & Institutional Trust Lands Administration (SITLA).

FFSL administers private, public and commercial uses of Utah Sovereign Land. Not to be confused with lands managed by SITLA, Utah Sovereign Land consists of the beds of Utah's navigable rivers and lakes including GSL. FFSL has direct management jurisdiction over lands below the GSL surveyed meander line. The surveyed meander line is not a constant elevation around the lake, but generally ranges from 1280.8 to 1283.8 m above mean sea level (amsl), sometimes crossing topographic features of higher elevation inland from the shoreline. However, the meander line is the adjudicated, fixed, and limiting boundary between sovereign land and upland owners. GSL is managed by FFSL under the Great Salt Lake Comprehensive Management and Mineral Leasing Plans (Utah Department of Natural Resources, 2013).

Physiography and Hydrography

Currey and others (1984) describe the GSL basin and the larger Lake Bonneville basin as situated in the northeastern Basin and Range physiographic province, which is typified by narrow, north-trending mountain ranges with intervening broad basins. The dominant north-south trending range in the center of the study region is the Promontory Mountains. The Promontory Mountains form the eastern limit of Gunnison Bay, which is bounded to the west by the Hogup Mountains, and to the north by the Hansel Mountains, North Promontory Range, and Blue Spring Hills. The Wasatch Mountains lie east of Bear River Bay (figure 2).

GSL is a terminal, hypersaline lake; a remnant of ancient glacial-age (28 ka–7 ka) Lake Bonneville (Currey and others, 1984). Changes in lake level are due to differences in net inflow and evaporation from the surface of the lake. At a water-surface altitude of 1280 m, a long-term average for GSL, the lake has a surface area of about 4300 km^2 and an average depth of 4.45 m. At GSL's average surface elevation (1280.2 m), the deepest part is in southern Gunnison Bay where depth is 10 m (Baskin, 2006).

The main body of GSL (figure 1) lies west of the Promontory Mountains and Antelope Island and consists of two bays, Gilbert Bay (southern) and Gunnison Bay (northern). Gunnison Bay is

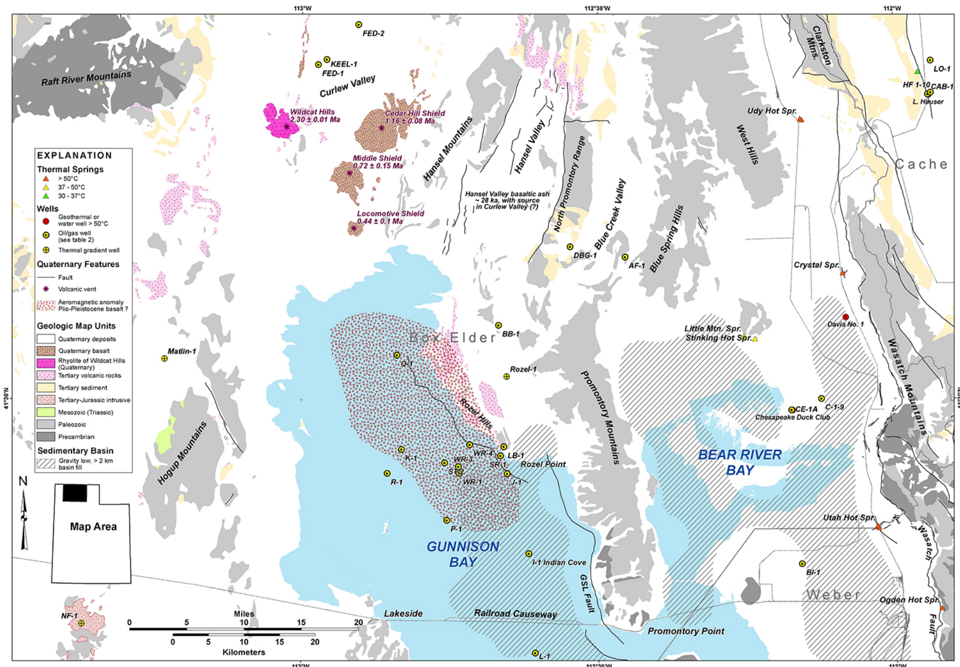


Figure 2. Northern Great Salt Lake study region showing geology and geothermal-related elements described in the text. Well labels refer to the summary information listed in table 2.

defined as that part of the lake north of the Lucin Cutoff (railroad causeway). Atwood (2006) presents a comprehensive description of GSL, and a history of the building of the Lucin Cutoff and the resulting effects to GSL.

Bathymetry of GSL (Baskin and Turner, 2006; Baskin and Allen, 2005) shows two left-stepping troughs, both trending south-southeast within GSL separated by a threshold[1] at about 1272 m amsl. The threshold is bounded to the east by an abrupt step just southwest of Promontory Point. The railroad causeway appears to bisect the Gunnison trough. On the south end of the Gunnison trough, the elevation of the nearly flat, lowest surface of the lake bed is about 1270 m. The threshold landform at 1272 m elevation forms the southern boundary of the Gunnison trough and is the natural sill separating the Gunnison and Gilbert troughs. South from this sill, the broad low part of the Gilbert Bay trough lies about 1271 m elevation. A submerged cliff-like feature appears in the bathymetry beginning just north of Rowley and extending northeastward toward Promontory Point. This is the Carrington fault (Holocene) described by Dinter and Pechmann (2005); it appears to relate to the left-step between the Gilbert and Gunnison troughs, notably oblique to other Basin and Range faults.

Stratigraphic Geothermal Resource Concept

High-temperature hydrothermal systems in the Great Basin related to high-angle normal faults and associated fractures that allow up-flow of geothermal fluids from depth are typically developed for power generation. These hydrothermal systems are often difficult to find and are relatively limited in size. Improved drilling technologies, however, may lead to developing large-scale power production from laterally extensive hot-water reservoirs in deep, high-heat-flow basins. Allis and others (2011, 2012, and 2013) describe the concept of basin-centered geothermal resources in sub-horizontal, stratigraphic reservoirs in regions of high heat flow. Potential geothermal reservoirs lie beneath thick sequences of unconsolidated sediments and shale with low thermal conductivity. Oil and gas exploration wells and water wells in the Great Basin have proven the existence of laterally extensive, high-permeability zones within Paleozoic carbonate rocks in the large, non-magmatic, high-heat-flow region of the Great Basin (Allis and others, 2011, 2013; Blackwell and Richards, 2004). An area of lower heat flow in the south-central part of the Great Basin defines a hydrologic heat sink due to inter-basin flow of water in carbonate rocks southward toward the Colorado River (Lachenbruch and Sass, 1977).

In general, the northern Great Basin has not been flushed by ground water, and typical heat flow here is 85 ± 10 mW/m^2 (Blackwell, 1983). This yields gradients of about 30 – 40ºC/km in bedrock formations (beneath the ranges), and about 55 – 75ºC/km in unconsolidated sediments and shale sequences (beneath the basins) due to the insulating effects of lower thermal conductivity sediments in basins. The potential exists for temperatures of 150 – 300ºC at 3 – 5 km depth in basins with thick basin fill, as supported by several oil exploration wells in the eastern Great Basin (> 200ºC at 3+ km depth). The main unknown about the geothermal potential is whether there is laterally extensive permeability in the 3 – 5 km depth range. The geologic evidence for near-horizontal Paleozoic formations at depth across much of the Great Basin, some of which are known to have characteristically high permeability, suggests the potential for a significant geothermal resource potential beneath the basins (Allis and others, 2011, 2012).

Allis and others (2011) offer three examples of deep wells that demonstrate this concept where a thick sequence of low thermal-conductivity, Neogene sediments overlie potential reservoirs comprised of pre-Cenozoic bedrock. Two of the wells (Pavant Butte 1 and Accord-1) are located in the Sevier-Black Rock Desert region of southwestern Utah. The third example is the Indian Cove (I-1) well drilled in 1978 by Amoco Production Company within Gunnison Bay of GSL.

As Basin and Range extension opened intermontane valleys between north-south trending mountain ranges over the past several million years, sediment filled the valleys, achieving sometimes more than 4 km in thickness. The combination of high heat flow and thick, fine-grained valley fill can yield elevated thermal gradients with equilibrium BHTs of > 230°C.

Geology and Geothermal-Related Resources

Geologic Setting

Doelling and others (1980) describe the unconsolidated and bedrock units in the northern GSL region. Consolidated rock units, mostly marine sedimentary and metamorphosed sedimentary rocks, range in age from Precambrian to Triassic (21 km thick). Jurassic and Cretaceous rocks are absent. Unconsolidated units are Neogene and Quaternary in age and fill broad basins between mountain ranges. Precambrian rocks are exposed in the Raft River, Promontory, and Wasatch Mountains (figure 2).

GSL is situated in the northeastern region of the Basin and Range physiographic province, characterized by series of north-south trending fault-bounded mountain ranges separated by wide valleys containing mostly semi-consolidated to consolidated Neogene sediment and volcanic rock. Extension over the past 20 million years has thinned brittle crust thereby breaking it into north-trending blocks, which either rotated or subsided to produce basins and ranges. Regional subsidence along the eastern margin of the province formed the Lake Bonneville basin. Pleistocene and Holocene fluvial and lacustrine sediment and some Pleistocene volcanic rocks overlie the Neogene basin fill.

Gunnison Bay lies in the central part of a north trending basin. Bedrock exposed around the bay ranges in age from Precambrian metamorphic units to Pleistocene basalt. Using observations of Miller (1997a), Atwood (2006) suggests that the topographic features of the region have resembled their present configuration for about the past 3 million years, and that the broad expanses of valley fill and wide distribution of Cenozoic sediments indicate that the region has been a center of sedimentation over that period and longer. Bortz (2002) noted that a volcanic tuff, yielding a fission-track age of 29.9 ± 1.3 Ma (Oligocene), penetrated in an Amoco well (L-1 on figure 2) at total depth (3679 m), indicates that locally some Paleogene units may underlie the Neogene units beneath GSL. Bortz (2002) also projected that, based on deep drilling data and seismic profiles, the deepest part of the north basin is near wells I-1 and L-1, where the total Tertiary section may be between 4300 and 4600 m thick.

Based on the work of Cook and others (1989), Atwood (2006) identified a large, north-trending gravity low, approximately coincident with portions of Gunnison and Gilbert Bays (figure 1). The gravity low is thought to be due to a thick section of relatively low-density Cenozoic sediments and volcanic rocks that underlie the east side of Gunnison Bay and extend south into Gilbert Bay. Drilling by Amoco (Bortz, 2002; Gwynn, 2006) showed that the gravity low is underlain by mainly Neogene units over 1830 m thick in the northern part of Gunnison Bay and over 3660 m thick in the southern part. Deeper parts of the basins in this region are shown by the hatch pattern on figure 1. This pattern represents the projected region of sediment accumulation in Neogene basins of more than 2000 m, as derived from gravity modeling of Saltus and Jachens (1995).

Atwood (2006) also noted that a large regional aeromagnetic high (from Zietz and others, 1976) is nearly coincident with the axis of Gunnison Bay, and can be largely explained by Cenozoic volcanism, including possible Quaternary basalt within lake sediments (see following discussion).

Quaternary Volcanism

Miller (1997b) and Miller and Langrock (1997a, b) describe basalt erupted to form three shield volcanoes along the east side of Curlew Valley (figure 2). Cedar Hill Shield (K-Ar 1.16 ± 0.08 Ma) is the largest at 215 m high and 5.5 km in diameter; Middle Shield (K-Ar 0.72 ± 0.15 Ma) is 140 m high and 4 km in diameter; and Locomotive Shield (K-Ar 0.44 ± 0.10 Ma) is 35 m high and 2 km wide. Smaller outcrops of basalt to the east and north of these shields are likely remnants of flows from these volcanoes.

Miller and others (2008) describe a basaltic ash bed of Late Pleistocene age (~28,000 years), identified at many locations in northern Utah, with a likely source area in Curlew Valley. They refer to the ash as the Hansel Valley ash because Hansel Valley contains the most outcrops of the bed. The Hansel Valley ash bed is dark brown and forms a distinctive bed between 5 to 10 mm thick near the base of the pale-colored marl of Lake Bonneville. The marl ranges in age from about 29,000 to 14,000 years. The ash bed is near the base of the marl, which yields radiocarbon dates on distributed organic material in cores. Oviatt and Miller (1997) established that the ash fell into Lake Bonneville when the lake was about 60 m deep at an altitude of about 1335 m

Miller and others (2012) provide mapped descriptions of Quaternary basalt (Qb), that yielded an 40Ar/39Ar groundmass age of 2.21 ± 0.02 Ma (Felger and others, in preparation), and Pleistocene Rhyolite of the Wildcat Hills (Qwr), which yielded a K-Ar sanidine age of 2.1 ± 0.1 Ma (Miller and others, 1995) (figure 2).

The Utah Geological Survey (UGS) in partnership with the U.S. Geological Survey (USGS) carried out an aeromagnetic survey in a region that included GSL in 2011. This survey shows a broad magnetic anomaly in the north arm of GSL where oil and gas exploratory drilling identified young (Pliocene-Pleistocene?) basalt within the upper part of the basin-fill sequence beneath GSL. Bortz (2002) projects a lateral extent of the basalt, referred to as the Pliocene "West Rozel" basalt and composed of numerous flows that probably came from volcanic vents in the northwestern part of the Rozel Hills. The approximate outline of the aeromagnetic anomaly in GSL from the 2011 survey that is believed to represent the bulk of the "West Rozel" basalt is shown on figure 2. This basalt forms the reservoir rocks for oil accumulations in the Rozel Point - West Rozel oil field discussed below.

Neogene - Quaternary Structure

The eastern Great Basin is tectonically active. Seismic profiles within GSL (Bortz, 2002) document normal faults in Gunnison Bay, along with other evidence of tectonism such as surface faulting, distribution of Paleozoic bedrock, and morphology of the Gunnison-Gilbert troughs. Faults in this region are shown on the Quaternary fault map of Utah (Hecker, 1993; Black and others, 2003) (figure 2). The eastern bounding fault for Gunnison and Gilbert Bays, named the East Great Salt Lake fault (EGSLF) by Cook and others (1980), is also called the Great Salt Lake fault. Dinter and Pechmann (2005) describe the EGSLF as an active, segmented, west-dipping normal fault submerged beneath GSL and situated 30 - 65 km west of the Wasatch fault (figure 1). The footwall is marked by a discontinuous topographic high defined, from north to south, by the Promontory Mountains, and by Fremont and Antelope Islands. The north and south main basins of GSL, containing possibly more than 4000 m of Neogene sediment, lie west of the EGSLF in its hanging wall (Dinter and Pechmann, 2005).

Atwood (2006) also reported that Gunnison Bay may have experienced historical fault displacement and ground shaking associated with historical earthquakes. Utah's seismograph networks have had the capabilities to precisely identify epicenters of Utah earthquakes only since about the 1950s. According to newspaper accounts, the 1909 Hansel Valley earthquake, estimated at a Richter magnitude of 6 (~ 6 M), reportedly caused a water wave on GSL which overtopped the 3.5 m high railroad causeway, continued to GSL's southern shore and sent water across the bath-house pier at Saltair resort. The Hansel Valley earthquake of 1934 (6.6 M) reportedly caused down-to-the-east scarps with vertical displacement of about 50 cm and horizontal displacement of about 25 cm along a rupture length of about 11 km (DuRoss and Hylland, 2011).

Bortz (2002) uses palynology to correlate Miocene through Pleistocene sediments in the north arm, showing Miocene sediments extending to +3660 m in the Amoco Indian Cove (I-1) well. The well Amoco L-1 (Bridge Well), located about 6 km south of the railroad causeway, reportedly penetrated a volcanic tuff at TD (3680 m) which yielded a zircon fission-track date of 29.9 million years (29.9 Ma, Oligocene) (figure 2). Bortz (2002) projected Precambrian rocks just below the measured total depth of well L-1.

Oil and Gas Occurrences, Amoco Indian Cove Well, and Cenozoic Basins

Gwynn (2006) provides an overview of exploration for oil and gas in Box Elder County for the past century, reporting that more than 110 exploratory wells have been drilled. Tar-like seeps of heavy, high-sulfur oil occur at Rozel Point and were explored by well drilling beginning in about 1904. Since then operators drilled numerous wells, however, none are currently producing. Amoco Production Company conducted an extensive exploration program in and around GSL in the late 1970s and early 1980s, drilling 15 wells and establishing the West Rozel oil field (Bortz, 2002). Amoco's production operations at the West Rozel field ended in late 1980 due to "the high water cut in the produced oil, and the high cost of operating an 'offshore' field" (Gwynn, 2006).

Bortz (2002) reported that the West Rozel oil field produced from fractured Pliocene basalt at depths between 640–730 m.

The trap is a faulted, closed anticline covering about 930 ha. The Amoco No. 1 West Rozel Unit discovery well reportedly had an oil column of 88 m but produced at a rate of only 2 to 5 barrels of oil per hour. The oil is 4° API gravity, contains 12.5% sulfur, and has a pour point of 24°C.

Natural gas has been encountered in a number of wells, mainly in the area west from Brigham City and east of the Bear River National Wildlife Refuge. None of the wells has sustained production for many years, however. The Chesapeake Duck Club is located in this area, and wells drilled there reportedly encountered thermal water and natural gas. These wells are discussed in the following sections.

The Amoco Indian Cove (I-1) oil test, drilled and completed by Amoco Production Company in November 1978 (Doelling and others, 1980), encountered higher than expected temperatures (a measured BHT of 214°C) at total depth of 3800 m. Correcting the BHT[2] data for the Indian Cove well yielded an estimated in situ BHT of 230°C. Mud and sample logs dated 20 October 1978 available through the Utah Division of Oil, Gas and Mining (DOGM) yielded geologic intercepts for the Indian Cove well shown on table 1. These intercepts indicate that Cenozoic valley fill in the Indian Cove well is about 3780 m in thickness.

Table 1. Geologic intercepts reported by Utah DOGM in the Amoco Indian Cove (I-1) well.

Geologic Intercept	Depth, feet	Depth, meters
Pleistocene/Pliocene	1094	333
Pliocene/Miocene	4248	1295
geologic marker	5656	1724
volcanic tuff	5808	1770
color change	6182	1884
anhydrite	9700	2957
volcanic ash	10,240 -10,318	3121-3145
Farmington Can. Complex (p€)	12,416	3784
total depth	12,470	3801

Seismic reflection studies by Mikulich and Smith (1974) indicated that Cenozoic basin-fill increases southward from near Rozel Point to about the railroad causeway, and continues to deepen southward. Well Amoco L-1, reported previously, substantiates the observation for deepening of basin-fill southward.

Northern Wasatch Front Thermal Springs

Six areas of significant thermal springs (figure 2) are located along the Wasatch Front[3] in the study region. Brief descriptions of the springs follow.

Udy Hot Springs, also known as Belmont Springs, issue near the town of Plymouth in northeastern Box Elder County on the flood plain of the Malad River. The springs consist of a number of seeps on the western flank of the river, and flow from fractured Paleozoic limestone. Temperatures range from 34° to 53°C. The springs are situated between the Wasatch Range on the east and the West Hills to the west. The two ranges are separated by Basin and Range structures beneath the Malad River Valley (Murphy and Gwynn, 1979). Water is a sodium-chloride type with TDS values approaching 8,400 mg/L.

Crystal (Madsen) Hot Springs are the source waters for Crystal Springs Resort located just north of the town of Honeyville. The springs flow from the base of a small salient of fractured Paleozoic rocks extending west from the Wellsville Mountains at temperatures between 49.5°C and 57°C. Murphy and Gwynn (1979) reported that one thermal-gradient borehole at the site reached a depth of 67 m and yielded a BHT of 61ºC. The springs and seeps drain southwest along Salt Creek with estimated discharge at a rate of about 15,300 L/min. The main hot spring discharges at about 6370 L/min. Water is a sodium-chloride type with TDS values above 46,000 mg/L, the highest of any spring in Utah.

Little Mountain Warm Spring and Stinking Hot Spring are located about 10 km southwest of Bear River City. The springs issue from faulted Mississippian limestone at the base of the south end of Little Mountain. Stinking Hot Springs get their name from the presence of hydrogen sulfide gas in the vapors. Temperatures range between 39.5° and 51°C. Discharge ranges from 19 to 170 L/min. TDS content of the sodium chloride-type water ranges from 29,000 to 37,000 mg/L. Klauk and Budding (1984) suggest that both Little Mountain Warm Spring and Stinking Hot Spring may be related to the same fault system and reservoir rocks.

Utah Hot Springs, located about 13 km northwest of Ogden just west of the Pleasant View salient along the Box Elder-Weber County line, issues from alluvium near outcrops of complexly faulted Cambrian quartzite, shale, dolomite, and limestone. Temperature is fairly constant, ranging from 57.5° to 58.5°C. Thermal water, once used for swimming pool and spa heating, is used for space-heating a small greenhouse. Klauk and Budding (1984) reported the water as sodium-chloride type, ranging in TDS from 18,900 to 25,200 mg/L.

Ogden Hot Spring, located at the mouth of Ogden Canyon on the east side of Ogden in Weber County, issues from fractures in Precambrian rocks along the Ogden River. Nelson and Personius (1993) show the surface trace of the Wasatch fault a few tens of meters west of the springs. Undoubtedly, some (or even most) of the bedrock fractures near the springs are associated with the Wasatch fault. Since the late 1800s, workers have reported temperatures for the springs ranging from 49°C to 66°C, but averaging about 57°C (Mundorff, 1970). Flow rates recorded for the springs have been as high as 380 L/min, although most records indicate that the flow rate is about 132 L/min. TDS content of the sodium-chloride-type water from the springs generally varies from 8650 to 8820 mg/L.

Chesapeake Duck Club Wells

Goode (1978) reported that in 1925, a 153-m water well was drilled for the Chesapeake Duck Club about 13 km west-southwest of Brigham City (figure 2). The well reportedly produced gas and fluid at a temperature of 74°C and was later plugged. Goode (1978) also reported that a second well was drilled to a depth of 152 m and was also plugged due to gas production. No temperature was recorded for the second well. The two wells are located in an area where faulting was noted by Bjorklund and McGreevy (1973, 1974). The faults, which may have been encountered during drilling of these wells, may be conduits for thermal fluid circulation (Klauk and Budding, 1984).

Davis No. 1 Geothermal Well

The Davis No. 1 geothermal well, located about 13 km northwest of Brigham City (figure 2), was a joint venture between Utah Power & Light Company and Geothermal Kinetics, Inc. The well was completed on 22 August 1974 and the total drilled depth was 3354 m. Goode (1978) suggested that the BHT was 105°C, lower than anticipated, and reported a dissolved solids content of the fluid of 85,000 mg/L. A later review of geophysical log headers for the Davis #1 well by one of the authors (Blackett) indicated that uncorrected BHTs were at least 131°C.

Jensen and King (1999) presented interpretations of the geologic units penetrated by the Davis No. 1 well based on cuttings and geophysical logs. They placed the base of the valley-fill (Quaternary) units between 177 and 207 m. They placed the base of Tertiary units (Salt Lake Formation) and the top of pre-Cenozoic rocks (Paleozoic carbonate) between 1335 and 1353 m. They also placed the intersection of upper Proterozoic rocks of the Caddy Canyon Formation at a fault contact near 2391 m, and the upper Proterozoic Maple Canyon Formation between 3179 and 3228 m.

Austin and others (2006) described the Renaissance geothermal project, based upon unpublished proprietary data gathered from the Davis No.1 well at the time of drilling. They reported that the well spontaneously flowed while drilling between the depths of 2504 m and 2530 m. The flow rate to the surface from this interval was measured at 13,250 L/min. The temperature of this flow was measured at 141°C, and they considered this temperature as a minimum value, taken from the expanded fluid at the surface, from the "blooie" line, and not representative of the temperature of the fluid in the reservoir. They refer to anecdotal information that down-hole temperatures approached 200°C. They also reported a chemical analysis of fluid produced from the 2477 – 2530 m interval as brine with a TDS content of 54,305 mg/L, and that produced from the lower, uncased part of the well as brine with a TDS content of 95,230 mg/L. Austin and others (2006) disagreed with the interpretations by Jensen and King (1999), suggesting that the well bottomed in upper Paleozoic strata rather than Cambrian or Precambrian rocks.

Thermal Studies

Edwards (2013) included the Great Salt Lake region as part of a geothermal assessment of the Basin and Range Province of western Utah. His assessment combined new and existing heat flow determinations (~500 total), surface ground temperatures established continuously throughout Utah, and a comprehensive thermal conductivity database (> 2300) for Utah geologic units. He also used measured BHTs from oil and gas wells in the region, and corrected them to estimate equilibrium temperatures using the methods of Henrikson (2000). Table 2 gives a summary of oil and gas wells (shown on figure 2) used by Edwards (2013) to determine BHTs and heat flow in this region. Edwards (2013) predicts that the northwest-southeast axis of the GSL basin (Gunnison and Gilbert Bays) is part of a broad swath of elevated heat flow exceeding 100 mWm^{-2}. He concluded that the depth to the 150°C isotherm was less than 3 km across the GSL basin and that the combination of elevated heat flow, low thermal conductivity sediments, and depth to basement ". . . result in temperatures and thermal potential that flag the region as prospective and a priority for geothermal exploration." He further points out that geothermal resource potential here is favored when coupled with the proximity to population centers, and utility and transportation corridors along the Wasatch Front.

Rozel-1 and Matlin-1 Thermal Gradient Wells

The U.S. Geological Survey's Geology, Minerals, Energy, and Geophysics Science Center (USGS/GMEG), in cooperation with the UGS, drilled and completed two thermal gradient wells adjacent to the north arm of Great Salt Lake during fall 2012. The wells, named Rozel-1 and Matlin-1, were completed to 186 m and 125 m, respectively. The Rozel-1 and Matlin-1 wells are situated on opposite sides of Gunnison Bay (figure 2) and were drilled by the USGS Western Region Research Drilling Program. Drill cuttings were collected over 3 m intervals, sealed in plastic bags, and preserved for thermal conductivity, X-ray diffraction, and other studies. Samples from Rozel-1 comprised mainly clay and sand with some gravel, and as much as 27 m of basalt between about 119 m and 146 m depth. Samples from Matlin-1 comprised mainly coarse sand, gravel, and some clay. Drilling of Matlin-1 was terminated following total loss of circulation after penetrating fractured, cavernous basalt at about 120 m. Both wells were completed with 5-cm diameter schedule-80 PVC pipe, sealed and filled with fresh water for temperature profiling. Bentonite grout (30 percent solids) fills the annulus between the PVC and wellbore.

Wireline geophysical surveys (gamma, electric, and sonic) were acquired by the UGS Groundwater Program in the Rozel-1 and Matlin-1 thermal-gradient wells. The interpreted lithologies from the wireline logs were consistent with those observed in the drill cuttings. These data sets were submitted to the National Geothermal Data System (www.geothermaldata.org) and are also available at http://geology.utah.gov/geothermal/ngds accessible through hyperlinks under the heading "Supplemental Data Collection."

Temperature-depth profiles were recorded more than 105 days after well completion at each site to eliminate drilling–induced temperature disturbances (figure 3). Logging equipment and procedures are described in Blackett (2011) and Gwynn and others (2013).

Thermal conductivity measurements (figure 3) were conducted on the recovered drill cuttings using divided-bar equipment at the USGS/GMEG in Menlo Park, California. Uncertainty for chip samples on this equipment is considered to be about ±5% (Colin Williams, USGS, Personal Communication, 17 March 2014). The USGS results were reported as matrix conductivity, so these values were adjusted using sonic porosity from the geophysical logging to estimate the in situ thermal conductivity. Additional thermal conductivity measurements were made on the fine–grained samples by UGS personnel using a Decagon Devices KD2 Pro Thermal Properties Analyzer (needle probe). The specified accuracy for the needle probe is ±10%, which is about ±0.15 W/m·K for these samples.

In the Rozel-1 well, 10 of our needle probe measurements duplicated USGS/GMEG measurements using the divided bar. Differences in these samples were smaller than ± 0.2 W/m·K for all but one sample (- 0.5 W/m·K). Average needle probe values for the duplicated samples were 1.50 W/m·K compared to 1.52

Table 2. Wells used for corrected BHT determinations in the GSL North study region by Edwards (2013). See Figure 2 for well locations.

Well Name	API No.	Label (Fig. 2, 4)	Operator	Drill Depth (m)	Measure Depth (m)	Measure Temp (°C)	Correct Temp (°C)	Measure Date
Adams Fee 1	4300310409	AF-1	Gulf Oil	2731	2733	74.4	89.0	8/5/1963
Leonora-Bullen 1	4300310410	LB-1	Gulf Oil	744	744	75.6	81.3	12/7/1963
State-Rozel 1	4300310411	SR-1	Gulf Oil	1068	1068	61.1	68.0	2/11/1964
Federal 2	4300311401	FED-2	Utah Southern Oil	2305	2307	85.6	97.1	9/27/1956
Bar-B 1	4300320071	BB-1	Utah Southern Oil	871	871	19.4	23.8	10/27/1951
Federal 1	4300320089	FED-1	Utah Southern Oil	1970	1971	70.0	79.9	1/12/1956
Keeler 1	4300320091	KEEL-1	Utah Southern Oil	1451	1452	76.1	83.4	12/1/1954
ST of UT I 1	4300330002	I-1	Amoco Production	1076 2400 3801	1077 2402 3796	64.4 138.9 213.9	76.3 149.4 235.0	7/6/1978 8/11/1978 10/15/1978
West Rozel ST U 1	4300330003	WR-1	Amoco Production	865 2591 2591	834 1878 2592	39.4 66.1 98.9	42.4 77.2 101.7	12/9/1978 2/2/1979 2/3/1979
ST of UT J 1	4300330007	J-1	Amoco Production	732 2075 2073	729 2033 2073	46.1 94.6 100.0	48.6 100.4 115.6	3/3/1979 4/9/1979 4/9/1979
ST of UT K 1	4300330008	K-1	Amoco Production	1369	1279	53.3	58.1	5/18/1979
West Rozel St 2	4300330009	WR-2	Amoco Production	714 824	708 827	36.7 55.6	39.1 58.4	5/29/1979 6/12/1979
ST of UT L 1	4300330010	L-1	Amoco Production	3490 3490 3679	2868 3492 3672	143.5 151.1 148.3	154.1 168.0 190.3	3/4/1980 3/4/1980 3/16/1980
West Rozel St 3	4300330014	WR-3	Amoco Production	680 850	677 852	50.0 48.9	52.6 55.4	7/26/1980 8/9/1980
West Rozel St 4	4300330015	WR-4	Amoco Production	674	674	37.8	42.3	11/13/1980
ST of UT P 1	4300330016	P-1	Amoco Production	1033 2391	1025 2389	43.9 96.7	45.5 100.0	9/1/1980 10/4/1980
ST of UT Q 1	4300330017	Q-1	Amoco Production	369 1488	366 1486	25.6 57.6	26.9 59.8	11/20/1980 12/11/1980
Donald B Green 1	4300330018	DBG-1	WEM Petroleum	609	610	30.0	32.0	10/7/1980
ST of UT R 1	4300330020	R-1	Amoco Production	522	501	44.4	47.8	12/20/1980
Christensen 1-9	4300330021	C-1-9	Burnett Oil	1829	1829	68.9	76.4	8/3/1981
Chesapeake Co 1A	4300330023	CE-1A	Burnett Oil	1020 1402	1020 1408	74.4 84.4	81.4 87.2	6/27/1981 7/9/1981
C A Brown 1	4300510611	CAB-1	Karmis Oil & Gas	1587	1588	76.7	84.6	5/27/1957
H. & V. Clark 3	4300530011	HVC-3	WEM Petroleum	916	919	32.8	34.7	6/27/1981
Lower 1	4300530012	LO-1	Drillco	511	482	52.2	54.3	7/16/1981
Hauser Farms 1-10	4300530013	HF-1-10	North American	2195	2192	88.9	95.9	10/25/1984
Hauser Farms 7-10	4300530014	HF-7-10	North American	1615	1624	68.9	73.2	12/30/1984
Basin Inv. Co 1	4305730001	BI-1	Burnett Oil	308 1468	300 1470	36.7 75.0	38.7 75.8	8/14/1981 8/25/1981
Newfoundland-1	9900300015	NF-1	Chapman, 1978	153	153	17.0	17.0	9/30/1978
Matlin-1	9900300053	Matlin-1	UGS, 2013	125.8	125.8	20.3	20.3	3/13/2013
Rozel-1	9900300054	Rozel-1	UGS, 2013	185.5	185.5	21.8	21.8	3/13/2013

W/m·K for the divided bar. Only 4 of our needle probe measurements were duplicated with the divided bar for the Matlin-1 well.

Heat-flow values for each well were calculated by entering thermal conductivity data into geotherm[4] models generated using a spreadsheet. These models adjust the heat flow value (product of geothermal gradient and thermal conductivity) to calculate and plot the temperature gradient over the defined intervals. The heat flow value can then be adjusted to yield a calculated temperature–depth plot that is coincident with appropriate (linear/conductive) segments of the measured temperature–depth plot to determine the heat flow. Thermal conductivity data gained from both methods were used for discreet sample intervals while divided-bar results were used for duplicated intervals.

The Rozel-1 temperature profile is largely non-linear, which in a conductive thermal regime will be due primarily to changes in lithologies where thermal conductivities differ. Unfortunately, the profile shift at about 35 m suggests a subsurface cross flow of slightly warmer water. The similar, but less pronounced, profile shift at about 135 m may also indicate a cross flow. The advective signatures in the well complicate making accurate calculations of heat flow. The calculated geotherm for most of the length of the well does deflect slightly with changes in lithology (thermal conductivity), but is more linear than the measured temperature plot and does not correlate well. This geotherm results in a heat flow of 49 mW/m². The bottom 34 m of the temperature profile is more linear and may reflect a more conductive zone. The geotherm and temperature data in this segment match reasonably well and yield a heat flow value of 44 mW/m². Although the overall temperature–depth profile appears to somewhat track along with the typical Basin and Range bedrock gradient of 36°C/km, the low heat flow suggests that the well may be artificially cooled by substantial groundwater flow. The heat flow map of Edwards (2013) suggests the heat flow in this well should be about 105 mW/m² while the heat flow map of Blackwell and others (2011) suggests that the well should fall in the 95-100 mW/m² range.

The Matlin-1 temperature profile is somewhat linear below about 40 m, and the gradient calculated from 96 m to total depth at 126 m is about 49°C/km. Material within this interval is valley-fill material consisting mainly of alternating clay, silt, sand, and pea gravel. Basalt was penetrated below about 120 m, which coincides with the largest deflection of the temperature profile. Such a deflection should be expected, based on the lithology change and probable differences in thermal conductivities. The overall profile suggests that the well is largely conductive. A geotherm model from 52 to 118 m matches reasonably well with the measured temperature plot and results in a calculated heat flow of 92 mW/m², slightly higher than the product of the average gradient and thermal conductivity over this section of the well bore (88 mW/m²). The heat flow value of 92 mW/m² is reasonably close to the heat flow values of about 100 mW/m² predicted by Edwards (2013) and fits within the 90-95 mW/m² range from Blackwell and others (2011). High heat-flow areas of the Great Basin typically exhibit values of 80-100 mW/m² (Lachenbruch and Sass, 1977; Blackwell, 1983; Blackwell and others, 1991; Tester and others, 2006), and the Matlin-1 well falls into this range.

Well NF-1, situated about 40 km southwest of the Matlin-1 well (figure 2), was drilled (total depth 152.5 m) into a Late Jurassic (158–147 Ma) quartz monzonite intrusive complex, part of the Newfoundland Mountain range, described by Allmendinger and Jordan (1989). The temperature profile is linear with a thermal gradient reported by Chapman and others (1978) of 30°C/km, an average thermal conductivity of 2.38 W/m•K, and a calculated heat flow of 71 mW/m². Edwards (2013) included this well in his heat flow map, which contributes to a lower heat flow anomaly in this area. The anomaly is not reflected in the heat flow map of Blackwell and others (2011), where heat flow is predicted to be 90-95 mW/m².

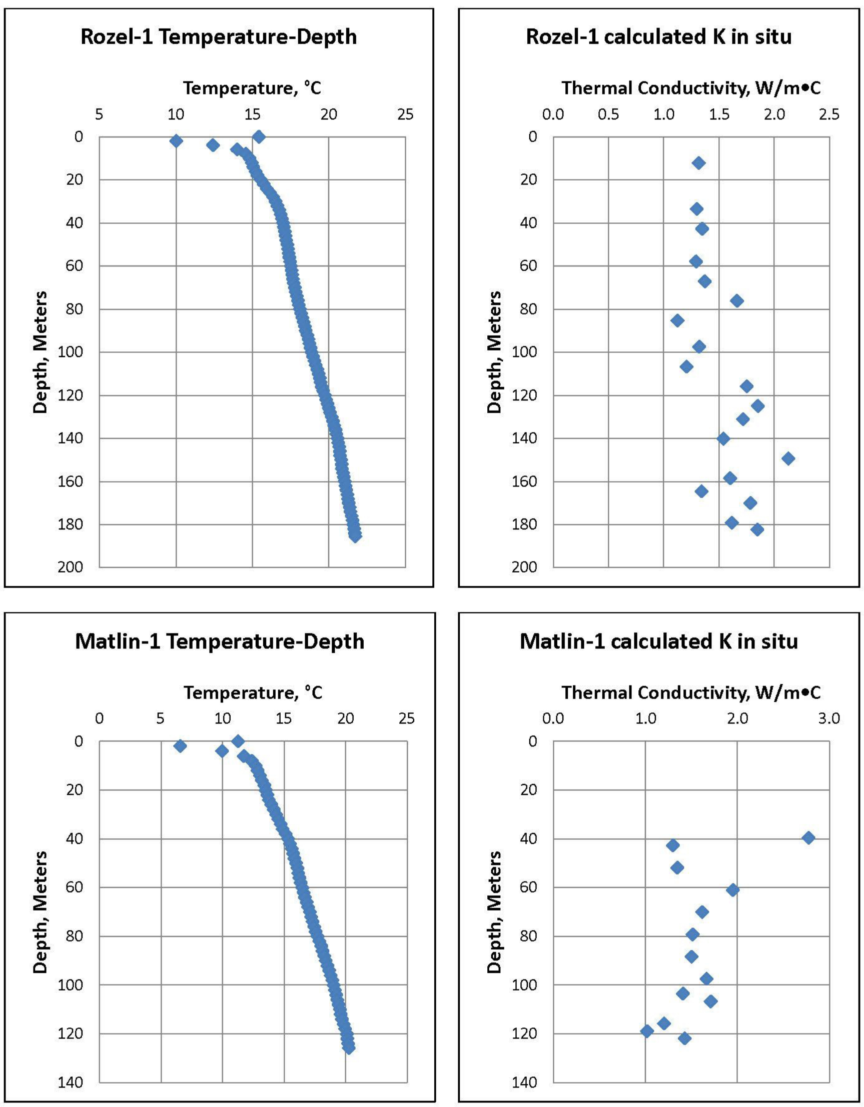
Discussion

GSL lies within several Neogene basins where locally more than 4000 m of sediments have accumulated. The region is also part of the northeastern Basin and Range Province, where, because of crustal thinning, heat flow is elevated with respect to the adjacent Rocky Mountains and Colorado Plateau provinces, sometimes exceeding 100 mW/m². Basin-fill sediments beneath GSL are commonly fine-grained lacustrine deposits and volcaniclastic units with relatively low thermal conductivity (< 2 W/m°C) with respect to bedrock units exposed in surrounding mountains.

Pleistocene volcanic rocks, mostly middle to upper Pleistocene basalt with less voluminous lower Pleistocene rhyolite flows, are spread out over an area of roughly 24 by 32 km north of GSL. Pliocene volcanic rocks, also present throughout the region, indicate a period of several million years of ongoing volcanism. A large aeromagnetic anomaly within Gunnison Bay probably reflects the presence of basalt (West Rozel basalt) within lake sediments; the Rozel Hills to the east are possibly the source of the basalt. The region is also situated within the Intermountain seismic belt, a zone of seismicity that runs north-south through the Intermountain region from northwestern Montana through Wyoming, Idaho, and Utah, and into southern Nevada/northern Arizona. Quaternary faults bounding the Promontory and Wasatch mountains as well as other ranges are evidence of active seismicity.

Hydrothermal convection systems manifest through a number of hot springs located mostly along the Wasatch Front, spatially associated with the Wasatch and other Basin-and-Range faults. Hydrothermal resources have also been reported during drilling either for water (Chesapeake Duck Club wells) or as a result of geothermal exploration (Davis No. 1 well).

BHTs from oil and gas wells, mainly in and around Gunnison Bay (figures 2 and 4), indicate an elevated (> 230°C) thermal regime below the thick sedimentary basin fill units (> 3.8 km) within pre-



[Figure 3. Temperature-depth profiles (recorded 13 Mar 2013) and computed thermal conductivity values for thermal-gradient wells Rozel-1 and Matlin-1(figure 2, table 2).]

Cenozoic bedrock, mostly lower Paleozoic and Precambrian units. This elevated temperature regime is likely due to a combination of thick, low-thermal-conductivity sediments overlying basement rocks in a region of high heat flow. The combination of these conditions results in relatively high geothermal gradients (~ 57°C/km in Indian Cove I-1 well). Continued research should focus on the lateral distribution of the elevated temperature field and the porosity-permeability (geothermal reservoir) characteristics of the bedrock formations below the sediment-filled basins.

Temperatures exceeding 200°C have been measured in the high-heat-flow, deep (> 3.6 km) southern part of Gunnison Bay from past oil and gas exploration (Indian Cove well I-1). However, this region of prospective geothermal value is also situated off-shore in GSL thereby offering special technical, as well as environmental and institutional, challenges to any future development. Gravity data suggest similar deep basins exist east of the Promontory Mountains in the Bear River Bay and Wasatch Front regions, but deep drilling and heat flow data are lacking here. The Chesapeake Energy well (CE-1A on figures 2 and 4) may indicate high heat flow in this region, and the Davis-1 well may provide insight to geothermal fluid movement on a deep basin margin, but more inquiry is needed. Bear River Bay comprises expanses of shallow saline and brackish water in various impoundments across federal and state wildlife reserves. Outside these reserves are mostly mud flats, which may also challenge exploration and development. The urbanized northern Wasatch Front, however, appears to have deep sedimentary basins located in the high-heat-flow eastern Basin and Range Province. Coupled with proximity to power transmission corridors, infrastructure and load centers, the northern Wasatch Front region may offer more attractive, deep sedimentary basin, geothermal development prospects.

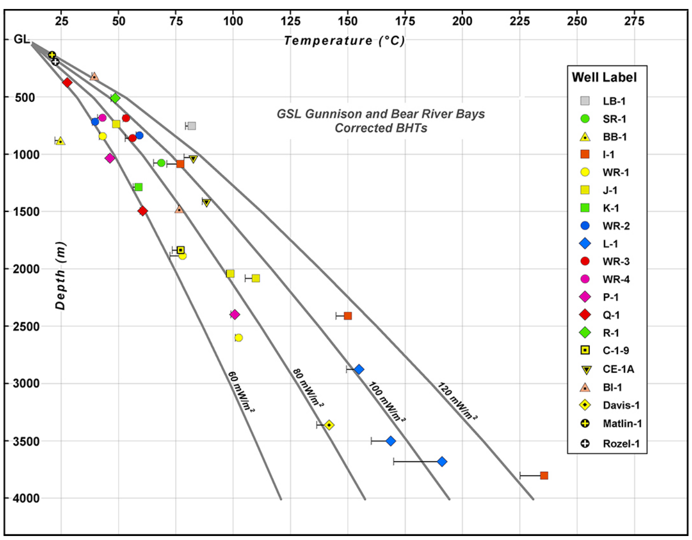


Figure 4. Corrected BHTs from oil and gas wells in and around Gunnison Bay and Bear River Bay (see table 2). Measured BHTs, taken from geophysical well log headers, were corrected to estimate thermal equilibrium using methods described by Edwards (2013). The four geotherms, for heat flow ranging from 60 to 120 mW/m^2 and shown for reference, are adjusted for increasing thermal conductivity with depth using typical compaction curves for wells in Great Salt Lake. A matrix thermal conductivity of 3.2 W/m•K was used in combination with decreasing porosity and pore-water volume (thermal conductivity of water = 0.6 W/m•K) as sediment compaction occurs with increasing depth. Horizontal error bars depict one-half of the corrected BHT minus the measured BHT. The Davis-1 well is shown for reference (see description in text).

Acknowledgements

Much of the BHT and heat flow information was derived from the recent work by Mason Edwards, formerly of the University of Utah. The USGS/GMEG through Colin Williams in Menlo Park, California provided funding for well drilling and completion of the Rozel-1 and Matlin-1 wells. The USGS Western Region Research Drilling Program performed well drilling and completion. Peter Galanis (USGS/GMEG) provided well site geology and field coordination for the drilling effort. USGS/GMEG also performed thermal conductivity testing on drill cuttings from these wells. Tracey Felger of USGS Flagstaff (AZ) Science Campus provided GIS information and other data on young volcanic rocks north of GSL. Robert Baskin of USGS Utah Water Science Center and Buck Ehler of Utah FFSL provided GIS information and other data on the bathymetry of GSL. Wil Stokes (retired) of Utah School and Institutional Trust Lands Administration (SITLA) helped expedite exploratory drilling permits on two SITLA land tracts for the Rozel-1 and Matlin-1 wells. Jim Goddard and Kelly Horne (Utah Division of Water Rights) helped expedite approval of drilling permits. Kevin Thomas (UGS Groundwater Program) performed geophysical well logging in the Rozel-1 and Matlin-1 wells. This paper is part of a project titled: "Novel Geothermal Development of Sedimentary Basins in the United States," Moore, J.N., and Allis, R.G. (co-Principal Investigators), which is partially funded by the Geothermal Technologies Program of the U.S. Dept. of Energy (Award DE-EE0005128).

References

Allis, R., B., Blackett, M. Gwynn, C. Hardwick, J. Moore, C. Morgan, D. Schelling, and D. Sprinkel, 2012. "Stratigraphic reservoirs in the Great Basin – the bridge to development of enhanced geothermal systems in the U.S." Geothermal Resources Council Transactions, v. 36, p. 351–357.

Allis, R.G., J.N. Moore, T. Anderson, M. Deo, S. Kirby, R. Roehner, and T. Spencer, 2013. "Characterizing the power potential of hot stratigraphic reservoirs in the Great Basin, U.S." Stanford, California, 38th Workshop on Geothermal Reservoir Engineering, SGP-TR-198, 11 p.

Allis, R., J. Moore, B. Blackett, M. Gwynn, S. Kirby, and D. Sprinkel, 2011. "The potential for basin-centered geothermal resources in the Great Basin." Geothermal Resources Council Transactions, v. 35, p. 683–688.

Allmendinger, R.W., and T.E. Jordan, 1989. "Geologic map of the Newfoundland Mountains, northwestern Utah." U.S. Geological Survey Miscellaneous Field Studies Map 2087, scale 1:31,680.

Atwood, G., 2006. "Gunnison Bay – present terminus of the Great Salt Lake drainage basin and naturally low area of the Bonneville Basin." Utah Geological Association Publication 34, p. 1–19.

Austin, C.F., R.R. Austin, , and M.C. Erskine, 2006. "Renaissance – a geothermal resource in northern Utah." Geothermal Resources Council Transactions. v. 30, p. 853–857.

Baskin, R.L., 2006. "Calculation of area and volume for the north part of Great Salt Lake, Utah." U.S. Geological Survey Open-File Report 2006-1359, 6 p.

Baskin, R.L., and D.V. Allen, 2005. "Bathymetric map of the south part of Great Salt Lake, Utah." U.S. Geological Survey, Scientific Investigations Map 2894.

Baskin, R.L., and J. Turner, 2006. "Bathymetric map of the north part of Great Salt Lake, Utah, 2006." U.S. Geological Survey, Scientific Investigations Map 2954.

Bjorklund, L.J., and L.J. McGreevy, 1973. "Selected hydrologic data, lower Bear River drainage basin, Box Elder County, Utah." U.S. Geological Survey, Utah Basic-Data Release no. 23, 22 p.

Bjorklund, L.J., and L.J. McGreevy, 1974. "Ground-water resources of the lower Bear River drainage basin, Box Elder County, Utah." Utah Department of Natural Resources Technical Publication no. 44, 65 p.

Black, B.D., S. Hecker, M.D. Hylland, G.E. Christenson, and G.N. McDonald, 2003. "Quaternary fault and fold database and map of Utah." Utah Geological Survey Map 193DM.

Blackett, R.E., 2011. "Temperature profiles of water monitoring wells in Snake Valley, Tule Valley, and Fish Springs Flat, Millard and Juab Counties, Utah." Utah Geological Survey Open-File Report 578, 13 p, appendix.

Blackwell, D.D., 1983. "Heat flow in the northern Basin and Range Province," in "The role of heat in the development of energy and mineral resources in the northern Basin and Range Province." Geothermal Resources Council Special Report, 13, p. 81–92.

Blackwell, D.D. and M. Richards, 2004. "Heat flow map of North America." American Association of Petroleum Geology, map scale 1:6,500,000.

Blackwell, D., M. Richards, Z. Frone, J. Batir, A. Ruzo, R. Dingwall, and M. Williams, 2011. "Temperature at depth maps for the conterminous US and geothermal resource estimates." Geothermal Resources Council Transactions, v. 35.

Blackwell, D.D., J.L. Steele, and L.S. Carter, 1991. "Heat-flow patterns of the North American continent — a discussion of the Geothermal Map of North America," in Slemmons, D.B., E.R. Engdahl, M.D. Zoback, and D.D. Blackwell, eds., "Neotectonics of North America." Boulder, Colorado, Geological Society of America, Decade Map, v. 1, p. 423–436.

Bortz, L.C., 2002. "Heavy-oil deposit, Great Salt Lake, Utah," in Gwynn, J.W., "Great Salt Lake – an overview of change." Utah Department of Natural Resources Special Publication, ISBN 1-55791-667-5, p. 243–250.

Chapman, D.S., D.D. Blackwell, W.T. Parry, W.R. Sill, S.H. Ward, and J.A. Whelan, 1978. "Regional heat flow and geochemical studies in southwest Utah." University of Utah unpublished report to U.S. Geological Survey, Contract 14-08-0001-G-341, 120 p.

Cook, K.L., V. Bankey, D.R. Mabey, and M. DePangher, 1989. "Complete Bouguer gravity anomaly map of Utah." Utah Geological and Mineral Survey Map 122, scale 1:500,000.

Cook, K.L., E.F. Gray, R.M. Iverson, and M.T. Strohmeier, 1980. "Bottom gravity meter regional survey of the Great Salt Lake, Utah," in Gwynn, J.W., editor, "Great Salt Lake – a scientific, historical and economic overview." Utah Geological and Mineral Survey, Bulletin 116, p. 125–143.

Currey, D.R., G. Atwood, and D.R. Mabey, 1984. "Major levels of Great Salt Lake and Lake Bonneville." Utah Geological and Mineral Survey Map 73, scale 1:750,000.

Dinter, D.A., and J.C. Pechmann, 2005. "Segmentation and Holocene displacement history of the Great Salt Lake fault, Utah," in Lund, W.R., editor, "Basin and Range Province—Seismic Hazards Summit II." Utah Geological Survey Miscellaneous Publication 05-2, CD.

Doelling, H.H., J.A. Campbell, J.W. Gwynn, and L.I. Perry, 1980. "Geology and mineral resources of Box Elder County, Utah." Utah Geological and Mineral Survey, Bulletin 115, 251 p, 3 maps at scale 1:125,000.

DuRoss, C., and M. Hylland, 2011. "1934 M 6.6 Hansel Valley earthquake—analog for antithetic fault rupture?." Basin and Range Province Earthquake Working Group II, online http://geology.utah.gov/ghp/workgroups/pdf/brpewg/BRPEWGII_Presentations.pdf.

Edwards, M.C., 2013. "Geothermal resource assessment of the Basin and Range Province in western Utah." Salt Lake City, University of Utah, M.S. thesis, 113 p.

Felger, T.J., D.M. Miller, and R.J. Fleck, in preparation (2013). "Geologic map of the Kelton Pass SE and Monument Peak SW quadrangles, Box Elder County, Utah." Utah Geological Survey Miscellaneous Publication, scale 1:24,000.

Goode, H.D., 1978. "Thermal waters of Utah." Utah Geological and Mineral Survey Report of Investigation 129, 183 p.

Gwynn, J.W., 2002. "Great Salt Lake, Utah—chemical and physical variations of the brine and effects of the SPRR causeway, 1966-1996," in Gwynn, J.W., ed., "Great Salt Lake—an overview of change." Utah Department of Natural Resources, p. 88–106.

Gwynn, J.W., 2006. "Petroleum and gas occurrences and development history in Box Elder County, Utah." Utah Geological Association Publication 34, p. 1–13.

Gwynn, M., B. Blackett, R. Allis, and C. Hardwick, 2013. "New geothermal resource delineated beneath Black Rock desert, Utah." Stanford, CA, Proceedings, 8th Workshop on Geothermal Reservoir Engineering, SGP-TR-198, p. 1511–1519.

Hecker, S., 1993. "Quaternary tectonics of Utah with emphasis on earthquake-hazard characterization." Utah Geological Survey, Bulletin 127, 157 p.

Henrikson, A., 2000. "New heat flow determinations from oil and gas wells in the Colorado Plateau and Basin and Range of Utah." University of Utah, M.S. thesis, 69 p.

Henrikson, A., and D.S. Chapman, 2002. "Terrestrial heat flow in Utah." University of Utah unpublished report, 47 p., online http://geology.utah.gov/emp/geothermal/pdf/terrestrialhf.pdf.

Jensen, M.E., and J.K. King, 1999. "Geologic map of the Brigham City 7.5-minute quadrangle, Box Elder and Cache Counties, Utah." Utah Geological Survey Map 173, 46 p., 2 plates, scale 1:24,000.

Klauk, R.H., and K.E. Budding,1984. "Geothermal assessment of the lower Bear River drainage and northern East Shore ground-water areas, Box Elder County, Utah." Utah Geological and Mineral Survey Report of Investigation, 186, 98 p.

Lachenbruch, A.H. and J.H. Sass, 1977. "Heat flow in the United States and the thermal regime of the crust," in, "The Earth's Crust." Geophysical Monograph Series 20, American Geophysical Union, p. 626–675.

Mikulich, M.J., and Smith, R.B., 1974, Seismic reflection and aeromagnetic surveys of the Great Salt Lake, Utah: Geological Society of America Bulletin, v. 85, p. 991–1002.

Miller, D.M., 1997a. "Cretaceous to Quaternary geologic evolution of the Great Basin," in "Great Basin aquatic system history." Salt Lake City, University of Utah, conference proceedings, 9 p.

Miller, D.M., 1997b. "Interim geologic map of the Locomotive Springs quadrangle, Box Elder County, Utah: Utah Geological Survey Open-File Report 349, 34 p.

Miller, D.M., D.L. Clark, M.L. Wells, C.G. Oviatt, T.J. Felger, and V.R. Todd, 2012. "Progress report geologic map of the Grouse Creek 30' x 60' quadrangle and Utah part of the Jackpot 30' x 60' quadrangle, Box Elder County, Utah, and Cassia County, Idaho (year 3 of 4)." Utah Geological Survey Open-File Report 598, 25 p., 6 figures, 1 plate.

Miller, D.M., and H. Langrock, 1997a. "Interim geologic map of the Monument Peak quadrangle, Box Elder County, Utah." Utah Geological Survey Open-File Report 344, 34 p.

Miller, D.M., and H. Langrock, 1997b, "Interim geologic map of the Monument Peak SW quadrangle, Box Elder County, Utah and Oneida County, Idaho." Utah Geological Survey Open-File Report 347, 34 p.

Miller, D.M., J.K. Nakata, C.G. Oviatt, W.P. Nash, and D.W. Fiesinger, 1995. "Pliocene and Quaternary volcanism in the northern Great Salt Lake area and inferred volcanic hazards," in Lund, W.R., editor, Environmental and Engineering Geology of the Wasatch Front Region." Utah Geological Association Publication 24, p. 469–482.

Miller, D.M., C.G. Oviatt, and B.P. Nash, 2008. “Late Pleistocene Hansel Valley basaltic ash, northern Lake Bonneville, Utah, USA.” Quaternary International, v. 178, p. 238–245.

Mundorff, J.C., 1970. “Major thermal springs of Utah.” Utah Geological and Mineral Survey Water Resources Bulletin 13, 60 p., 2 plates.

Murphy, P., and J.W. Gwynn, 1979. “Geothermal investigations at selected thermal systems of the northern Wasatch Front, Weber and Box Elder Counties, Utah.” Utah Geological and Mineral Survey Report of Investigations, no. 141, 50 p.

Nelson, A.R., and S.F. Personius, 1993. “Surficial geologic map of the Weber segment, Wasatch Fault zone, Weber and Davis counties, Utah.” U.S. Geological Survey Miscellaneous Investigation Series Map I-2199, scale 1:50,000.

Oviatt, C.G., and D.M. Miller, 1997. “New explorations along the northern shores of Lake Bonneville,” in, Link, P.K., and B.J. Kowallis, editors, “Mesozoic to Recent Geology of Utah.” Brigham Young University Geology Studies, v. 42 (Part II), p. 345–371.

Saltus, R.W, and R.W. Jachens, 1995. “Gravity and basin-depth maps of the Basin and Range Province, Western United States.” U.S. Geological Survey Geophysical Investigations Map GP-1012, scale 1:2,500,000.

Tester, J. W., B. Anderson, A. Batchelor, D. Blackwell, R. DiPippo, E. Drake, J. Garnish, B. Livesay, M.C. Moore, K. Nichols, S. Petty, N. Toksoz, R. Veatch, C. Augustine, R. Baria, E. Murphy, P. Negraru, and M. Richards, 2006. “The future of geothermal energy, impact of enhanced geothermal systems (EGS) on the United States in the 21st Century.” Massachusetts Institute of Technology, INL Subcontract No. 63 00019, INL/EXT-06-11746, ISBN: 0615134386, 372 p.

Utah Department of Natural Resources, 2013. “Final Great Salt Lake comprehensive management plan and record of decision.” Utah Division of Forestry, Fire and State Lands report online http://forestry.utah.gov/images/statelands/greatsaltlake/2010Plan/OnlineGSL-CMPandROD-March2013.pdf.

Zietz, I., R. Shuey, and J.R. Kirby, 1976. “Aeromagnetic map of Utah.” U.S. Geological Survey Geophysical Investigations Map GP-907, scale 1:1,000,000.

[1] Bortz (2002) refers to this threshold as an arch or horst, separating the north basin (Gunnison) from the south basin (Gilbert).

[2] No continuous temperature logs were run in any of the wells, so Edwards (2013) used BHT data from well log headers to determine deep subsurface temperatures. Edwards corrected the measured BHTs using the methods of Henrikson (2000) and Henrikson and Chapman (2002).

[3] A long, narrow urban corridor at the western base of the foothills of the Wasatch Range and extending southward from Brigham City for about 160 km.

[4] In general, temperatures increase with depths within the Earth along curves known as “geotherms.” The shape of geotherms can vary dependent on local or regional geological, hydrological, and tectonic conditions.