HYDROGEOLOGY OF THE MALAD–LOWER BEAR RIVER BASIN, NORTH-CENTRAL UTAH AND SOUTH-CENTRAL IDAHO

by Hugh Hurlow

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Cover photo: View east of Wellsville Mountains, town of Honeyville in foreground.

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CONTENTS

FIGURES

TABLES

PLATES

HYDROGEOLOGY OF THE MALAD–LOWER BEAR RIVER BASIN, NORTH-CENTRAL UTAH AND SOUTH-CENTRAL IDAHO

by Hugh Hurlow

ABSTRACT

The Malad–Lower Bear River basin is an intermontane basin in north-central Utah and south-central Idaho in the eastern Basin and Range Province. Two major streams, the Bear River, which originates outside of the basin, and the Malad River, which is sourced by springs within the basin, flow south to the northeastern arm of Great Salt Lake. Groundwater is stored in and moves through a basin-fill aquifer composed of Quaternary and Tertiary alluvial and lacustrine sediment and bedrock aquifers composed of variably faulted and folded Paleozoic carbonate rocks. Major Quaternary to Tertiary-age normal faults underlie the steep mountain fronts that bound the basin on the east and west. This report focuses on the Utah part of the basin.

Surface water and, to a lesser extent, groundwater in the Malad–Lower Bear River basin are used for agriculture, and groundwater is also used for domestic supply and industry. U.S. Geological Survey data indicate that recharge and discharge of the surface water–groundwater system are in long-term balance. Continued population and industrial growth in the region, however, will inevitably increase demands for water supply during the next several decades. Groundwater pumping from new water-supply wells would eventually deplete stream flow and spring flow. The timing and magnitude of depletion depend in part on the geometry and hydraulic properties of the major aquifers and confining units. To assist the evaluation of the effects of potential new wells, this report summarizes the hydrogeology of the Utah part of the Malad–Lower Bear River basin, particularly the lithology of the upper basin fill, i.e., the Quaternary-Tertiary deposits above the Tertiary Salt Lake Formation.

Geologic formations in the study area include late Proterozoic to early Paleozoic quartzite; Paleozoic carbonate, shale, and quartzite; middle to late Tertiary conglomerate, sandstone, mudstone, and limestone; middle to late Tertiary volcanic flows and pyroclastic deposits in the Idaho part of the study area; and late Tertiary to Quaternary alluvial and lacustrine gravel, sand, and clay, denoted as the younger basin fill. These formations are grouped into thirteen hydrogeologic units based on their known or inferred hydraulic properties.

The subsurface compositional variability of the younger basin fill in the Malad–Lower Bear River basin was characterized by analyzing lithologic data from 277 water-, petroleum-, and geothermal-exploration well logs. The analysis delineated eight lithologic units in the younger basin fill having geologically reasonable lateral persistence and thickness variations. A facies transition exists from well-defined, alternating fine- and coarse-grained deposits beneath the valley floor to predominantly coarse-grained deposits interlayered with fine-grained deposits lacking lateral persistence beneath the mountain front (lithologic units gsf1 and gsf3). The facies transition approximately coincides with the mountain front–valley floor boundary and the distal parts of the alluvial fans and lacustrine deltas deposited along the mountain fronts. On the valley-floor side of the facies transition, seven basin-fill lithologic units include, from top to bottom (i.e., youngest to oldest), (1) upper sand and gravel deposits (gsf1); (2) an upper predominantly fine-grained (mostly clay) unit (f1); (3) a predominantly sand and gravel unit (gsf2); (4) a middle predominantly fine-grained unit (f2); (5) a second predominantly sand and gravel unit (gsf4); (6) a lower predominantly fine-grained unit (f3); and (7) a lower sand, gravel, and clay unit (gsf5). Individual lithologic units range in thickness from 5 to over 350 feet and markedly thicken in the southern part of the study area to more than 1000 feet locally.

The younger basin-fill stratigraphy delineated in this study is consistent with previously established stratigraphy in the Malad–Lower Bear River basin and adjacent basins, and with Pleistocene to late Tertiary lake levels in the Bonneville basin. The upper and middle predominantly fine-grained layers (lithologic unit f1 and f2, respectively) are interpreted as clay and marl deposited during high stands of the Pleistocene Lake Bonneville and Cutler Dam lake cycles, respectively. The middle two coarse-grained deposits (gsf2 and gsf4) are interpreted as interlacustrine alluvium and/or transgressive or regressive lacustrine deposits.

The lithologic units in the younger basin fill are grouped into four hydrostratigraphic units. The valley-floor side of the facies transition has three units which are, in descending order, the shallow sand and gravel aquifer, composite confining unit, and principal sand and gravel aquifer. The mountain-front sand and gravel aquifer on the mountain-front side of the facies transition has two hydrostratigraphic units, the shallow and mountain-front sand and gravel aquifers. The shallow, mountain-front and deep sand and gravel aquifers correspond to lithologic units gsf1, gsf3, and gsf5, respectively. The composite confining unit includes three fine-grained layers (f1, f2, and f3) that alternate with two coarse-grained layers (gsf2 and gsf4). Defining these hydrostratigraphic units provides a conceptual framework for interpreting possible groundwater flow paths and streamflow depletion by wells.

Groundwater pumping from the shallow sand and gravel aquifer would affect surface flow in streams and springs by virtue of their direct hydraulic connection. Pumping from the deep sand and gravel aquifer beneath the valley floor could result in comparatively delayed and more distributed depletion of stream flow and spring flow. Pumping from the mountain-front aquifers would capture groundwater that would otherwise move into the shallow and deep sand and gravel aquifers.

INTRODUCTION

The Malad–Lower Bear River hydrographic basin is located in south-central Idaho and north-central Utah (figures 1 and 2; plate 1). The hydrographic basin includes Malad Valley in the Idaho–northern Utah part of the basin and Bear River Valley in the southern part of the basin (figures 1 and 2). This study focuses on the Utah part of the basin, referred to hereafter as the main study area. The primary objective was to delineate the stratigraphy and structure of basin-fill deposits that form the principal aquifers in the basin, providing a conceptual framework for understanding groundwater flow.

The Malad–Lower Bear River hydrographic basin (U.S. Geological Survey hydrolographic area 273; Harrill and Prudic, 1988) occupies about 1200 mi^2 in northeastern Box Elder County, Utah, and southern Oneida County, Idaho (figure 1). The Malad River originates from springs in the northern part of the basin, and the Bear River flows into the basin at its east-central boundary. The Malad River flows into the Bear River about 8 miles northeast of its confluence with the northeastern arm of Great Salt Lake. In the main study area, Bear River water is the primary source of irrigation, which accounts for about 95% of total anthropogenic water use (Utah Division of Water Resources, 2004, p. 11). In addition, the Bear River Migratory Bird Refuge (figure 2) holds rights to about 425,000 acre-feet per year (acre-ft/yr) of Bear River flow to maintain its ecology (Utah Division of Water Resources, 2004, p. 32).

Population growth in eastern Box Elder County has occurred in the recent past and is expected to continue in the future, from about 50,000 in 2010 to perhaps 70,500 in 2050 (Utah Governor's Office of Management and Budget, 2012; Utah Foundation, 2014a, figure 9). Demand on water resources, particularly for local municipal and industrial uses, will increase proportionately (Utah Foundation, 2014b). Based on the Utah Division of Water Resources' Bear River Basin management plan (author's analysis of projections in the appendix of Utah Division of Water Resources, 2004), water demand on municipal suppliers in the main study area may increase from about 12,000 acre-ft/yr in 2010 to between 16,000 and 22,000 acre-ft/yr in 2050, depending on details of actual population growth and conservation practices. Agricultural water use will likely remain constant (Utah Division of Water Resources, 2004, p. 21). If the increased municipal and industrial supply comes from increased groundwater withdrawals by wells, surface flow and/or groundwater discharge to the Bear River Migratory Bird Refuge and nearby areas in the southern part of the study area would eventually be impacted. The possibility of exporting water to more densely populated parts of the Wasatch Front in Davis and Salt Lake Counties is also under consideration (Utah Division of Water Resources, 2004).

This report builds upon previous work by Bjorklund and McGreevy (1973, 1974), who summarized the hydrogeology and hydrology of the Malad–Lower Bear River basin in Utah, and Dr. Robert Q. Oaks, Jr., who reviewed an engineering study of the potential Washakie Reservoir site (Oaks, 2008) and evaluated potential water-supply well sites along the west and east sides of the Wellsville Mountains (Oaks, 1998, 2000, 2003a, 2003b). Interpretation of the lithologic succession in the younger basin fill presented here is based on work by Oaks (1998, 2000, 2008) in the northern Utah part of Malad Valley and northern Bear River Valley, and by Williams (1962), Bjorklund and McGreevy (1971), Robinson (1999), Oaks (2000), and Oaks and others (2014) in Cache Valley, the next valley east of the main study area. Other previous hydrogeologic studies include Anderson and others (1994), who delineated primary and secondary recharge areas and discharge areas in basins along the Wasatch Front; Lowe and others (2005), who produced a pesticide vulnerability map of eastern Box Elder County; and Wallace and others (2010), who studied the hydrogeology and possible sources of saline water in Bothwell Pocket in the southwestern part of the main study area. The geologic map (plate 1) was compiled from Long and Link (2007), Miller and Felger (2013), and Hintze and others (2000). Stolp and others (in preparation) conducted a hydrologic study of the Malad–Lower Bear River basin.

This report includes cross sections and isopach maps, constructed from well drillers' lithologic logs, that show lithologic units and their thicknesses in the younger basin fill of the Malad–Lower Bear River basin. The interpreted stratigraphy is consistent with the established Quaternary to early Tertiary geologic history of the main study area. The lithologic units can be grouped into four hydrostratigraphic units—shallow, deep, and mountain-front sand and gravel aquifers, and a composite confining unit composed of three clay-rich confining units and

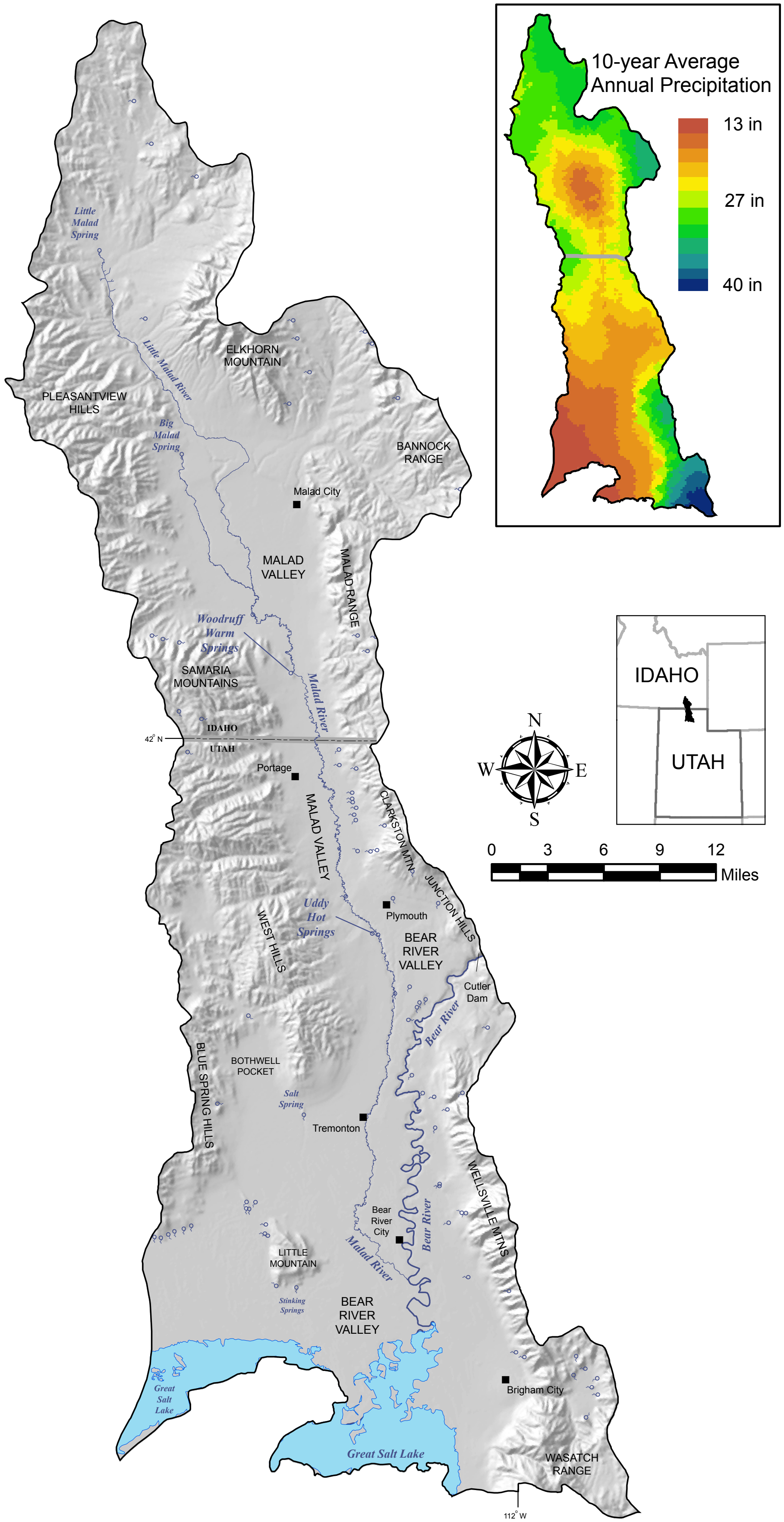


__Figure 1.__ Location of the Malad–Lower Bear River hydrologic basin in north-central Utah and south-central Idaho. This study focuses on the Utah part of the basin, referred to in the text as the main study area. Inset: Average annual precipitation, in inches, from PRISM Climate Group (2012).

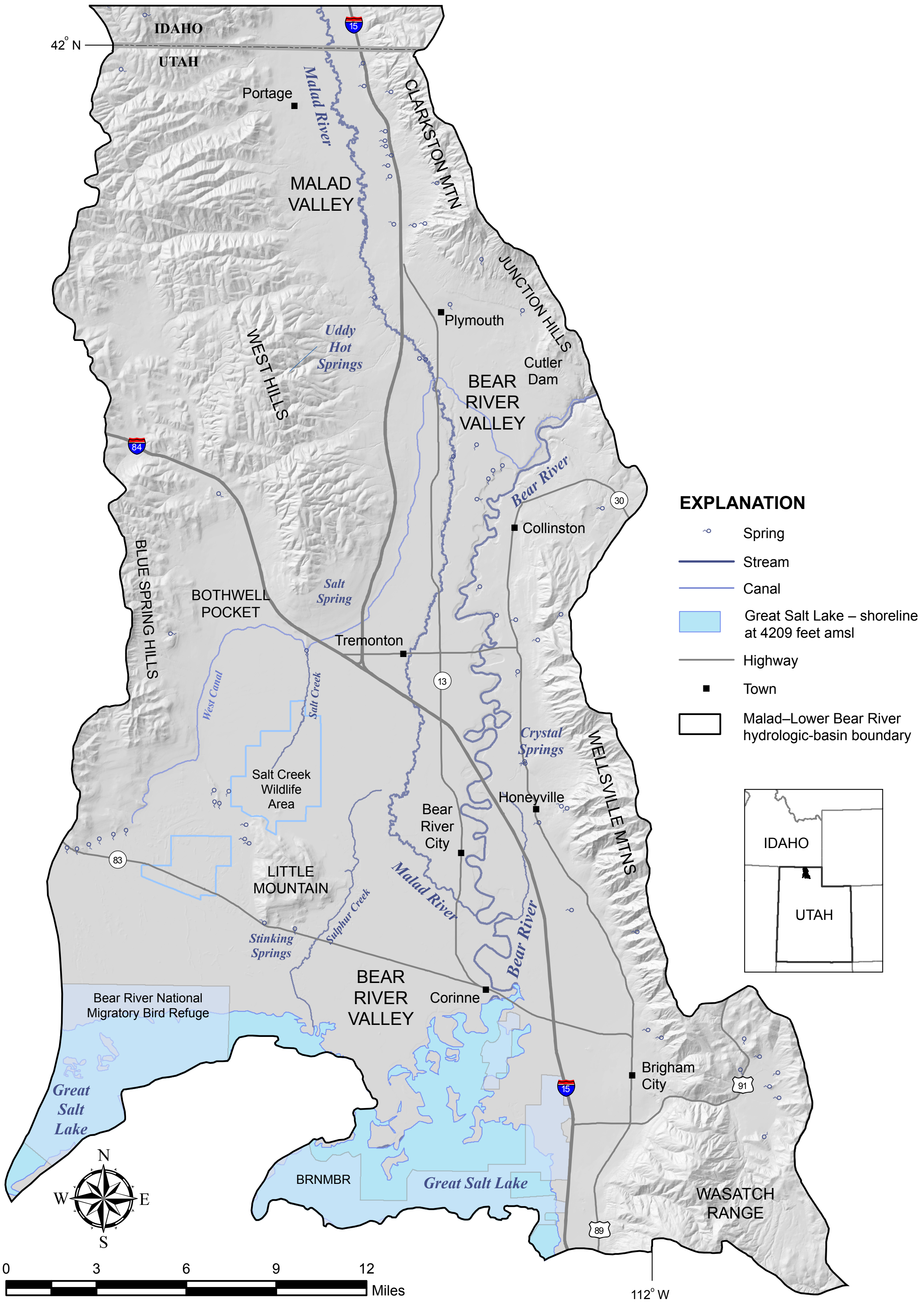


Figure 2. *Detailed location map of the Malad–Lower Bear River hydrologic basin in north-central Utah, the main study area for this report.*

two intercalated sand and gravel aquifers. The thicknesses of the composite confining unit and the upper and lower sand and gravel aquifers and the locations and hydraulic properties of major faults affect groundwater flow patterns and the location and timing of potential depletion of surface water by wells.

HYDROGEOLOGIC SETTING

Geography

The Malad–Lower Bear River basin is in the Wasatch Front Valleys section of the northeastern Basin and Range physiographic province (Stokes, 1977). The Basin and Range Province is characterized by north-trending, elongate, flat valleys, abrupt mountain fronts, and steep mountain ranges. Most basins have internal surface drainage, i.e., streams terminate in valley-floor lakes or playa within their basin of origin, though the Bear River in the main study area is an exception. Late Tertiary to Holocene normal- and oblique-slip faults uplifted the ranges and formed syntectonic sedimentary basins composed of detritus eroded from the ranges.

The Malad–Lower Bear River basin includes Malad Valley in Idaho and northern Utah and Bear River Valley in Utah, south of Malad Valley (figure 2). Valley-floor elevation ranges from about 5300 feet in the Malad River headwaters in Idaho to about 4200 feet at Great Salt Lake. The valleys are bounded on the east by steep mountain ranges that vary in peak elevation from about 7000 to 9000 feet, and on the west by more subdued ranges having peak elevations from about 6500 to 7200 feet. In the southwestern part of the main study area, Bothwell Pocket is a northward valley protrusion of Bear River Valley between the West Hills and Blue Hills, and Little Mountain is an isolated bedrock horst (figure 2).

Hydrology

Average annual precipitation on the valley floor is about 13 inches per year in southeastern Bear River Valley, 15 to 18 inches per year along the Wasatch Front, and about 13 inches per year in the Idaho part of Malad Valley (figure 1 inset) (Moller and Gillies, 2008; Western Regional Climate Center, 2015). Model-estimated precipitation in the mountains ranges from about 18 to 41 inches per year (PRISM Climate Group, 2012).

The Bear River headwaters are in the northwestern Uinta Mountains, about 100 miles southeast of the main study area. The river is impounded by Cutler Dam where it enters the east-central boundary of the study area. Average annual flow of the Bear River is 1.1×10^6 acre-ft/yr below Cutler Dam and 1.3×10^6 acre-ft/yr about 9 miles upstream of its confluence with Great Salt Lake near Corinne, Utah (Utah Division of Water Resources, 2004, table 1). The Malad River originates at several springs in the northwestern part of Malad Valley in south-central Idaho and flows south about 60 miles to its confluence with the Bear River.

Stream flow data for the Malad River and Bear River reported by McGreevy (1972) and the U.S. Geological Survey (2016) show that the Bear River and Malad River are hydraulically connected to shallow groundwater and are gaining streams along much of their courses in Utah (L.E. Brooks and B.J. Stolp, U.S. Geological Survey, written communication, 2016). Malad River flow in September 2012 was 9.7 cubic feet per second (cfs) at a site 2 miles south of the Utah-Idaho border, and 43.9 cfs at a site 6 miles (approximate linear river distance) north of its confluence with the Bear River. Bjorklund and McGreevy (1974, p. 9) noted a similar increase in Malad River flow from north to south during water years 1966 to 1970 and interpreted that much of this gain was due to groundwater inflow. The Bear River gained about 116,000 acre-ft/yr from groundwater and shallow cross flow from the Malad River during water years 1964 to 1971 between U.S. Geological Survey gages near Collinston, Utah, and Corinne, Utah (Bjorklund and McGreevy, 1974, p. 9).

Bjorklund and McGreevy (1974) delineated principal and shallow groundwater systems in the Malad–Lower Bear River basin. The principal groundwater system includes confined and unconfined groundwater in basin-fill and bedrock aquifers. They did not describe their shallow, unconfined groundwater system in detail, but drew contours for this system near the Bear River, Malad River, major canals, and in the southern one-third of the main study area (Bjorklund and McGreevy, 1974, plate 2). Groundwater elevation in their principal groundwater system ranges from 4700 feet in the northeastern part of the main study area to less than 4250 feet in the southern part of the main study area (Bjorklund and McGreevy, 1974, plate 2). In the Utah part of Malad Valley, groundwater flow is mainly west or east from the mountain fronts to the valley axis where it turns generally southward. In Bear River Valley south of Tremonton, Utah, groundwater flows perpendicular to topographic contours along the mountain fronts and generally south toward Great Salt Lake beneath the valley floors.

Springs are present in several different geologic and geographic settings in the main study area (figure 2) (Bjorklund and McGreevy, 1974). Numerous springs lie along the mountain front that bounds the eastern valley margin (figure 3A) (Bjorklund and McGreevy, 1974; Hurlow, 1999). Woodruff Warm Springs in southern Idaho (figure 1) contributes about 12 cfs to the Malad River (McGreevy, 1972). Uddy (aka Udy) Hot Springs, at the southern end of Malad Valley (figure 2), contributes about 5 cfs to the Malad River (McGreevy, 1972), and Salt Spring, at the southern end of the West Hills (figure 2), discharges about 22 cfs of saline groundwater from late Paleozoic limestone of the Oquirrh Formation (Bjorklund and McGreevey, 1974). Numerous small saline to freshwater springs and seeps and diffuse

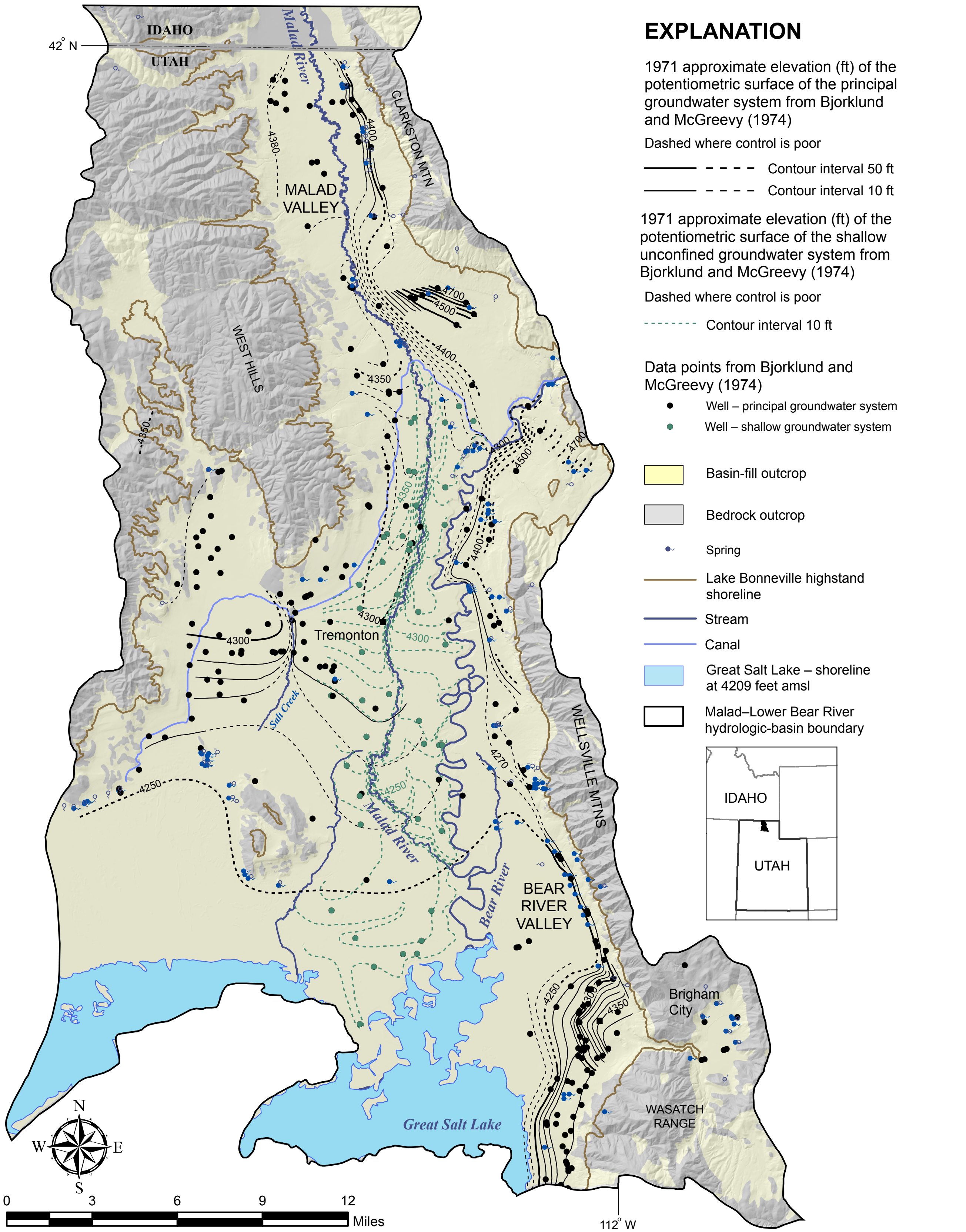


Figure 3A. *Hydrogeologic features of the Malad–Lower Bear River basin in north-central Utah. Groundwater-level contours from Bjorklund and McGreevy (1974). Black contours and control points are for their principal groundwater system, which includes basin-fill and bedrock units, and green contours and control points are for their shallow unconfined groundwater system. For both sets of contours, lines are dashed where control is poor. Groundwater flow in the principal aquifer, interpreted as generally perpendicular to the contours, is toward the valley centers below the mountain fronts and toward Great Salt Lake below the valley floor.*

groundwater upwellings flank the Malad and Bear Rivers north of Tremonton, and discharge occurs by diffuse seepage in the southern one-third of the study area (Bjorklund and McGreevy, 1974). Springs along the local stream valleys south of West Canal (figure 2) may be sourced largely by unconsumed irrigation water. Major springs and diffuse upwelling in the southern half of the study area are likely sourced primarily by groundwater moving up from the principal groundwater system.

Although they contribute a relatively small amount of groundwater discharge and surface flow to the hydrologic system compared to the Malad and Bear Rivers, many of these springs are economically and environmentally important. Several mountain-front springs, particularly along Clarkston Mountain and the Wellsville Mountains, are used for culinary supply and stock watering. Uddy Hot Springs and Crystal Hot Springs have been developed for recreational use. Several springs in addition to Woodruff and Uddy contribute surface flow to the Malad River (McGreevy, 1972). Many of the springs and seeps in the lowlands south of Tremonton, Utah, support environmentally important wetlands and wildlife, including the Salt Creek Wildlife Management Area administered by the Utah Division of Wildlife Resources and the Bear River National Migratory Bird Refuge (figure 2).

Burden and others (2015) estimated that groundwater pumped from wells in the Malad–Lower Bear River basin is used as follows: municipal/domestic supply (7600 acre-ft/yr), agriculture (4100 acre-ft/yr), and industrial use (440 acre-ft/yr). As noted above, over the next 40 years, municipal and industrial groundwater use may increase by about 30 to 80% depending on population growth and conservation, and agricultural acreage is projected to remain relatively constant (Utah Division of Water Resources, 2004; Utah Foundation, 2014b). Most wells draw water from the basin fill, but Bjorklund and McGreevy (1974) noted several highly productive wells in bedrock, mainly late Paleozoic limestone.

Recharge to groundwater in the Malad–Lower Bear River basin comes from infiltration of precipitation and unused irrigation water (Bjorklund and McGreevy, 1974). Groundwater discharges from the study area by (1) shallow flow to the Bear River and Malad River; (2) springs in the mountains, along the mountain fronts, and on the valley floor; (3) evapotranspiration from irrigated and non-irrigated farmland, rangeland, wetlands, and open water along the rivers, and phreatophytes on the valley floors and in the mountains; (4) diffuse seepage in the southern part of the study area; and (5) pumping by wells for municipal, industrial, and agricultural use. Overall, the hydrologic system is thought to have long-term consistency with the system described by Bjorklund and McGreevy (1974) on the basis of surface-water diversions and land use, flow in the Bear River, seepage measurements on the Malad River, and stable groundwater levels from the 1930s to present (Bjorklund and McGreevy, 1974; L.E. Brooks and B. Stolp, U.S. Geological Survey, written communication, 2016).

Anderson and others (1994) delineated groundwater recharge and discharge areas in principal basin-fill aquifers along the Wasatch Front, including the Malad–Lower Bear River basin (figure 3B). They identified three hydraulic zones—primary recharge, secondary recharge, and discharge areas—based on water levels and perforation intervals in wells, well hydrographs, vertical gradients, springs, and lithologic and geophysical logs. Primary recharge areas are generally in the mountains and along the mountain fronts, secondary recharge areas are mainly near the valley floor–mountain front boundary where fine-grained layers are present in the basin fill, and discharge areas are present along the Malad and Bear River stream valleys north of Tremonton and in a broad discharge area that encompasses most of the basin south of Tremonton (figure 3B).

Geology

Stratigraphy and Geologic Evolution

Geologic units in the Malad–Lower Bear River basin range from Precambrian to Permian, and from Lower Cretaceous to Holocene (table 1). Plate 1 is a hydrogeologic map compiled from Hintze and others (2000), Long and Link (2007), and Miller and Felger (2013). Plate 2 shows unit correlations, and table 1 describes the hydrogeologic units. Lithologic descriptions and thicknesses (table 1) were compiled from Oviatt (1986a, 1986b), Jordan and others (1988), Jensen and King (1999), Biek and others (2003), and Janecke and others (2003).

The oldest rocks exposed in the study area are Neoproterozoic to Cambrian siliciclastic rocks (i.e., sandstone, quartzite, siltstone, argillite, and shale) in the southern Wellsville Mountains and the northern Wasatch Range (plate 1), where they are more than 8000 feet thick (figure 4). Bedrock exposed in the northern Wellsville Mountains and mountain ranges to the north is dominantly Cambrian through Mississippian carbonate (i.e., limestone and dolomite) deposited in the Cordilleran miogeocline (Armstrong, 1968; Burchfiel and others, 1992; Dickinson, 2004). Lower Cambrian rocks are interbedded carbonate and shale, and Middle Cambrian through Mississippian rocks are predominantly carbonate rocks deposited in marine environments. This sequence of rock is about 11,000 to 17,000 feet thick. Subsidence of North American continental crust during Late Mississippian time led to the deposition of the Manning Canyon Shale in a deep-marine environment, in contrast to the preceding deposition in predominantly shallow-water and platform environments. The Manning Canyon Shale is not well exposed but is present in the northern Wellsville Mountains and the West Hills, and is about 900 feet thick. Pennsylvanian and Permian carbonate and siliciclastic rocks that crop out in the northern Wellsville Mountains, Blue Spring Hills, and West Hills were deposited in shallow marine conditions in the

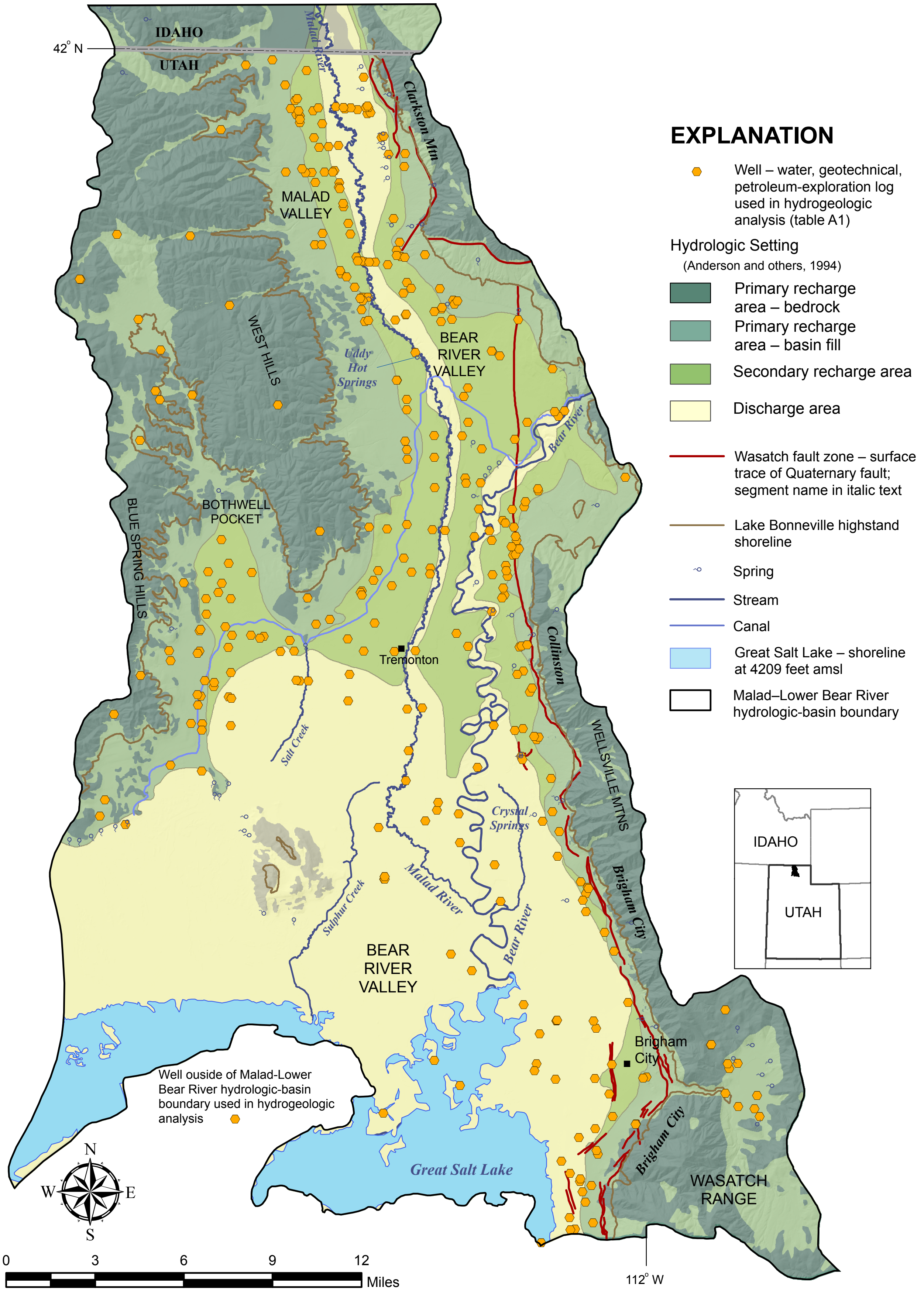


Figure 3B. *Hydrogeologic features of the Malad–Lower Bear River basin in north-central Utah. Groundwater recharge and discharge areas from Anderson and others (1994), and fault scarps and segments of the Wasatch fault zone from Black and others (2003).*

Table 1. *Summary descriptions of the hydrogeologic units defined in this study. See figure 4 and plate 2 for more details. Lithologic descriptions and thicknesses are based primarily on Jordan and others (1988), Jensen and King (1999), Biek and others (2003), Long and Link (2007), and Miller and Felger (2013). Evaluations of porosity and permeability and aquifer characteristics are based on Bjorklund and McGreevy (1974), Oaks (1998), Hurlow (1999), Belcher and others (2001), and Sweetkind and others (2007), and the lithologic descriptions cited above.*

Hydrogeologic Unit		Lithology and Hydraulic Characteristics	Key Geologic Units
Qcs	Predominantly coarse-grained sediment	Sand, gravel, and cobbles with variable amounts of clay and silt. Well sorted in discrete sedimentary layers, to unsorted, intermixed gravel and clay. Porosity and hydraulic conductivity are moderate to high and are derived from primary sedimentary texture. Yields water to wells for municipal/domestic, agricultural, and industrial uses, and to springs along the mountain fronts and locally on the valley floor. Thickness varies from as much as about 200 feet in alluvial-fan deposits on the mountain fronts, to as little as 5 feet on the valley floors.	Alluvium, alluvial-fan, and lacustrine sand and gravel, eolian sand, and mass-movement surficial deposits shown on source maps.
Qfs	Predominantly fine-grained sediment	Clay and silt, with minor but variable amounts of sand and gravel. Well sorted in discrete sedimentary layers, to unsorted, intermixed clay and sand or gravel. Porosity and hydraulic conductivity are relatively low. Thickness variations and/or gradations in grain size may localize some springs. Upper part may contain shallow groundwater that interacts with streams, and forms overburden that confines the aquifers below. Thickness varies from a few feet in the facies transition zones along the mountain fronts to about 100 feet below the valley floor in the southern part of the study area.	Lacustrine clay, mudflat deposits, and distal fluvial overbank deposits, loess, and distal parts of alluvial-fan deposits shown on source maps.
QTs	Older basin fill	Unconsolidated to semi-consolidated gravel, sand and clay, well sorted into laterally discontinuous layers or unsorted. Comprises the main basin-fill aquifer in the study area along with unit Qcs and parts of Ts. Porosity and hydraulic conductivity likely vary with depth and location and are derived from primary sedimentary texture modified by diagenesis. Yields water to wells and springs. Thickness below valley floors ranges from about 0 to 5 feet in the northern part of the study area to more than 1000 feet in the southern part of the study area, based on interpretations of well-drillers' logs.	Older alluvial and lacustrine deposits above the tuffaceous part of the Salt Lake Formation, and Quaternary-Tertiary pediment-gravel and alluvial-fan map units.
Ts	Tertiary sediment	Semi-consolidated gravel, tuffaceous siltstone, sandstone, mudstone, conglomerate, limestone, and tephra (Biek and others, 2003; Janecke and others, 2003). Porosity and hydraulic conductivity vary with lithology and are derived from primary sedimentary texture modified by diagenesis; gravel, sandstone, and conglomerate likely have the highest. Locally yields significant water to wells in Cache Valley and possibly to some of the deeper wells in the study area. Thickness ranges from about 900 to 6500 feet based on mapping in and near the study area (Goessel and others, 1999; Biek and others, 2003; Janecke and others, 2003).	Salt Lake Formation
Tv	Tertiary volcanic rocks	Basaltic tuff and flows, and rhyolitic tuff, flows, breccia, and debris flows in the northern part of the basin in Idaho. Laterally discontinuous layers having variable thickness and texture. Porosity and hydraulic conductivity likely vary strongly with lithology, and are lowest in debris flows due to poor sorting and cementation and highest in well-indurated tuff and flows due to fractures. Yields water to some springs and possibly some wells. Basaltic deposits are up to 120 feet thick, and rhyolitic deposits are up to 500 feet thick (Long and Link, 2007).	Upper tuff and basaltic unit, and rhyolitic unit of Salt Lake Formation in Idaho.
UPzs	Upper Paleozoic siliciclastic rocks	Sandstone, quartzite, and siltstone in the lower two-thirds, and interbedded limestone, dolomite, and sandstone in the upper third. Porosity and hydraulic conductivity are likely moderate to low, and are derived from both primary and secondary features (diagenetically altered pore spaces and fractures, respectively). Yields water to some wells and springs in the Bothwell pocket area in the southwestern part of the study area. Thickness is about 4500 to 9450 feet.	Upper part of Oquirrh Formation and Thatcher Mountain Formation.
UPzc	Upper Paleozoic carbonate rocks	Limestone, dolomite, and fine-grained sandstone. Porosity and hydraulic conductivity likely range from low to high and are derived from both primary and secondary features (diagenetically altered pore spaces and fractures, respectively). Yields water to some wells and springs near valley margins where unit is present in the subsurface and in ranges. Thickness is about 6150 to more than 10,200 feet.	Oquirrh Formation
MPzs	Middle Paleozoic siliciclastic rocks	Shale, mudstone, and thin beds of quartzite and limestone. Highly sheared in fault zones and folds. Porosity and hydraulic conductivity are low. Forms a confining layer. Does not likely yield water to wells or springs. Thickness is about 260 to 900 feet.	Manning Canyon Shale
MPzc	Middle Paleozoic carbonate rocks	Limestone and sandstone. Porosity and hydraulic conductivity are moderate to high and are derived primarily from solution-widened fractures in the carbonate rocks and fractures and matrix porosity in the sandstones. Yields water to wells and springs. Thickness ranges from about 2500 to 4050 feet.	Great Blue Limestone, Humbug Formation
LPzc2	Lower Paleozoic carbonate rocks 2	Limestone, dolomite, and minor sandstone. Porosity and hydraulic conductivity are moderate to high, and are derived primarily from solution-widened fractures in the carbonate rocks and fractures in the sandstones. Yields water to springs. Thickness is about 3000 to 4660 feet.	Hyrum, Fish Haven, and Laketown Dolomites
LPzs	Lower Paleozoic siliciclastic rocks	Quartzite and sandstone. Porosity and hydraulic conductivity are moderate to low, derived primarily from fractures. May form a leaky confining layer. Thickness is about 260 to 1150 feet thick.	Swan Peak Quartzite
LPzc1	Lower Paleozoic carbonate rocks 1	Limestone, silty limestone, dolomite, and shale. Porosity and hydraulic conductivity are moderate to high in the carbonate rocks, and are derived primarily from solution-widened fractures. Porosity and permeability are low in the shale, which may form local confining layers except where pervasively fractured. Thickness is about 5600 to 7000 feet.	Garden City, Saint Charles, Nounan, Bloomington, and Blacksmith Formations
€Zs	Cambrian-Proterozoic siliciclastic rocks	Shale and thinly bedded limestone in the upper one fourth, and quartzite and shale in the lower three fourths. Porosity and hydraulic conductivity are low, derived primarily from fractures in quartzite. May yield small amounts of water to wells and springs in highly fractured masses, but chiefly forms a confining layer. Thickness is more than 8000 feet.	Brigham Quartzite, Mutual Formation

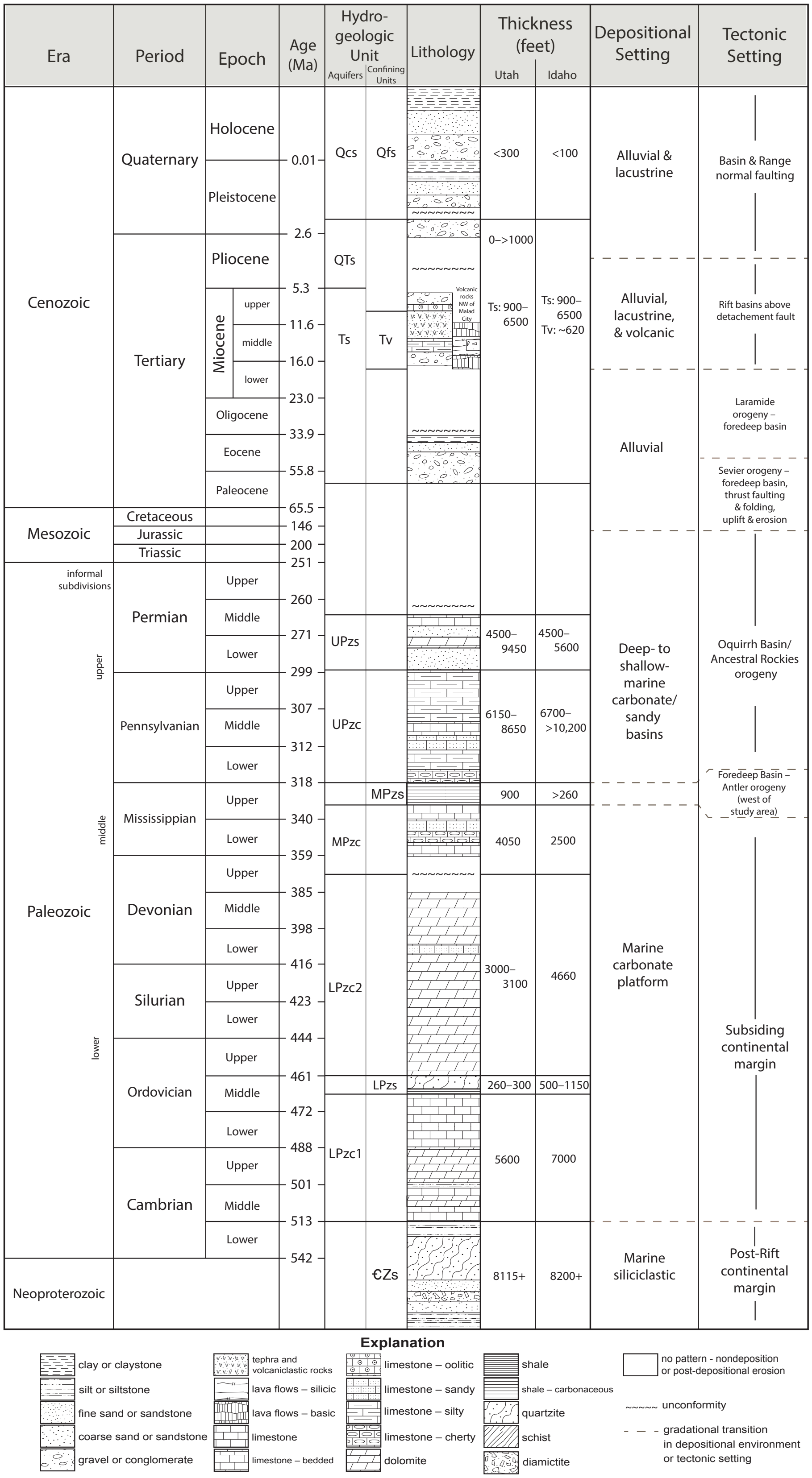


Figure 4. *Hydrogeologic units in the Malad–Lower Bear River basin in north-central Utah and south-central Idaho, their depositional environments, and the tectonic history of the area, based on Armstrong (1968), Burchfiel and others (1992), DeCelles (2004), Dickinson (2004), and sources cited in table 2. Hydrogeologic units:* Qcs*, predominantly coarse-grained sediment;* Qfs*, predominantly fine-grained sediment;* QTs*, older basin fill;* Ts*, Tertiary sediment;* Tv*, Tertiary volcanic rocks;* UPzs*, upper Paleozoic siliciclastic rocks;* MPzs*, middle Paleozoic siliciclastic rocks;* MPzc*, middle Paleozoic carbonate rocks;* LPzc2*, lower Paleozoic carbonate rocks 2;* LPzs*, lower Paleozoic siliciclastic rocks;* LPzc1*, lower Paleozoic carbonate rocks 1;* ЄZs*, Cambrian-Proterozoic siliciclastic rocks.*

rapidly subsiding Oquirrh basin, and are 4500 to more than 10,000 feet thick (Armstrong, 1968; Jordan and others, 1988).

Mesozoic sedimentary deposits were likely eroded due to Late Jurassic through middle Eocene regional uplift caused by east-directed thrust faulting and associated folding of the Sevier orogeny (Armstrong, 1968; Royse, 1993; DeCelles, 2004; Long, 2012). The Eocene Wasatch Formation, exposed in the northern Wellsville Mountains and immediately west of Cutler Dam (Goessel, 1999; Oaks, 2000), was deposited near the end of the Sevier orogeny in a basin configuration related to thrust faulting and folding. The subsurface extent of the Wasatch Formation in the main study area is poorly known, and although it may locally underlie Tertiary deposits, it is not considered part of the basin fill.

Basin-fill deposits in the Malad–Lower Bear River basin include, from oldest to youngest, (1) Eocene and Oligocene volcanic and volcaniclastic rocks exposed north of Malad City, Idaho, (2) Miocene and Pliocene Salt Lake Formation and overlying Pliocene pediment gravel, and (3) Quaternary unconsolidated to semi-consolidated sedimentary deposits, herein referred to as the younger basin fill. The Eocene and Oligocene volcanic rocks do not crop out in the main study area, nor were they identified on well logs analyzed for this study. The Salt Lake Formation is discontinuously exposed in foothills and along the mountain fronts in much of the study area and underlies the younger basin fill. The Salt Lake Formation includes tuffaceous sandstone and siltstone, tuff, conglomerate, and limestone deposited in alluvial and lacustrine environments in normal-fault-bounded sedimentary basins (Adamson and others, 1955; Smith, 1997; Goessel, 1999; Goessel and others, 1999; Oaks and others, 1999; Biek and others, 2003; Janecke and others, 2003; Carney and Janecke, 2005; Steely and others, 2005). Salt Lake Formation exposed in the Junction Hills in the main study area and in the Bannock Range in Idaho is complexly faulted and folded (Biek and others, 2003; Janecke and others, 2003). Deposition of Pliocene conglomerate beginning around 4 Ma likely coincided with a change in structural style to high-angle normal faults, including the Wasatch fault zone, which defined the present-day topography (Janecke and others, 2003; Steely and others, 2005). Thickness of the Salt Lake Formation varies abruptly from at least 1400 feet to more than 6500 feet in the main study area.

Younger basin-fill deposits are Quaternary mud, clay, silt, sand, gravel, and limestone in varying proportions, that formed in alluvial (chiefly alluvial-fan and fluvial) and lacustrine (deep-water, shore-zone, and mudflat) environments (e.g., Oviatt and others, 1999; Biek and others, 2003). Climate variations resulted in cycles of large lakes followed by subaerial conditions (e.g., Gilbert, 1890; Currey, 1990; Oviatt, 1997). Numerous Pleistocene lake cycles (figure 5) have been identified from sparse exposures and drill core (McCoy and others, 1987; Oviatt and others, 1992, 1999; Oaks and others, 2014). The final and best-known Pleistocene lake cycle is Lake Bonneville (Gilbert, 1890; Hunt and others, 1953; Williams, 1962; Oviatt and others, 1992; Janecke and Oaks, 2011).

Hydrogeologic Units

Geologic map units are grouped into 13 hydrogeologic units (HGU) (table 1; figure 4; plates 1 and 2) defined as groups of stratigraphically consecutive geologic formations having similar known or inferred hydraulic properties (i.e., porosity and hydraulic conductivity). Hydraulic-property estimates from aquifer-test data in the study area are sparse (Bjorklund and McGreevy, 1974). Bedrock HGUs are delineated based on studies in the central and southern Great Basin that have generally similar stratigraphy and more aquifer-test data (Belcher and others, 2001; Belcher, 2004; Sweetkind and others, 2007), and on field observations in the Wellsville Mountains (Hurlow, 1999). Tertiary and Quaternary HGUs are delineated based on lithologic descriptions in Jensen and King (1999), Biek and others (2003) and Janecke and others (2003), and hydrogeologic work by Smith (1997), Robinson (1999), and Inkenbrandt and Lachmar (2012).

Neoproterozoic-Paleozoic HGUs are sequences of predominantly carbonate or siliciclastic formations having reasonably uniform thicknesses, compositions, and grain sizes. Exceptions include thickness variations of Pennsylvanian-Permian rocks in Idaho and Utah and of Devonian sandstone. Carbonate and siliciclastic rocks have little primary porosity and permeability due to a long history of compaction and diagenesis, so variations in hydraulic properties are caused by differences in fracture density. Carbonate rocks and quartzite tend to be highly fractured, particularly where bed thickness is about 3 feet or less (Hurlow, 1999). Solution widening is common in Great Basin Paleozoic carbonates, which results in greater hydraulic conductivity than in quartzite (e.g., Winograd and Thordarson, 1975). Sandstone may have greater primary porosity and lower fracture (i.e., joint and fault) density than carbonate and quartzite. Shale has very low primary porosity and hydraulic conductivity and few, if any, throughgoing joints. Fracture density and, therefore, hydraulic conductivity in carbonate rocks, quartzite, and sandstone increases near faults. Generally, the carbonate HGUs have the greatest hydraulic conductivity, whereas shales have the least.

The Tertiary sediment (Ts, chiefly Salt Lake Formation) and Tertiary volcanic (Tv) HGUs were deposited in fault-bounded basins in alluvial, lacustrine, and volcanic depositional environments and as mass movements (Biek and others, 2003; Janecke and others, 2003; Steely and others, 2005; Long and Link, 2007), and are compositionally heterogeneous. Hydraulic properties in these HGUs likely vary accordingly, from relatively high porosity and hydraulic conductivity in conglomerate and non-tuffaceous sandstone of the Salt Lake Formation and fractured lava flows of the volcanic unit, to more impermeable claystone of the Salt Lake Formation and debris-flow and volcanic-breccia deposits of

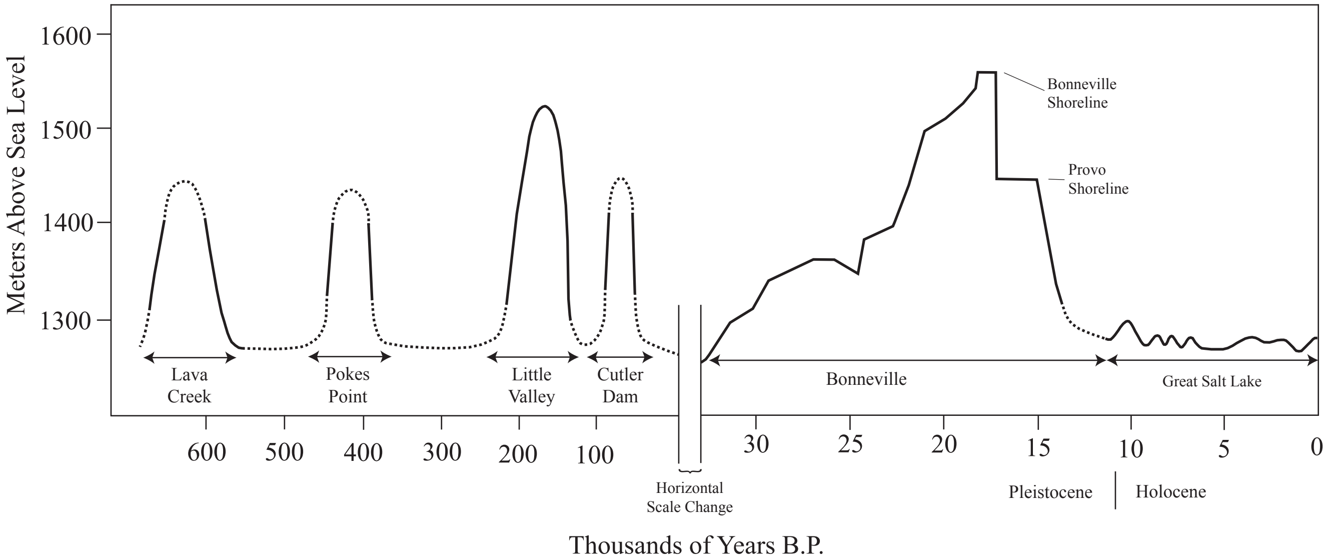


***Figure 5.** Lake cycles and approximate water levels during the past 600,000 years in the Bonneville basin, compiled from McCoy (1987, figure 7), Oviatt and others (1992, figure 2), Oviatt and others (1999, figure 2), Janecke and Oaks (2011, figure 3), and Oaks and others (2014).*

the volcanic unit. The Quaternary-Tertiary HGU is predominantly pediment and alluvial gravel (Biek and others, 2003; Long and Link, 2007) that is discontinuously exposed along the mountain fronts.

Quaternary surficial deposits are grouped into HGUs based on grain size and include the predominantly coarse-grained Qcs and predominantly fine-grained Qfs. Qcs is alluvium (including alluvial-fan and fluvial) and shore-zone lacustrine deposits, and Qfs is lacustrine clay, mud-flat, and distal alluvial-fan deposits (table 1; figure 4). These HGUs are derived from surficial map units (Long and Link, 2007; Miller and Felger, 2013) and are useful mainly for the map compilation (plate 1). Analysis of well logs in this study resulted in more detailed subdivision of the younger basin fill in the subsurface (see "Basin-Fill Lithology" section).

Structural Geology and Hydrogeology of Faults

The Malad–Lower Bear River basin is in the hanging wall of the Late Jurassic(?) to Late Cretaceous Paris branch of the Willard thrust, the western major thrust fault of the Sevier orogeny (Royse, 1993; Yonkee and Weil, 2011). The Paris thrust underlies the study area, but is too deep to substantially affect recharge-to-discharge groundwater flow paths in the basin. A northwest-striking, Sevier-age thrust fault is exposed in the southern Blue Spring Hills in the southwestern part of the main study area (plate 1) (Jordan and others, 1988), and the Manning Canyon detachment, exposed in the southwestern Pleasantview Mountains in Idaho just west of the main study area (Allmendinger and others, 1984; Long and Link, 2007), may underlie much of the West Hills. These thrust faults may affect groundwater flow in the mountain block where they are near the surface, particularly west of Malad Valley where the overlying upper Paleozoic carbonate HGU is exposed, by inhibiting downward flow to the lower Paleozoic carbonate HGUs. The Bannock detachment system is exposed in the Malad Range along the east side of the study area (Janecke and others, 2003; Carney and Janecke, 2005; and references therein). These faults juxtapose Salt Lake Formation and thin slivers of Proterozoic to Paleozoic units on older, often less permeable Proterozoic units which may create a zone that impedes downward groundwater flow.

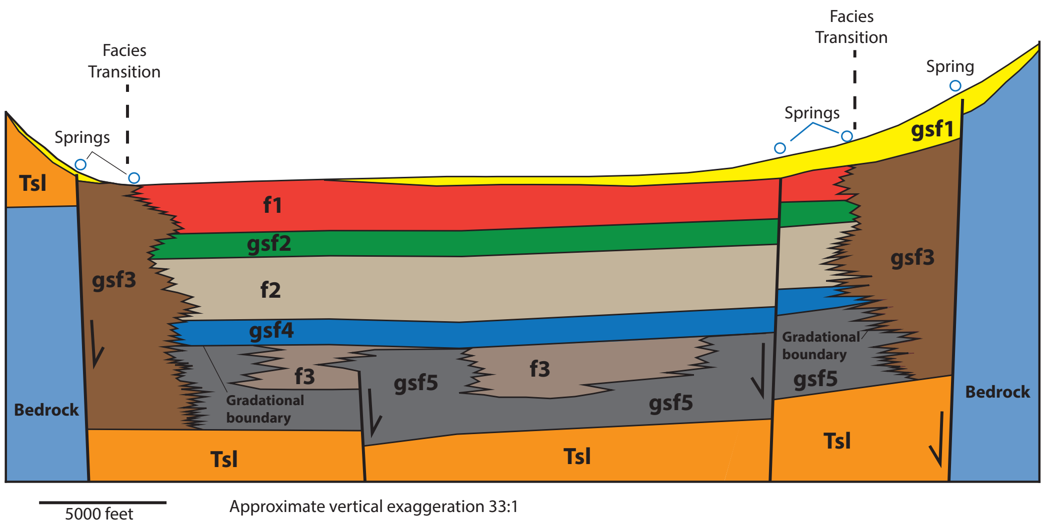
Numerous north-, northeast-, and east-striking, steeply dipping faults cut the Paleozoic stratigraphic section in the ranges that bound the east side of the valley (plate 1). These faults likely increase the hydraulic conductivity of the rocks by providing flow pathways parallel to their planes (e.g., Caine and others, 1996). Densely faulted parts of the ranges likely accommodate greater local infiltration of snowmelt and greater groundwater-flow rates from the mountain block to the basin fill compared to less densely faulted rock masses.

The Wasatch fault zone (WFZ) forms the structural boundary between the Malad–Lower Bear River basin and adjacent ranges to the east (Gilbert, 1928; Zoback, 1983; Machette and others, 1992). The WFZ initiated around 4 to 5 Ma in the main study area (Carney and Janecke, 2005) and around 10 to 12 Ma in Salt Lake Valley (Armstrong and others, 2003). Up to 13,000 feet of basin fill accumulated in its hanging wall in the main study area (Zoback, 1983, figure 6; Langenheim and others, 2014; R.Q. Oaks, Jr., written communication, 2016). The WFZ is active (Machette and others, 1992; Black and others, 2003), and the study area includes four of the fault's 10 segments: Malad City, Clarkston Mountain, Collinston, and the northern part of the Brigham City segment (figure 3B) (Machette and others, 1992; Black and others, 2003). Interpreta-

Basin Fill; Younger Basin Fill (gsf1 through gsf5)

Lithologic Unit	Lithology	Thickness (ft)	Interpreted Depositional Environment
gsf1	Gravel, sand, silt, clay	0–200	Alluvial
f1	Clay, silt, sand	0–100	Deep and nearshore lacustrine
gsf2	Gravel, sand	0–32	Inter-lacustrine alluvial and/or lacustrine fan
gsf3, f2	f2 – Clay, silt, sand gsf3 – Gravel, sand, silt, clay	f2 – 5–250 gsf3 – 0–200	Deep and nearshore lacustrine, mud flat Alluvial fan
gsf4	Gravel, sand	0–30	Inter-lacustrine alluvial and/or lacustrine fan
f3, gsf5	f3 – Clay, silt, sand gsf5 – Gravel, sand, silt, clay	f3 – 0–250 gsf5 – 0–1050	Deep and nearshore lacustrine, mud flat Inter-lacustrine alluvial and/or lacustrine fan
Tsl	Gravel, sand, clay, conglomerate, sandstone, claystone, limestone	1400–6500	Alluvial and lacustrine

A.



B.

Figure 6. *Description and schematic stratigraphic relations of lithologic units in the younger basin fill of the Malad–Lower Bear River basin, defined in this study from water-well logs. (A) Summary of stratigraphy, lithology, thicknesses, and interpreted depositional environments. (B) Schematic east-west cross section across northern Bear River Valley, representing the interpreted stratigraphic relations and geometry of the lithologic units in the younger basin fill. Unit thicknesses are approximately proportional to their average thicknesses in this area.*

tion of a geothermal-exploration borehole 7 miles northwest of Brigham City by Jensen and King (1999, plate 2) indicates that the WFZ dips about 40° west, and basin-fill deposits there are about 4400 feet thick.

Springs are aligned on or near much of the WFZ trace (figure 3B; plate 1). Where the springs are present, the fault zone likely impedes groundwater flow across its plane due to low hydraulic conductivity of gouge and cemented breccia in the main displacement zone, or to a contrast in hydraulic conductivity of rocks and/or sediments juxtaposed across its plane (Haneberg, 1995; Caine and others, 1996). Where springs are absent, cross faults or high hydraulic conductivity of rocks and/or sediment on either side of the fault zone may allow more cross-fault groundwater flow. At least some cross-fault flow from bedrock to basin-fill aquifers likely occurs along much of the fault zone and is likely greatest downgradient from areas of highest average annual precipitation and highest hydraulic conductivity of the mountain block (author's interpretation based on Manning and Solomon [2005] and Masbruch and others [2011, p. 9–12]).

Woodruff Warm Springs, Crystal Hot Springs, and Stinking Springs are located along normal-fault zones that juxtapose basin fill against bedrock and, therefore, presumably have substantial displacement. Uddy Hot Springs lies along a transverse fault zone delineated by Oaks (2000) that bounds the Malad Valley and Bear River Valley sedimentary basins.

BASIN-FILL LITHOLOGY

Introduction

The younger basin fill is currently the predominant source of groundwater in the Malad–Lower Bear River basin and is the most likely target for future development. A principal goal of this study was to delineate the subsurface stratigraphy of the younger basin fill from interpretation of well logs. The analysis resulted in delineation of eight lithologic units in the younger basin fill (figure 6), based primarily on profiles by Oaks (1998, 2000, 2003b, 2008) drawn through water-well logs in the Utah part of Malad Valley and northern Bear River Valley. Oaks demonstrated that stratigraphy in the younger basin fill closely corresponds to that in Cache Valley defined by Williams (1962), Bjorklund and McGreevy (1971), Robinson (1999), and Oaks (2000). These workers interpreted the younger basin fill to have been deposited in Pleistocene Lake Bonneville and earlier Pliocene(?) to Pleistocene lacustrine and interlacustrine cycles.

Methods

Lithologic units in the younger basin fill were delineated by the following steps.

1. Well logs were compiled from the Utah Division of Water Rights (water wells), Utah Division of Oil, Gas and Mining (petroleum- and geothermal-exploration wells), CH2MHill (2008) (geotechnical investigation wells), and Oaks (1998, 2000, 2008) (water wells and geotechnical investigation wells) (table A1). In all, logs for 336 wells within the study area were obtained, of which 277 were entirely or partially in the basin fill and were used to establish basin-fill lithology. Lithologic variations with depth, well-construction, and water-level data were entered into a well-analysis database. Land-surface elevations were obtained from Oaks (1998, 2000, 2008), CH2MHill (2008), or from topographic maps.
2. For each depth interval on the logs, a numeric code was entered that represented the lithology assigned to that interval by the driller, including multiple grain sizes within a single depth interval (e.g., sand and gravel). Most well logs were from water wells submitted by drillers to the Utah Division of Water Rights. The drillers indicated the depth intervals of different lithologic types based on cuttings returned up the borehole by the drilling fluid, typically water, mud, or air. The depth intervals and cuttings descriptions vary in their level of detail and, in part, reflect the experience and expertise of the driller. Some logs, therefore, were more useful than others in interpreting lithologic variations with depth. It was assumed that drillers easily recognize clay due to slow drilling and other problems, and sand or gravel due to different drilling characteristics and the likelihood that they contain groundwater, the drillers' primary objective. On most logs, a single lithologic type is listed for each depth interval. On some logs, clay and gravel are recorded together in a single depth interval. Where relative percentages are listed, the interval was classified as clay plus gravel where clay was more abundant, and as gravel plus clay where gravel was more abundant. Where relative percentages were not given, the interval was interpreted as mixed clay and gravel.
3. Thirty-two serial strip-log sections were constructed throughout the basin, mainly in east-west and north-south directions (see plate 3 inset for locations and wells used). Strip-log sections show lithologic columns for each well, and the distance between wells is the true map distance; therefore, the section direction typically changes between adjacent wells. Plate 3 shows four representative east-west sections that illustrate most of the lithologic variation and some of the issues in picking contacts and interpreting the subsurface geology (described in the "Results" section).
4. The first eight sections constructed corresponded to those of Oaks (1998, 2008) in the Utah part of Malad Valley and northern Bear River Valley to check his interpretation and establish a basic lithologic framework (section A–A′ on plate 3 is an example). In Oaks' sections (1998, 2000, 2008), the stratigraphically highest fine-grained interval below the valley floor, typically denoted as all clay on the drillers' logs, was correlated between adjacent logs. In some logs, the upper clay unit was overlain by gravel and/or sand. In most wells of sufficient depth and lithologic log detail, a clear stratigraphy could be delineated. The upper clay unit was underlain, from shallower to deeper, by a sand and gravel layer, a second dominantly clay layer, a second sand and gravel layer, and either a third predominantly clay layer or alternating, coarse- and fine-grained deposits that showed little lateral consistency between wells. These contacts defined a basic stratigraphy of six lithologic units within the younger basin fill. The contacts generally varied smoothly between wells and sloped gently upward toward the basin margins, where they were, in places, offset abruptly between adjacent wells, presumably by faults. Most wells beneath the mountain front lacked this stratigraphy and were composed predominantly of mixed or finely interlayered clay and gravel.
5. Oaks (2000, 2008, written communication, 2016) identified the top of the Salt Lake Formation below the younger basin fill using the following criteria: " (1) marl or sticky clay; (2) light-colored 'silt,' which is likely ash in some wells; (3) thick sequences of mixed clay and gravel, likely debris flow deposits, common in Tsl and in underlying formations, but also present as colluvium and landslide deposits close to the surface, near steep slopes, and locally

in Quaternary deposits; (4) 'talus' at depth, probably gravel with angular clasts that were not transported far, but have no recorded clay; and (5) abrupt change from dark, unoxidized colors to tans and brown in thick clay sequences." These criteria were followed in the construction of new strip-log sections. Some well logs lacked the criteria to identify the upper contact of the Salt Lake Formation. In such wells that were sufficiently deep to encounter the Salt Lake Formation, the contact was placed above the highest semi-consolidated gravel or subjectively to minimize structural relief between the nearest wells that contained the contact. In three petroleum-exploration wells in the southern part of the study area (287, 288, and 289, table A1), the upper contact of the Salt Lake Formation was picked by the well-site geologist based on fossil assemblages.

6. Twenty-four additional strip-log sections were drawn in the area of the first eight sections and in the southern two-thirds of Bear River Valley (locations on plate 3 inset) to test whether Oaks' (1998, 2000, 2008) stratigraphic framework could be applied to the entire main study area. The contacts could be satisfactorily drawn in most well logs, so the lithologic units were applied to the entire study area and were assigned new nomenclature that reflected their lithology (figure 6). Interpretations of depositional environment, age, and lake cycle presented later in the report are speculative because no cuttings were studied nor were any new age data obtained for this study. Some wells were not deep enough to encounter all of the contacts. In these cases the contacts were projected linearly from the nearest wells in which they could be identified. Below the mountain fronts, where logs lacked the clearly delineated stratigraphic succession established by Oaks (1998, 2000, 2008), the deposits were assigned a separate lithologic unit interpreted to grade laterally with the well-defined units beneath the valley floor. Some logs showed mixed clay and gravel in the depth range where a contact was expected based on adjacent wells. In these cases, contacts between predominantly fine- and coarse-grained layers were projected linearly from adjacent wells. In some logs, mainly in southern Bear River Valley, one or both of the upper gravel layers were absent. In these cases, the upper gravel layer(s) was assumed to pinch out on each side of the wells in which it was absent, and the contact between adjacent fine-grained layers was drawn by linear projection between wells in which the gravel layer was present.

7. The contacts in the younger basin fill were gridded using the inverse distance weighted method and viewed in three dimensions to ensure that there were no errant wells or contact picks, and that the interpreted surfaces were geologically reasonable, i.e., that there were no abrupt thickness or geometric changes that could not be explained by the local geology, particularly faults. Isopach maps for lithologic units in the younger basin fill were derived from the grids (figures 7 through 14).

Results

Lithologic Units

The younger basin fill was divided into eight lithologic units based on the methods described in the previous section. Figure 6 provides lithologic descriptions and schematically illustrates their stratigraphic relations. Lithologic units in the younger basin fill below the valley floor are, in descending stratigraphic order, gsf1, f1, gsf2, f2, gsf4, f3, and gsf5. In this nomenclature, f indicates predominantly fine-grained (clay and silt) and gsf indicates predominantly gravel and sand, plus comparatively minor fines. Throughout the main study area, an abrupt facies transition lies near the boundary between the valley floor and mountain front, where the distinct, alternating predominantly fine- and coarse-grained deposits grade laterally into mixed fine- and coarse-grained deposits, either mixed clay and gravel, or alternating coarse- and fine-grained deposits that lack lateral continuity and consistent stacking order. Lithologic units on the mountain-front side of the facies transition are units gsf1 and gsf3.

Lithologic unit gsf1 is the youngest predominantly sand and gravel unit and is present along the mountain fronts and in the top parts of many wells on the valley-floor side of the facies transition. Lithologic unit gsf1 includes the youngest alluvial-fan and coarse-grained stream deposits in the study area, and its thickness ranges from 0 to about 200 feet.

Lithologic unit f1, the youngest predominantly fine-grained layer, consists of clay and less abundant silt and is present in every well log on the valley-floor side of the facies transition. In north Bothwell Pocket and southeast of the West Hills, unit f1 was identified on the mountain-front side of the facies transition, based on the presence of a 5- to 30-foot-thick clay layer that exhibits lateral continuity with unit f1 in nearby wells on the valley-floor side of the facies transition. Unit f1 ranges from 0 to 130 feet thick and has local thickness maxima beneath Malad Valley and Bear River Valley northeast of Tremonton, Utah, and west of Brigham City, Utah (figure 7). The depositional maximum west of Brigham City is defined by eight water-well logs and three petroleum-exploration well logs (figure 7).

Lithologic unit gsf2 is the highest coarse-grained deposit below the upper clay deposits of unit f1 and consists mainly of gravel, but includes sand and gravel or only sand in some well logs. Unit gsf2 exhibits lateral continuity in most places on the valley-floor side of the facies transition, and its thickness ranges from 0 to 60 feet. Unit gsf2 is thickest beneath Bear River Valley north-northeast of Tremonton and northwest of Brigham City (figure 8). Lithologic unit gsf2 and underlying

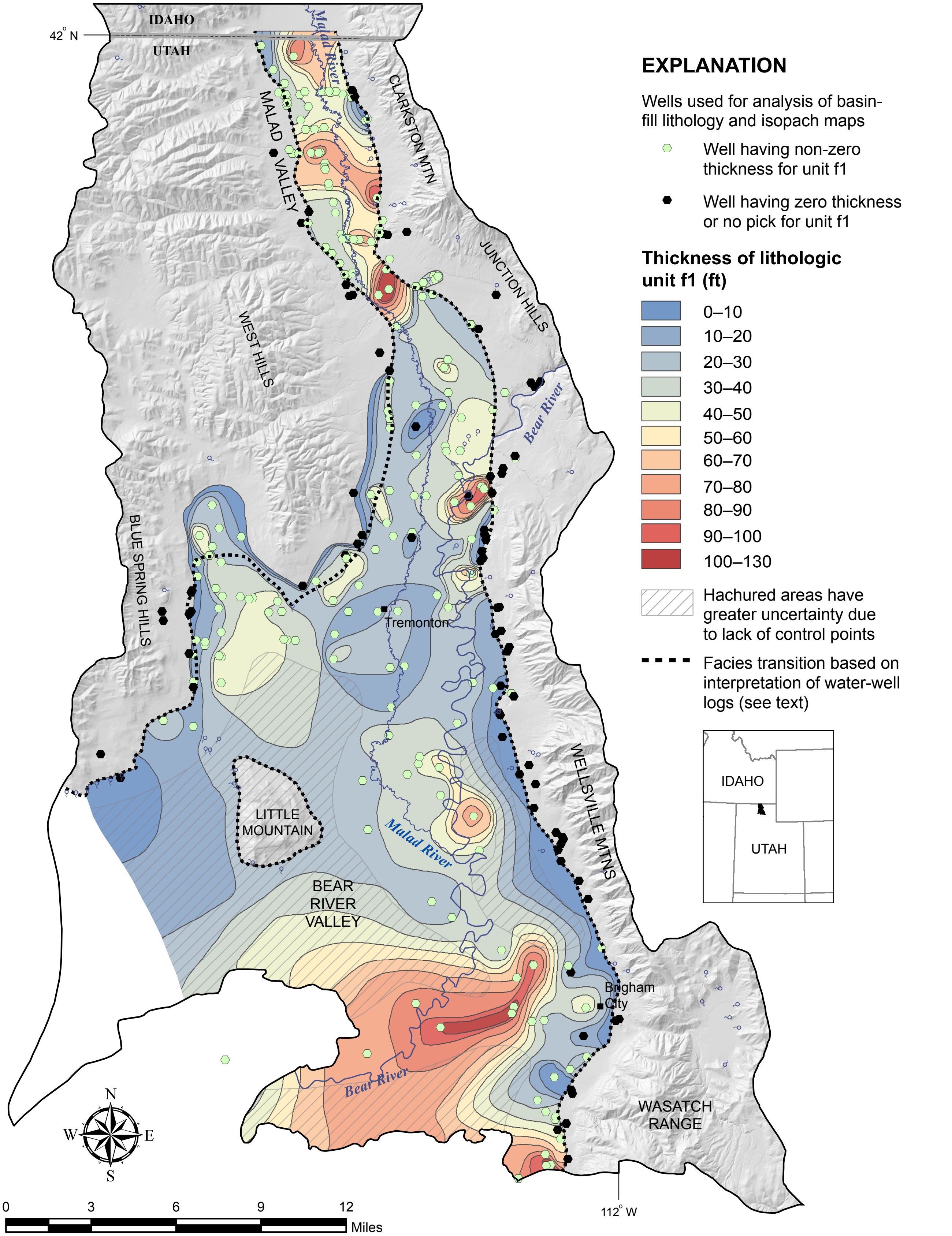


***Figure 7.** Isopach map of lithologic unit f1. See figure 6 and text for unit description and correlations. Unit f1 crosses the facies boundary in places where it was identified in wells on the mountain-front side of the facies transition, but as a rule grades laterally into unit gsf3. Where f1 grades laterally to gsf3, contours for f1 are shown to end abruptly at the facies transition. Where f1 crosses the facies transition, contours cross the facies transition.*

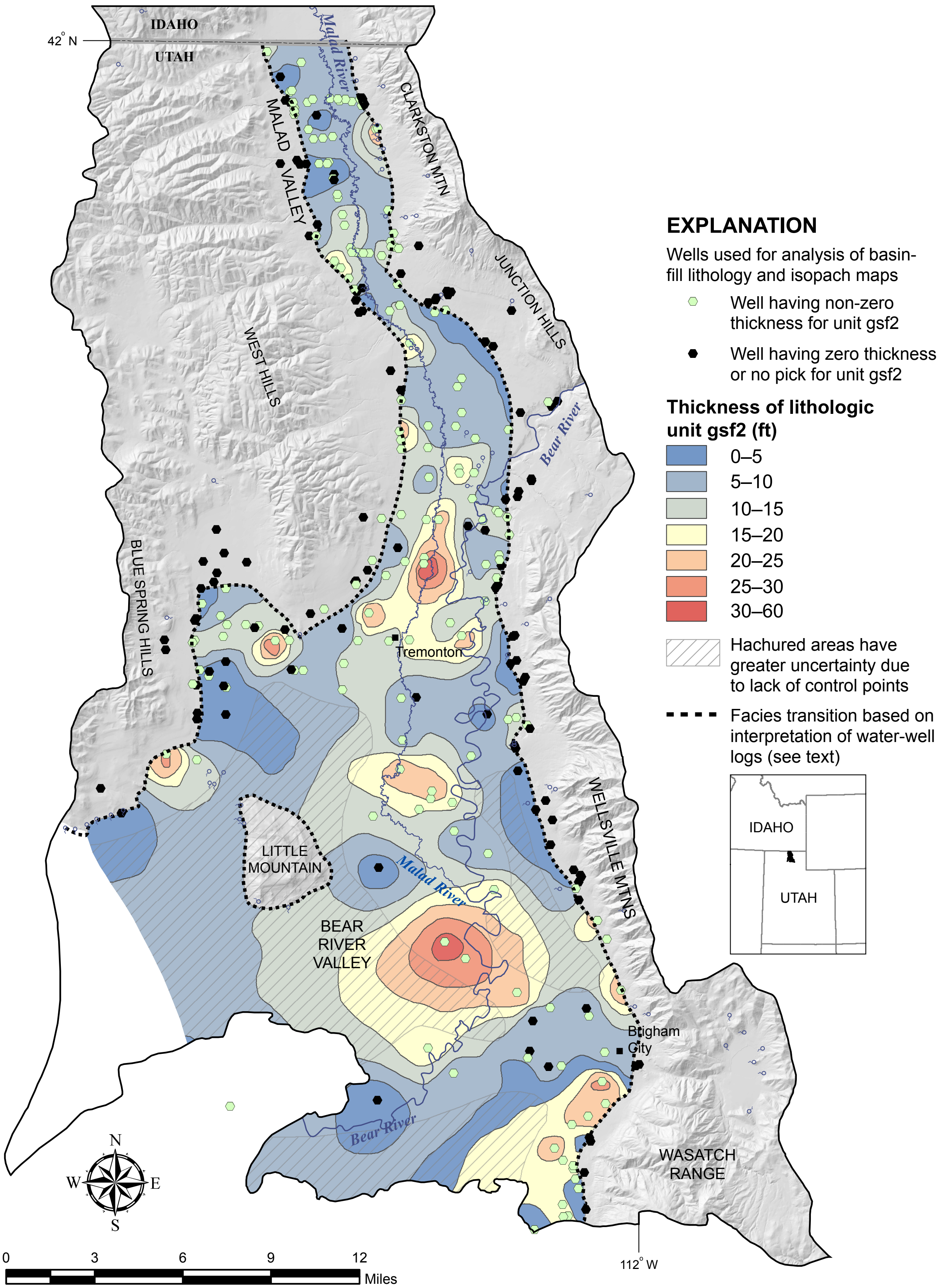


Figure 8. *Isopach map of lithologic unit gsf2. See figure 6 and text for unit description and correlation. Unit gsf2 grades laterally into unit gsf3 at the facies transition where its contours are shown to end abruptly, although deposits of the two units are continuous and thickness discontinuities exist only near faults.*

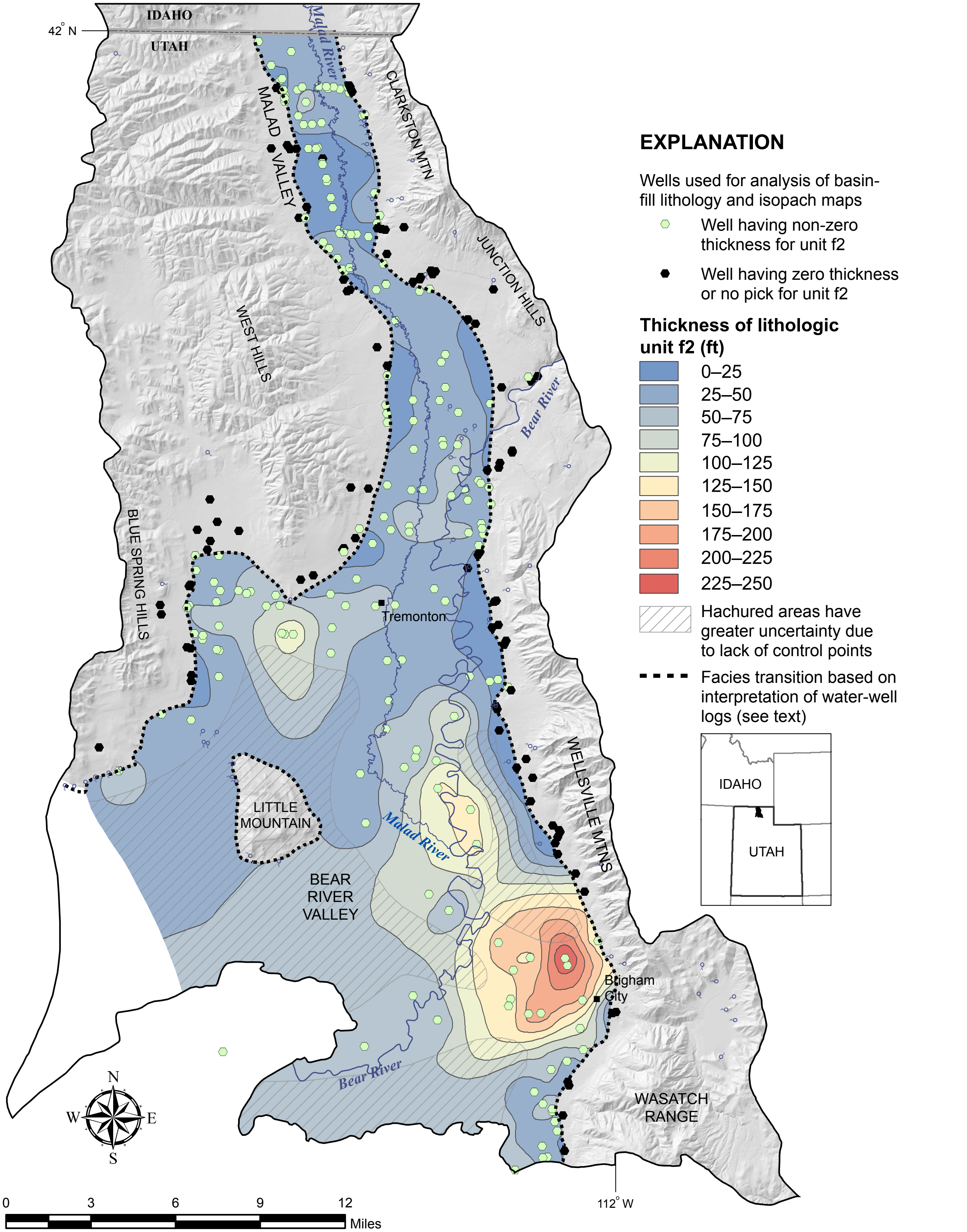


Figure 9. *Isopach map of lithologic unit f2. See figure 6 and text for unit description and correlation. Unit f2 grades laterally into unit gsf3 at the facies transition where its contours are shown to end abruptly, although deposits of the two units are continuous and thickness discontinuities exist only near faults.*

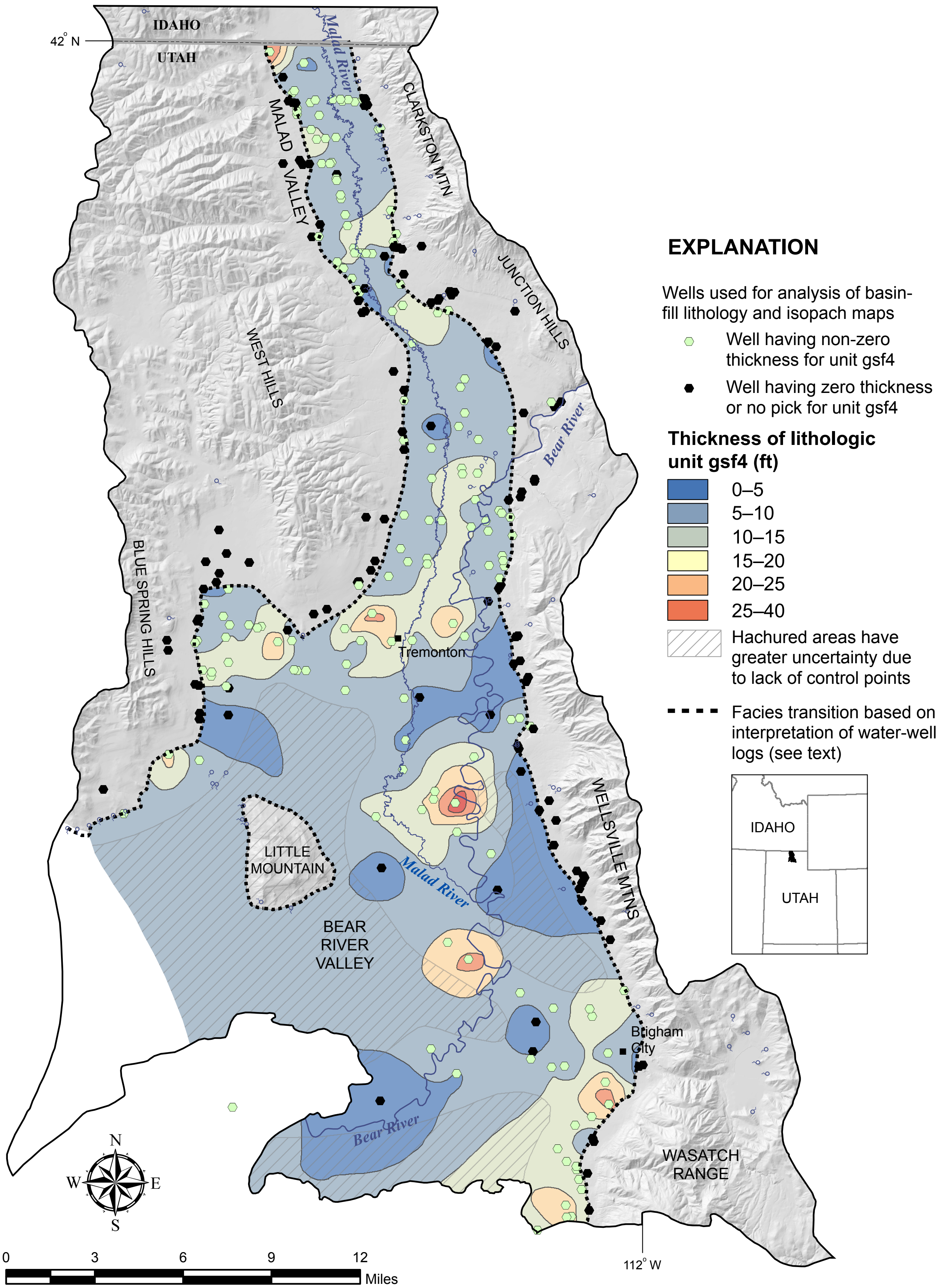


***Figure 10.** Isopach map of lithologic unit gsf4. See figure 6 and text for unit description and correlation. Unit gsf4 grades laterally into unit gsf3 at the facies transition where its contours are shown to end abruptly, although deposits of the two units are continuous and thickness discontinuities exist only near faults.*

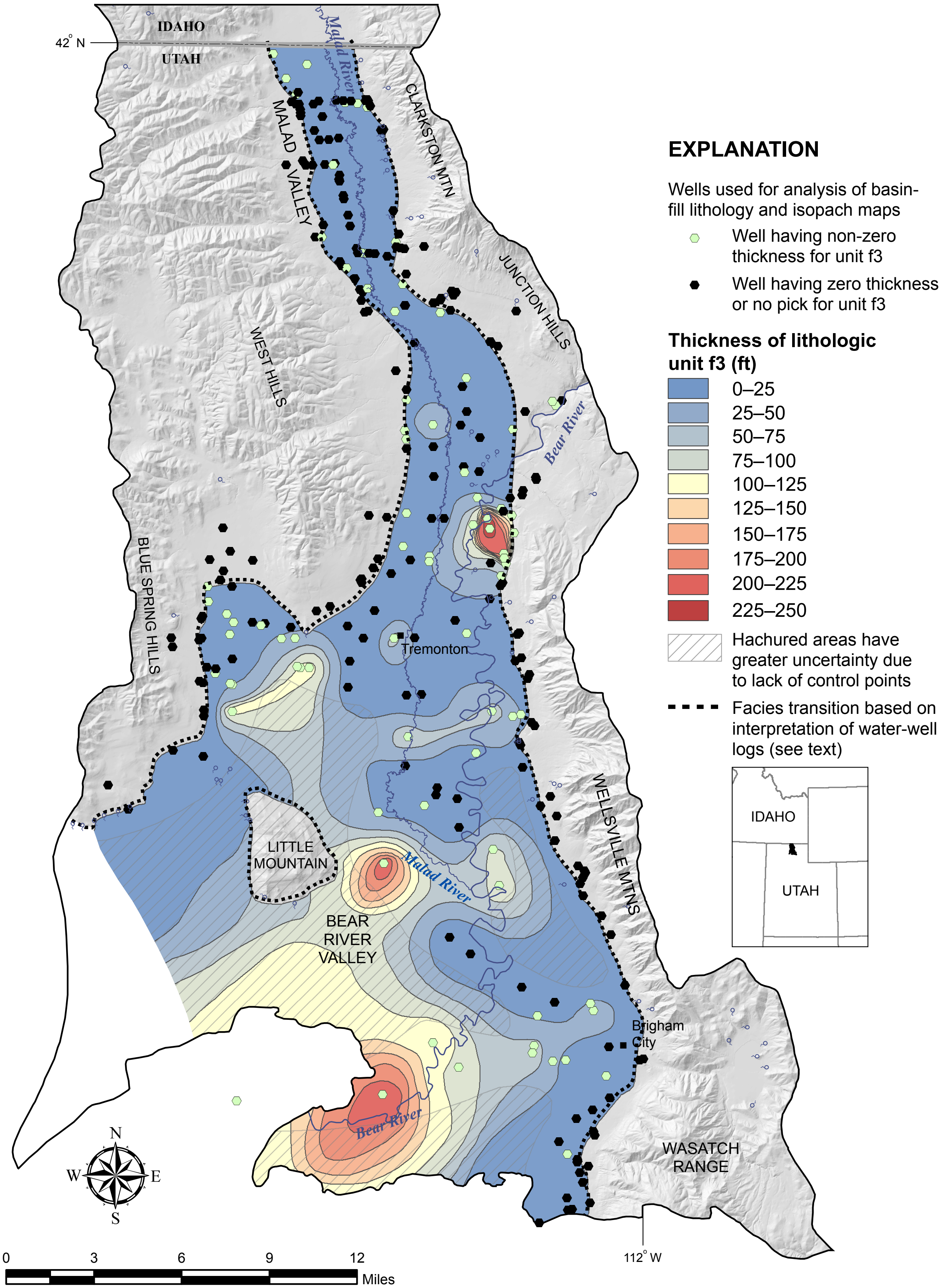


Figure 11. Isopach map of lithologic unit f3. See figure 6 and text for unit description and correlation. Unit f3 is interpreted to grade laterally and vertically into unit gsf5, so its contours are highly schematic.

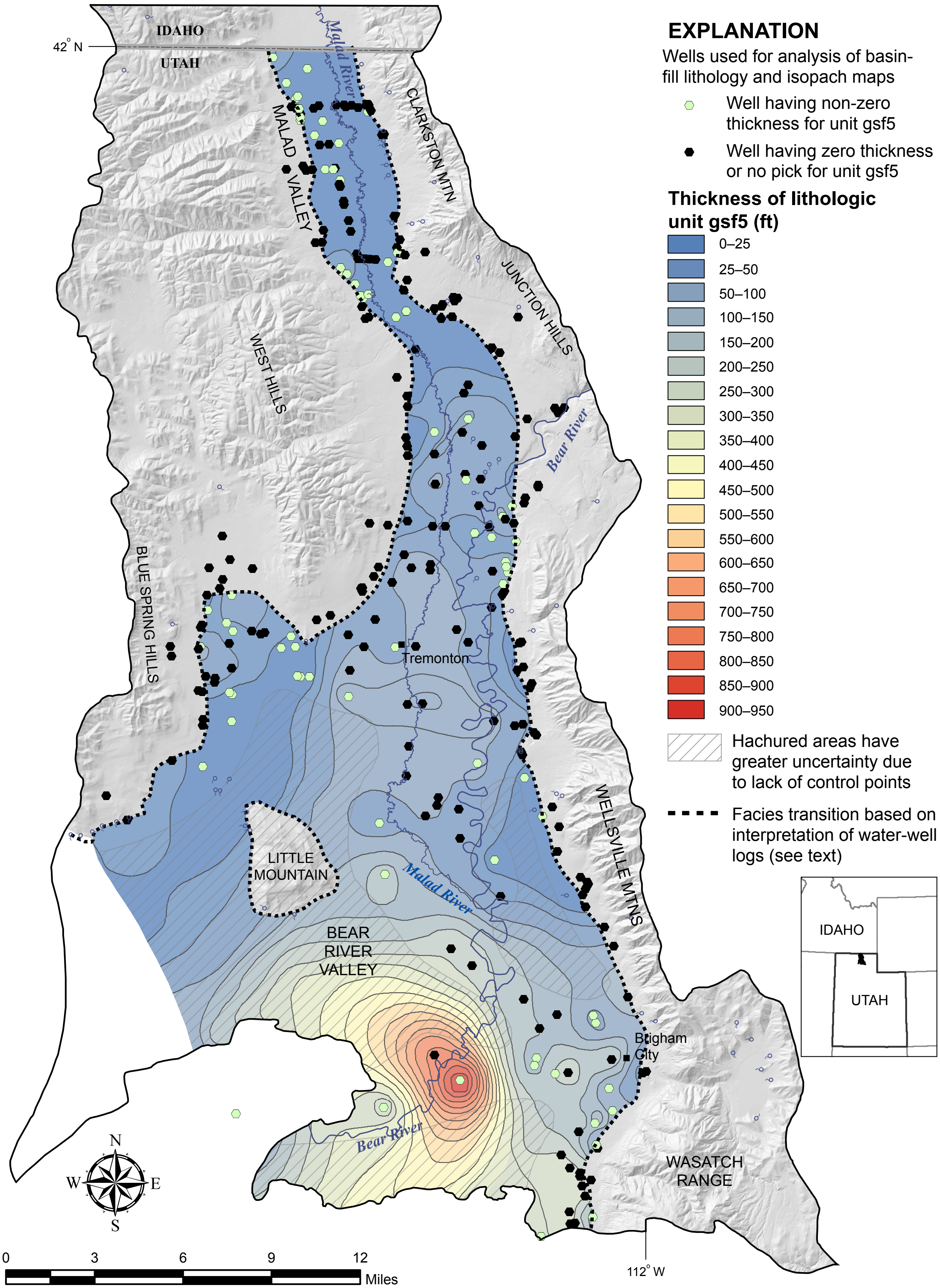


Figure 12. *Isopach map of lithologic unit gsf5. See figure 6 and text for unit description and correlation. Unit gsf5 grades laterally into unit gsf3 at the facies transition where its contours are shown to end abruptly, although deposits of the two units are continuous and thickness discontinuities exist only near faults.*

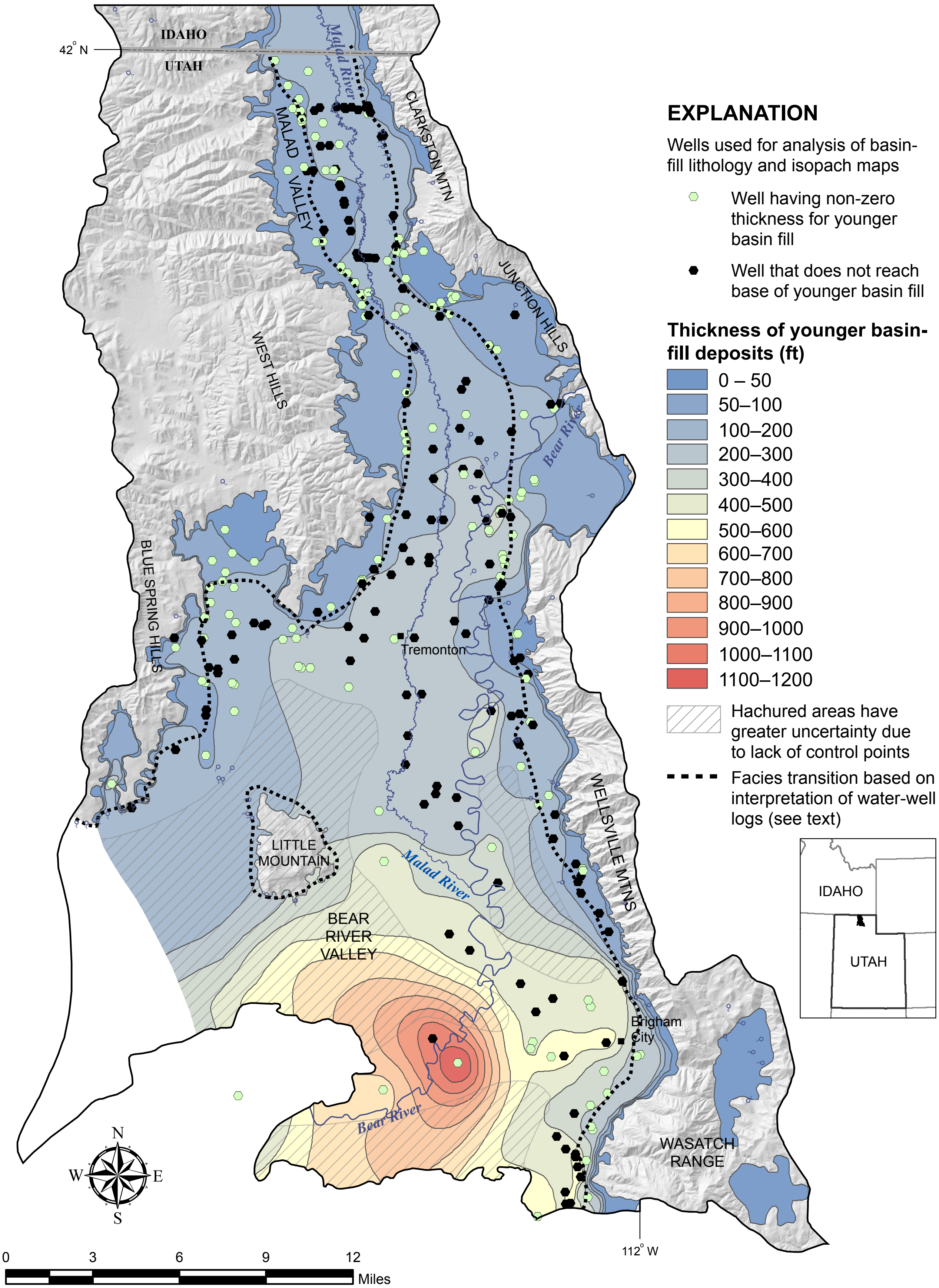


Figure 13. *Isopach map of the younger basin fill, i.e., lithologic units f1, gsf2, f2, gsf3, gsf4, f3, and gsf5 combined.*

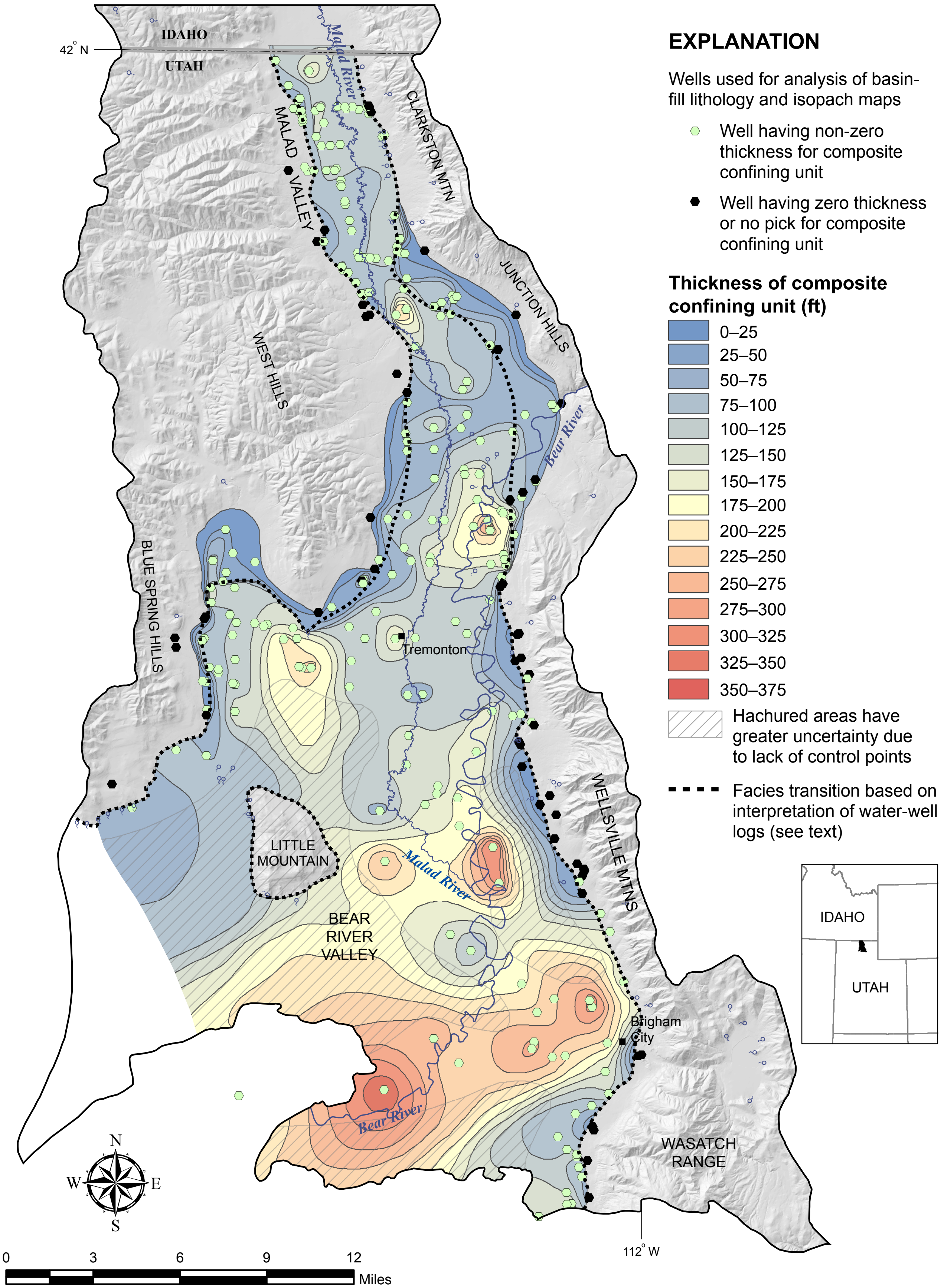


Figure 14. *Isopach map of the composite confining unit on the valley-floor side of the facies transition, i.e., lithologic units f1, gsf2, f2, gsf4, and f3.*

units of the younger basin fill are subsurface units that are not likely exposed in the main study area, except perhaps locally in gravel pits or deeply eroded gullies.

Lithologic unit f2 is a predominantly fine-grained deposit below the upper sand and gravel unit (gsf2). The unit exhibits lateral continuity on the valley-floor side of the facies transition and is absent on the mountain-front side of the facies transition. Unit f2 ranges from 5 to 250 feet thick, but is 25 to 75 feet thick throughout most of the main study area (figure 9). The thickness maximum is defined by 13 well logs beneath Bear River Valley west of Brigham City, Utah.

Lithologic unit gsf3 is composed of gravel, sand, and less abundant clay deposits, either as mixed clay and gravel or interlayered at a fine scale. This unit is present on the mountain-front side of the facies transition and grades laterally into the lithologic units defined below the valley floor. Unit gsf3 ranges from 0 to about 200 feet thick.

Lithologic unit gsf4 is the predominantly coarse-grained deposit below the middle clay layer (lithologic unit f2) and consists mainly of gravel, but includes sand and gravel or only sand in some well logs. Unit gsf4 exhibits lateral continuity in most places and its thickness ranges from 0 to 40 feet (figure 10). It is 5 to 15 feet thick throughout most of the study area and has four thickness maxima beneath Bear River Valley near and southeast of Tremonton, Utah, each defined by one to eight well logs (figure 10).

Lithologic unit f3 consists of predominantly fine-grained deposits below the second gravel unit (gsf4). The unit was delineated in logs where a clay layer at least 5 feet thick underlies unit gsf4. In logs lacking a distinct clay layer below gsf4, the lithologic unit was designated as gsf5 (next paragraph). Unit f3 is interpreted to overlie and grade laterally with lithologic unit gsf5, which contains variable amounts of clay (figure 6). Unit f3 is generally 50 to 125 feet thick and is more than 200 feet thick in two wells in the southern Bear River Valley (figure 11).

Lithologic unit gsf5 is composed of mixed clay and gravel deposits or interlayered gravel, sand, and clay below the lower gravel unit gsf4 or below lithologic unit f3 where present. Unit gsf5 is present throughout the main study area except in some well logs in Malad Valley where lithologic units f2 or gsf4 overlie the Salt Lake Formation. Only 76 wells on the valley-floor side of the facies transition penetrate the entire thickness of unit gsf5, so figure 12 shows its minimum thickness in most places. Figure 12 is a schematic representation of thickness given the relatively sparse well coverage combined with the gradational relationship with unit f3 and the uncertainty in identifying the top of the Salt Lake Formation. Thickness is variable and ranges from 0 to 300 feet across most of the main study area (figure 12). Unit gsf5 is generally less than 25 feet thick beneath Malad Valley and gradually thickens southward beneath Bear River Valley. A pronounced, northeast-trending thickness maximum of up to 1050 feet west of Brigham City is defined by 20 well logs, including four petroleum-exploration well logs (figure 12).

Figure 13 is a generalized isopach map of the entire younger basin fill (i.e., the eight lithologic units combined). This map includes both sides of the facies transition, in contrast to figures 8 through 12 which show the lithologic units only on the valley-floor side of the facies transition. Isopach values of the younger basin fill on the mountain-front side of the facies transition represent the combined thickness of lithologic units gsf1 and gsf3. The younger basin fill is less than 300 feet thick beneath Malad Valley and the northern half of Bear River Valley. At the latitude of Little Mountain, the younger basin fill thickens southward to a depositional maximum west of Brigham City where it is more than 1000 feet thick in two wells.

Figure 14 is a generalized isopach map of lithologic units f1, gsf2, f2, gsf4, and f3 combined, and shows the thickness of the predominantly fine-grained part of the younger basin-fill deposits. Together these units form a composite confining unit, as explained in the "Hydrostratigraphy" section. This map shows the minimum thickness of the composite confining unit, because not all of the wells penetrate it entirely. The thickness of the composite confining unit ranges from less than 10 feet to locally more than 200 feet in Malad Valley and the northern half of Bear River Valley. The unit is generally thicker, up to 375 feet, in the southern half of Bear River Valley.

Figure 15 is a schematic contour map of the elevation of the top of the Salt Lake Formation as identified in this study and is subject to the uncertainties in identifying its upper contact described in the "Methods" section. The elevation of the top of the Salt Lake Formation varies smoothly (figure 15) and is generally higher adjacent to the mountain fronts than beneath the valley floor where greater cumulative subsidence in the hanging wall of the WFZ has occurred. The pronounced deepening of the top of the Salt Lake Formation beneath southern Bear River Valley is defined by three well logs, two of which are from petroleum-exploration wells. This downwarp may be caused by a northwest-striking normal fault (i.e., a synthetic fault to the WFZ) in the basin or to southward-increasing displacement on the WFZ and resulting increased hanging-wall subsidence.

Strip-log Sections

The four strip-log sections on plate 3 show the lithology of the well logs, interpreted contacts between the lithologic units, lateral thickness variations of these units, the facies transition, and interpreted faults. The sections display many of the lithologic variations, stratigraphy, and interpretive problems encountered on the other 28 sections. In simplified three-dimensional view of selected contacts beneath Malad Valley, the contact surfaces and thicknesses vary in a geologically reasonable manner (figure 16A), and abrupt changes in contact elevations between adjacent wells can be explained by faults along the mountain front (figure 16B).

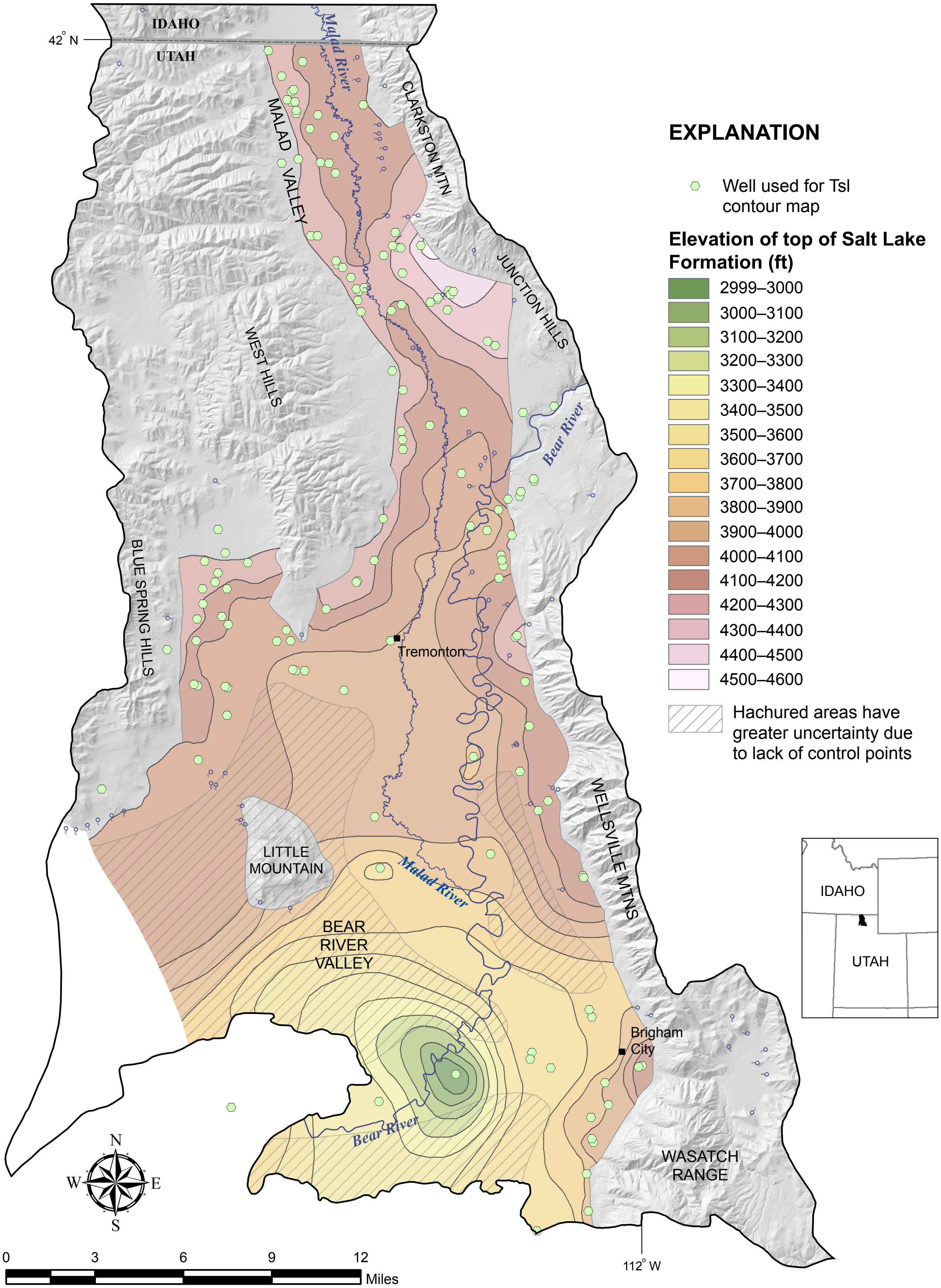


Figure 15. *Structure-contour map of the top of the Salt Lake Formation, equivalent to the base of lithologic unit gsf5.*

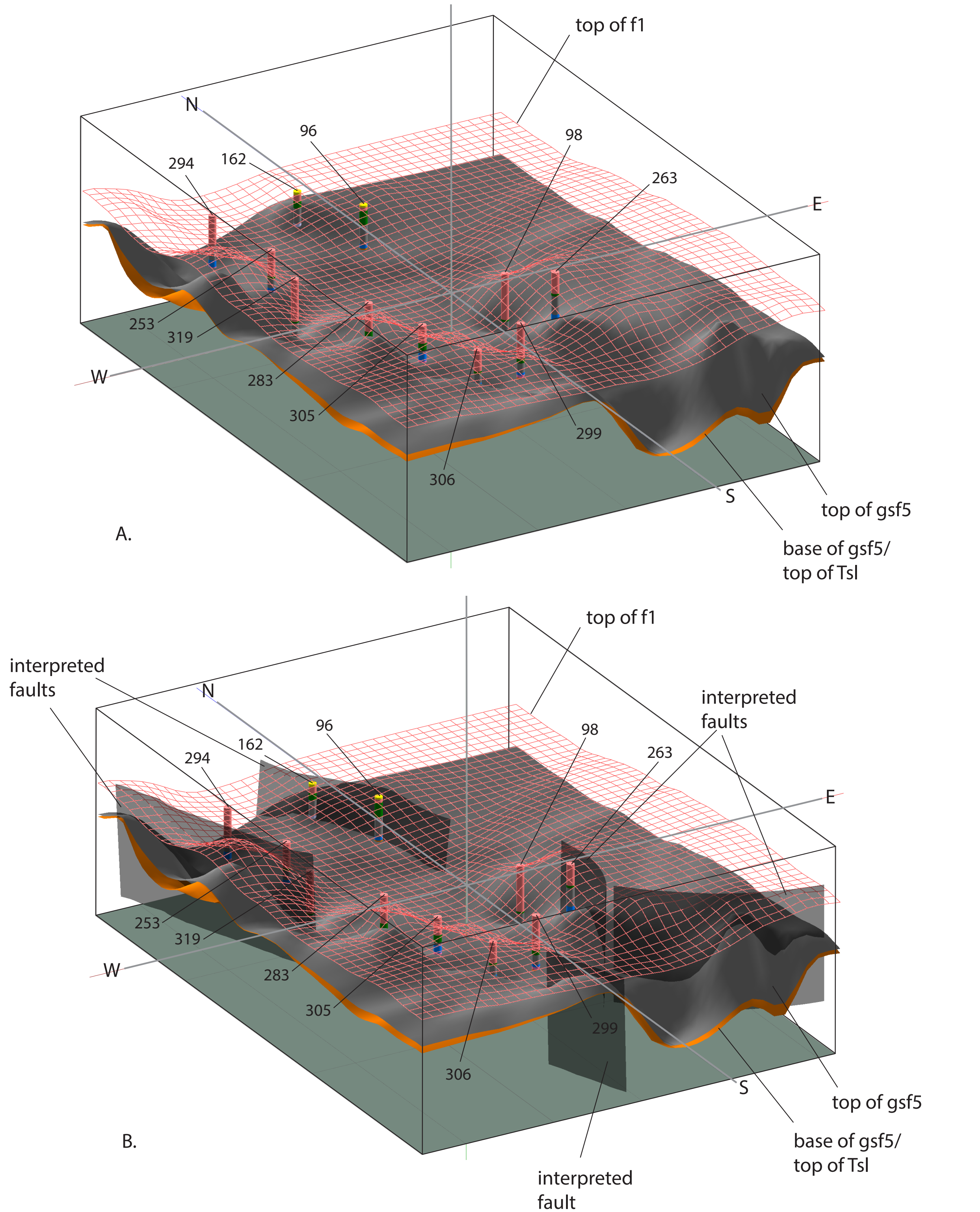


Figure 16. *Three-dimensional representation of the upper contact of lithologic unit f1 (red wire net symbol) and the upper and lower contacts of lithologic unit gsf5 (gray and orange surfaces, respectively) in the Utah part of Malad Valley where Oaks (1998, 2000, 2008) drew his cross sections that defined the lithologic and stratigraphic framework for the younger basin fill that forms the basis for the stratigraphy used in this study. The approximate location is shown in the plate 3 inset, and selected wells are shown for spatial reference. The volume between the upper contact of f1 and the upper contact of gsf5 composes the composite confining unit, and the volume between the upper and lower surfaces of gsf5 composes the deep sand and gravel aquifer. (A) Contact surfaces. (B) Contact surfaces and interpreted faults.*

Section A–A′ is based on one of eight sections by Oaks (2008) in the Utah part of Malad Valley (plate 3). Most contacts gradually increase in elevation toward the valley margins, due to a combination of differential subsidence/uplift during Quaternary normal faulting and paleotopography. Several wells are not deep enough to penetrate into unit gsf4 or to the top of the Salt Lake Formation (Tsl), so contacts are projected below these well logs, either between wells in this section or crossing sections. In the middle part of section A–A′, the lithologic units below gsf2 are at substantially different elevations in wells 281 and 151. This offset is based mainly on the interpreted location of the upper surface of Tsl. The offset could be due to an intrabasin normal fault as shown in the section, or unit gsf4 may pinch out laterally and its correlation between wells 281 and 151 may be incorrect. The facies transition is defined in section A–A′ by the compositional differences between well 274 (valley-floor side) and wells 152 and 102 (mountain-front side) on the west end of the section, and between well 162 (valley-floor side) and wells 284 and 259 (mountain-front side) on the east end of the section. In both cases, the lithologic units in the central part of the section do not extend to wells near the section ends. This example is typical of the facies transition in most sections. Although not the case in every section, the facies transition commonly coincides with an interpreted fault as observed on the west end of section A–A′.

Section B–B′ (plate 3) is at the northern end of Bear River Valley. In the central part of the section beneath the valley floor, lithologic units f1, gsf2, f2, and gsf4 are present in all wells except 210 and 148. At the western end of the section, wells 227, 224, and 225 are aligned from north to south. The upper four units of the younger basin fill are identified in these wells, lithologic unit gsf4 is present only in well 224, unit f3 is markedly thinner than beneath the valley floor, and unit gsf 5 is absent. The facies transition likely lies immediately west of these wells. Two east-dipping normal faults are interpreted at the western end of the section based on offset of the top of the Salt Lake Formation, but their existence is speculative considering the difficulty in picking this contact and the relatively great distance between wells 148 and 227. The contact may instead slope continuously between these two wells. The position of the facies transition is not closely constrained at the east end of section B–B′ due to the substantial distance between wells 237 and 238. The facies transition likely coincides with normal faults, interpreted from offset of the top of Tsl and Paleozoic bedrock, and thickness variations in Tsl. The eastern end of section B–B′ traverses the Junction Hills mountain front and the WFZ, so the interpreted normal faults on the section are consistent with the known geologic setting (Goessel, 1999; Goessel and others, 1999; Oaks, 2000).

Section C–C′ (plate 3) is in the central part of Bear River Valley. In the central part of the section beneath the valley floor, the younger basin-fill lithologic units are present and exhibit geologically reasonable lateral persistence and thickness variations. Lithologic unit gsf2 is interpreted to pinch out on either side adjacent to the central part of the section, unit f3 thins toward the eastern part of the section and pinches out in the west, and unit gsf5 is thickest in the central part of the section. At the western end of the section, the facies transition is not well constrained due to the substantial distance between wells 202 and 203. The facies transition is interpreted to coincide with an east-side-down normal fault between the two wells based on the vertical offset of the contact between basin fill and bedrock of at least 600 feet between wells 203 and 131. At the eastern end of the section, the facies transition is interpreted to lie between wells 329 and 39, at an east-side-down normal fault interpreted from the vertical offset of the basin fill-bedrock contact. The east end of the section crosses the Collinston segment of the WFZ. The interpreted fault at the east end of section C–C′ may be a small antithetic fault within the WFZ.

Section D–D′ (plate 3) is in southern Bear River Valley. In the western and central parts of the section, beneath the valley floor, the younger basin-fill lithologic units are identified in most of the logs, but units gsf2 and gsf4 are absent in wells 289 and 169, and gsf2 is absent in well 12, where they are interpreted to locally pinch out. Lithologic units f3 and gsf5 are difficult to delineate in wells 289 and 288, illustrating the degree of uncertainty in the isopach maps (figures 11 and 12) for these units beneath southern Bear River Valley. In the central part of the section, wells 287, 288, and 289 are petroleum-exploration wells (table A1) in which the upper contact of the Salt Lake Formation was picked by the well driller's geologist based on fossils, so is considered reliable. Wells 169 and 12 are water wells in which the top of the Salt Lake Formation is picked based on the shallowest appearance of green clay in the logs. The top of the green clay in well 169 is about 250 feet higher than in well 12 to the east and about 180 feet higher than the top of Tsl in well 288. These relations suggest that well 169 may occupy a small horst in the basin fill, as shown by the interpreted normal faults on either side of the well log in the section. At the east end of the section, the facies transition is poorly constrained due to the substantial distance between well 17 on the valley floor and wells 170, 155, and 113 along the mountain front.

Water Wells in the Younger Basin Fill

The strip-log sections show the perforated intervals and water levels from the driller's logs, where available. The water levels were measured after drilling and through a wide range of years, so this data cannot be used to define a potentiometric surface. In most wells on the valley-floor side of the facies transition that have restricted open intervals (generally less than one-third of the total well depth), the water level is above the overlying predominantly fine-grained lithologic unit, indicating confined conditions. Most wells on the mountain-front side of the facies transition are open to lithologic unit gsf3 and/or the underlying Salt Lake Formation or bedrock. Water levels in wells open to underlying formations are variable, but most are higher than the base of unit gsf3, suggesting that fine-grained parts of that unit locally create confined conditions.

Table 2 summarizes the number of well screens in the younger basin-fill lithologic units on the valley-floor side of the facies transition. The numbers are subject to the uncertainties associated with defining these units from the well logs as discussed in the "Methods" section. Most wells have one perforated interval, but some have three or more. Each perforated interval is treated as a "well" in table 2. Most wells are open to at least part of one of the three predominantly coarse-grained units below unit f1 (gsf2, gsf4, or gsf5), and each has a roughly similar number of screens. Table 2 suggests that each of these three units supplies water to a significant number of wells in Malad and Bear River valleys, and each can be considered an aquifer. Lithologic unit f2 has a surprisingly large number of partial screens, suggesting that contact locations and/or casing perforation techniques are imprecise, but based on its dominant grain-size composition, unit f2 does not likely yield significant amounts of water to wells compared to the predominantly coarse-grained units.

Correlations

The lithologic units in the younger basin fill of the Malad–Lower Bear River basin defined in this study are based on, and generally consistent with, results from previous work in the Utah part of Malad Valley and northern Bear River Valley (Oaks, 2000, 2003b, 2008) and Cache Valley (Williams, 1962; Bjorklund and McGreevy, 1971; Robinson, 1999; Oaks and others, 2014). Table 3 shows that the lithologic units are consistent with previous work along the Wasatch Front (Gilbert, 1890; Hunt and others, 1953; Varnes and Van Horn, 1961) and central Utah (Oviatt and others, 1994). Formational and lake-cycle nomenclature has evolved through more than 100 years of study, but the basic lithologic succession and its relation to lake cycles has remained consistent. Several of the previous studies interpreted the second lowest clay-rich lithologic unit (f2 in this study) as having been deposited during an older part of the Bonneville lake cycle, whereas Oaks and others (2014) correlated these deposits with the Cutler Dam lake cycle (table 3), the interpretation adopted here. Cores recovered from deep boreholes along the northern shore of Great Salt Lake show similar lithologic succession and thickness ranges to the lithologic units defined in the Malad–Bear River basin for this study, based on the author's evaluation of logs published by Eardley and Gvosdetsky (1960, plate 1) and Eardley and others (1973, figure 1). The interpreted depositional environments and lake cycle of the lithologic units defined in this study (figures 5 and 6; table 3), described in the following paragraphs, are based on the tentative correlations shown in table 3.

Interpreted Depositional Environments

Lithologic unit gsf1 comprises modern alluvial-fan and fluvial deposits and shore-zone sand and gravel that were deposited during the Lake Bonneville cycle (figure 5). Lithologic unit gsf3 is interpreted as mixed alluvial-fan and lacustrine deposits, older and below the surficial deposits of gsf1, that were deposited along the mountain fronts and cannot be separated readily into distinct units. Jensen and King (1999) mapped deltaic deposits near Brigham City, so some of lithologic unit gsf3 is likely mixed lacustrine-deltaic and alluvial-fan deposits in the Brigham City area and perhaps along parts of the mountain front to the north. Unit gsf3 is interpreted to grade laterally across the facies transition into lithologic units f1, gsf2, f2, gsf4, and f3, and gsf5.

The youngest two fine-grained units (f1 and f2) are interpreted as lake-bottom clay and marl deposited during the Lake Bonneville and Cutler Dam lake cycles, respectively, following Oaks and others (2014). By analogy with the work of Oviatt and others (1994), units gsf2 and gsf4 are interpreted here as alluvium deposited between lake cycles, and/or sublacustrine-fan deposits formed during transgressive or regressive phases of the lake cycles. The lithologic-unit contacts, therefore, may not directly coincide with lake- cycle boundaries. Transition between lake cycles likely included changes in depositional environment, shallow-water reworking, and subaerial erosion, explaining some of the observed compositional variability and thickness variations.

Table 2. *Number of open intervals in each lithologic unit of the Malad–Lower Bear River younger basin fill. An open interval includes perforations in steel casing, screens in PVC, and the base of the casing for non-perforated wells. Several wells have multiple open intervals so may count as open to two or more lithologic units.*

Lithologic Unit	Number of Open Intervals	Number of Fully Penetrating Open Intervals	Number of Partial Open Intervals
f1	20	0	20
gsf2	36	13	23
f2	55	8	46
gsf4	49	15	34
f3	17	1	16
gsf5	43	15	29
Tsl	91	77	14

Table 3. *Comparison of basin-fill lithologic units in this study and previous publications.*

<table>
<tr><th>Gilbert (1890)</th><th>Hunt and others (1953)</th><th>Varnes and Van Horn (1961)</th><th>Williams (1962)</th><th colspan="2">Oviatt and others (1994)</th><th>Oaks (2008)</th><th colspan="2">Robinson (1999)</th><th colspan="2">This Study</th><th>Lake Cycle</th></tr>
<tr><td></td><td>Post-Provo Formation Deposits</td><td></td><td>Post-Lake Bonneville Deposits</td><td colspan="2">po-BS</td><td>Q</td><td colspan="2">Qau</td><td colspan="2">gsf1</td><td>Great Salt Lake</td></tr>
<tr><td>White Marl</td><td rowspan="2">Provo Formation</td><td>Bonneville Formation</td><td>Provo Formation</td><td>BM</td><td rowspan="3">BS</td><td>Qlb</td><td>B1</td><td rowspan="4">C1</td><td>f1</td><td rowspan="4">gsf3</td><td rowspan="2">Bonneville</td></tr>
<tr><td>Alluvial Gravel</td><td>Intra-Alpine-Bonneville Deposits</td><td>Alluvium</td><td>BFG, BRU</td><td>“Highest Gravel”</td><td>A1</td><td>gsf2</td></tr>
<tr><td>Yellow Clay</td><td>Alpine Formation</td><td>Alpine Formation</td><td>Alpine and Bonneville Formations</td><td>BM</td><td>Qlv</td><td>B2</td><td>f2</td><td>Cutler Dam</td></tr>
<tr><td colspan="3" rowspan="4"></td><td rowspan="3">Pre-Lake Bonneville Deposits</td><td colspan="2">BTU
LVA</td><td>“2nd Gravel”</td><td rowspan="3">A2</td><td>gsf4</td><td rowspan="2">Little Valley(?)</td></tr>
<tr><td colspan="2" rowspan="2">LVM
LVA
p-LVA</td><td rowspan="2">Q</td><td></td><td>f3</td><td></td></tr>
<tr><td></td><td colspan="2">gsf5</td><td>pre-Little Valley(?)</td></tr>
<tr><td>Tsl</td><td colspan="2"></td><td>Tsl</td><td colspan="2"></td><td colspan="2">Tsl</td><td></td></tr>
</table>

After Oaks and others (2014)

Oviatt and others (1994): po-BS – post-Bonneville sediment; BM – Bonneville marl; BFG – Bonneville fluvial gravel and overbank silt; BRU – Bonneville regressive-phase underflow-fan deposits; BS – Bonneville sediment undivided; BTU – Bonneville transgressive-phase underflow fan; LVA – Little Valley alluvium; LVM – Little Valley marl; p-LVA – pre-Little Valley alluvium.

Oaks (2008): Q – Quaternary deposits undivided; Qlb – Lake Bonneville deposits; Qlv – Little Valley lake deposits.

Robinson (1999): Qau – Quaternary alluvium undifferentiated; B1 – upper confining layer; A1 – upper confined aquifer; B2 – lower confining layer; C1 – deltaic deposits; A2 – lower confined aquifer.

The Quaternary surficial HGUs (Qcs and Qfs) and the younger basin-fill lithologic units delineated in this study have different nomenclatures to reflect different sources and levels of detail. The surficial HGUs were derived from published geologic maps (Long and Link, 2007; Miller and Felger, 2013), whereas the lithologic units are subsurface units derived from analysis of well logs. Lithologic units gsf1 and f1 are the only upper basin-fill units that are exposed and are part of surficial HGUs Qcs and Qfs, respectively (figure 16).

Informal Hydrostratigraphic Units

The lithologic units in the younger basin fill of the Malad–Lower Bear River can be grouped into hydrostratigraphic units (i.e., aquifers and confining units). A hydrostratigraphic unit is “…a body of rock distinguished and characterized by its porosity and permeability [hydraulic conductivity]” (Seaber, 1988, p. 13) that may or may not coincide with all or parts of one or more geologic formations or members (Seaber, 1988, p. 13) and has “…considerable lateral extent [and] acts as a reasonably distinct hydrologic system [and is]…hydraulically continuous, mappable, and scale-independent” (Macfarlane, 2000, p. 3). Few measurements of the porosity and hydraulic conductivity of the younger basin fill of the Malad–Lower Bear River basin exist (table 4) (Bjorklund and McGreevy,

Table 4. *Summary of transmissivity estimates of basin fill by Bjorklund and McGreevy (1974) from the study area and by Inkenbrandt and Lachmar (2012) from Cache Valley.*

Lithologic Unit	Transmissivity (ft^2/day) Average Value; Range	Storage Coefficient
gsf1	1; 0-3500[1]	-
gsf2	9575; 1430–20,000[1]	-
gsf5	13,907; 67–320,000[1] 2000; - [2] 13,000; - [2] 20,000; - [2] 20,000; - [2]	- - - - 6×10^{-4}
Tsl	256; 10–3500[1]	-
Bedrock	2534; 509–36,000[1] 140,000; - [2]	-

Notes:
- Data not available

[1]Inkenbrandt and Lachmar (2012)

[2]Bjorklund and McGreevy (1974)

1974), so informal hydrostratigraphic units in the younger basin fill are assigned here based on predominant grain size. This approach is supported by the similarity in basin-fill stratigraphy between the main study area and Cache Valley (table 2), for which Robinson (1999) and Inkenbrandt and Lachmar (2012) used abundant well-log and well-test data to define hydrostratigraphic units.

Informal hydrostratigraphic units include the shallow sand and gravel aquifer, the composite confining unit, the underlying deep sand and gravel aquifer, and the mountain-front sand and gravel aquifer (figure 17). The shallow sand and gravel aquifer exists on either side of the facies transition and includes lithologic unit gsf1 and uppermost parts of the underlying lithologic unit f1 that may include some sand and have the capacity to store and transmit ground water. On the valley floor, this aquifer consists primarily of alluvium and it is up to about 20 feet thick based on descriptions of surficial map units in the Clarkston and Portage 7.5-minute quadrangles (Biek and others, 2003) and the Brigham City 7.5-minute quadrangle (Jensen and King, 1999). Along the mountain fronts, the shallow sand and gravel aquifer consists of alluvial-fan and lacustrine shore-zone deposits and is as much as 40 feet thick based on descriptions of surficial map units in the Clarkston and Portage 7.5-minute quadrangles (Biek and others, 2003) and the Brigham City 7.5-minute quadrangle (Jensen and King, 1999). The shallow sand and gravel aquifer defined in this study corresponds to Robinson's (1999) "Quaternary alluvium undifferentiated" (Qau) in Cache Valley, for which Inkenbrandt and Lachmar (2012) estimated a mean transmissivity of 1 ft^2/day (table 4).

The composite confining unit separates the overlying shallow sand and gravel aquifer from the underlying deep sand and gravel aquifer. The composite confining unit includes lithologic units f1, gsf2, f2, gsf4 (where it is underlain by lithologic unit f3), and f3 where present. The composite confining unit includes two relatively thin (less than 35 feet thick) sand and gravel aquifers (gsf2 and gsf4) separated by a clay-rich unit (f2) (figure 17). The composite confining unit ranges in thickness from 5 to 370 feet (figure 14), and is more than 150 feet thick beneath southeastern Bear River Valley. The younger, thin sand and gravel unit within the composite confining unit (gsf2) is likely hydraulically isolated to some extent by the clay-rich deposits that bound it. Unit gsf2 may be hydraulically connected to the mountain-front sand and gravel aquifer near the facies transition (figure 17). The older sand and gravel unit (gsf4) within the composite confining unit is likely hydraulically isolated where it is underlain by clay deposits of lithologic unit f3. Unit gsf4 may be hydraulically connected to the principal sand and gravel aquifer where lithologic unit f3 is absent or thin, and may be hydraulically connected to the mountain front sand and gravel aquifer near the facies transition (figure 17).

The composite confining unit was defined based on the relative thicknesses of the predominantly fine- (f1, f2, and f3) and coarse-grained (gsf2, gsf4) lithologic units and their stratigraphic relations, i.e., the thin aquifers are bounded above and below by clay-rich deposits. Alternatively, the younger basin fill could be divided into four aquifers and three confining units that correspond with the lithologic units, but this approach may be too detailed considering the relative lack of data on the hydraulic properties of the units. The composite confining unit defined here includes the "upper confining layer" (B1), "upper confined aquifer" (A1), and "lower confining layer" (B2) of Robinson (1999) in Cache Valley.

The deep sand and gravel aquifer includes sand, gravel, and clay deposits of lithologic unit gsf5. This aquifer ranges in thickness from 0 to 950 feet and is more than about 300 feet thick beneath southern Bear River Valley (figure 12). The upper contact of the deep sand and gravel aquifer is lithologically and hydraulically indistinct and gradational where it is overlain by lithologic unit gsf4 (figure 17). Bjorklund and McGreevy (1974, table 5) reported transmissivity estimates for their principal groundwater system from two recovery tests and two pumping tests that ranged from 2000 to 140,000 ft^2/day. One recovery test and one pump test each yielded transmissivity estimates of 20,000 ft^2/day, probably the best estimate for the transmissivity of their principal aquifer and the deep sand and gravel aquifer of this study. The deep sand and gravel aquifer corresponds to Robinson's (1999) "lower confined aquifer" (A2) in Cache Valley, for which Inkenbrandt and Lachmar (2012) estimated a mean transmissivity of 13,907 ft^2/day (table 4).

The mountain-front sand and gravel aquifer lies below the shallow sand and gravel aquifer on the mountain-front side of the facies transition and corresponds to lithologic unit gsf3 (figure 17). This hydrostratigraphic unit consists primarily of well layered to poorly sorted alluvial-fan and lacustrine shore-zone deposits and is up to 200 feet thick based on well logs analyzed in this study, although this estimate is uncertain because its lower contact with the Salt Lake Formation is difficult to determine in some well logs. The mountain-front sand and gravel aquifer approximately corresponds in stratigraphic and spatial position to Robinson's (1999) "deltaic deposits" (C1) in Cache Valley. However, as discussed in the previous section, most of unit gsf3 is interpreted here to have formed in alluvial-fan and shallow-lacustrine depositional settings. Inkenbrandt and Lachmar (2012) did not estimate transmissivity for the "deltaic deposits" hydrostratigraphic unit of Robinson (1999).

The Salt Lake Formation is a heterogeneous hydrostratigraphic unit that includes aquifers and local confining units. Where exposed, the Salt Lake Formation is highly faulted and folded and its thickness varies abruptly, ranging from about 900 to 3300 feet in Malad Valley and northern Bear River Valley (Goessel and others, 1999). The formation is likely similarly structurally complex below the valley floor, considering its depositional and deformational history (see

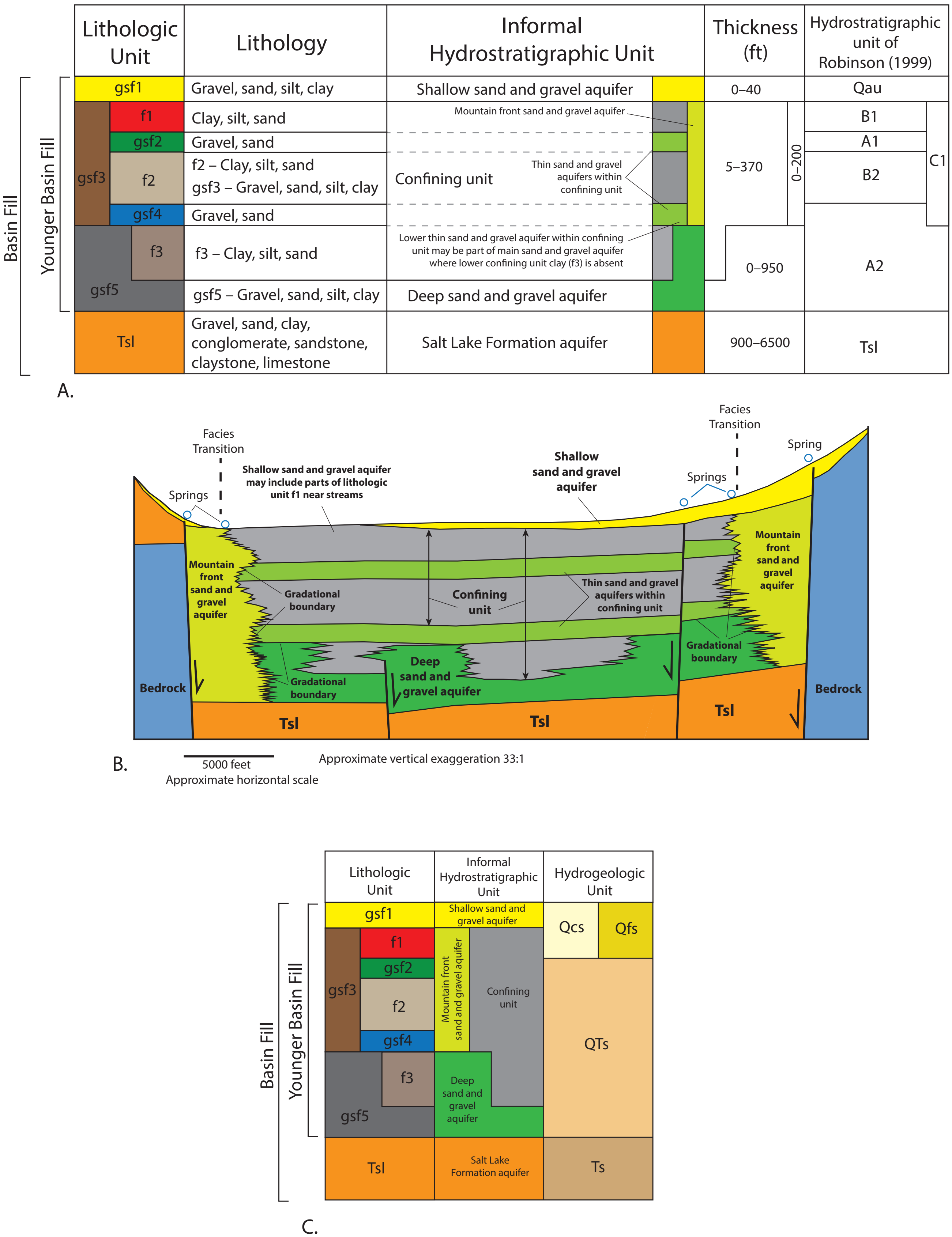


Figure 17. *Description, schematic cross section, and correlations of the informal hydrostratigraphic units defined in this study, derived from the lithologic units (figure 6). (A) Descriptions and stratigraphic relations of informal hydrostratigraphic units and their relation to lithologic units, and correlation with the hydrostratigraphic units of Robinson (1999) in Cache Valley. (B) Schematic cross section of hydrostratigraphic units.(C) Correlations among lithologic, informal hydrostratigraphic, and hydrogeologic units derived in this study.*

Janecke and others, 2003). The Salt Lake Formation is semi-consolidated to consolidated, and its degree of compaction and cementation likely increase with depth, resulting in decreasing hydraulic conductivity with depth. The Salt Lake Formation hydrostratigraphic unit is equivalent to that (Tsl) of Robinson (1999) in Cache Valley, though differences in facies and thicknesses, plus folds and faults, between the two areas likely result in highly variable aquifer characteristics in both areas. Inkenbrandt and Lachmar (2012) estimated a mean transmissivity of 256 ft^2/day for the Salt Lake Formation hydrostratigraphic unit in Cache Valley (table 4).

DISCUSSION

Interpreted Lithologic Units and Informal Hydrostratigraphic Units

Lithologic data (plate 3), isopach maps and grids (figures 7–15), and conceptual models of basin-fill stratigraphy (figure 6) and hydrostratigraphy (figure 17) presented here quantify the structure and physical dimensions of younger basin-fill deposits in the Malad–Lower Bear River basin. Below the valley floor, the shallow sand and gravel aquifer is composed of coarse- to fine-grained deposits of lithologic units gsf1 and, in places, f1. The shallow sand and gravel aquifer overlies a composite confining unit that includes alternating predominantly fine- (f1, f2, and f3) and coarse-grained (gsf2 and gsf4) lithologic units. The composite confining unit overlies a heterogeneous deep sand and gravel aquifer (gsf5) composed of interbedded coarse- and fine-grained deposits, and ranges from about 5 to 360 feet thick (figure 14). The upper two fine-grained lithologic units (f1 and f2) and the upper sand and gravel unit (gsf2) are present in most well logs at consistent depths below the surface, and their thicknesses are consistent, so they provide the best constrained contacts. The thicknesses and distributions of lithologic units f3 and gsf5 are less well constrained, and the position of the upper surface of the Salt Lake Formation is subject to uncertainty. The lithologic units defined here vary to some degree in composition and thickness but, based on the author's evaluation of the well logs, are sufficiently consistent to warrant their delineation.

Comparison to the more thoroughly studied basin-fill stratigraphy of Cache Valley (Williams, 1962; Bjorklund and McGreevy, 1971; Robinson, 1999; Oaks and others, 2014) reinforces this interpretation (table 3). Based on this comparison, the transmissivity estimates of Inkenbrandt and Lachmar (2012) for hydrostratigraphic units in Cache Valley are reasonable, generally representative estimates for correlative units in the Malad–Lower Bear River basin.

Other workers illustrated varying degrees of heterogeneity in their conceptual hydrostratigraphic models of basin-fill deposits for other Wasatch Front valleys, including (1) a general model of lens-shaped, interbedded confining layers and aquifers lacking substantial lateral continuity (Anderson and others, 1994, figure 3); (2) a well-defined, shallow confining unit that separates a shallow, unconfined aquifer and a deeper, confined, heterogeneous principal aquifer composed of interbedded coarse- and fine-grained deposits (Hely and others, 1971, figure 57; Inkenbrandt and Lachmar, 2012); and (3) well defined, alternating predominantly fine- and coarse-grained layers that span much of the depositional basin and grade laterally to heterogeneous interbedded fine-and coarse-grained layers below the valley center (e.g., Clyde and others, 1984). The interpretation of the Malad–Lower Bear River basin-fill hydrostratigraphy presented here is generally similar to the second two conceptual models; the main differences are that the composite confining unit defined in this study is laterally continuous below the valley floor and includes two thin, interbedded, predominantly coarse-grained layers, and the deep sand and gravel aquifer is quite thin in the northern part of the main study area.

Conceptual Model of Groundwater-Flow Patterns

Figure 18 shows a simplified version of the hydrostratigraphy and geometry of the younger basin fill in the Malad–Lower Bear River basin fill to illustrate possible conceptual groundwater-flow paths (this section) and hypothetical scenarios for the effects of new groundwater pumping (next section). Groundwater recharge occurs by infiltration of precipitation, snowmelt, and runoff into bedrock in the mountain blocks and into the younger basin-fill deposits (shallow and mountain-front sand and gravel aquifers) along the mountain fronts (Bjorklund and McGreevy, 1974). Groundwater flows toward the valley floor in the shallow sand and gravel aquifer, or down through the mountain-front sand and gravel aquifer and bedrock, and laterally across the range-bounding normal-fault zones into the deep sand and gravel aquifer, the Salt Lake Formation, or bedrock beneath the basin fill. Most lateral flow diverges above and below the composite confining unit. Groundwater may also enter the thin sand and gravel aquifers within the composite confining unit, either laterally from the mountain-front sand and gravel aquifer or through the predominantly fine-grained deposits. Some groundwater flows upward along the range-bounding normal-fault zones to supply springs.

Flow in the shallow sand and gravel aquifer is toward the streams and the valley center, and the groundwater is hydraulically connected to stream water (figure 18, S1 and S2). The composite confining unit is "leaky,", i.e., it accommodates vertical groundwater flow from the deep sand and gravel and bedrock aquifers to the surface where the hydraulic head is sufficient, as demonstrated by the discharge area that composes the southern third of the study area in the broad valley floor south of Tremonton (figure 3B) (Bjorklund and McGreevy, 1974; Anderson and others, 1994). The Salt Lake Formation and bedrock aquifers also store and transmit groundwater (Bjorklund and McGreevy, 1974; Smith, 1997; Inkenbrandt and Lachmar,

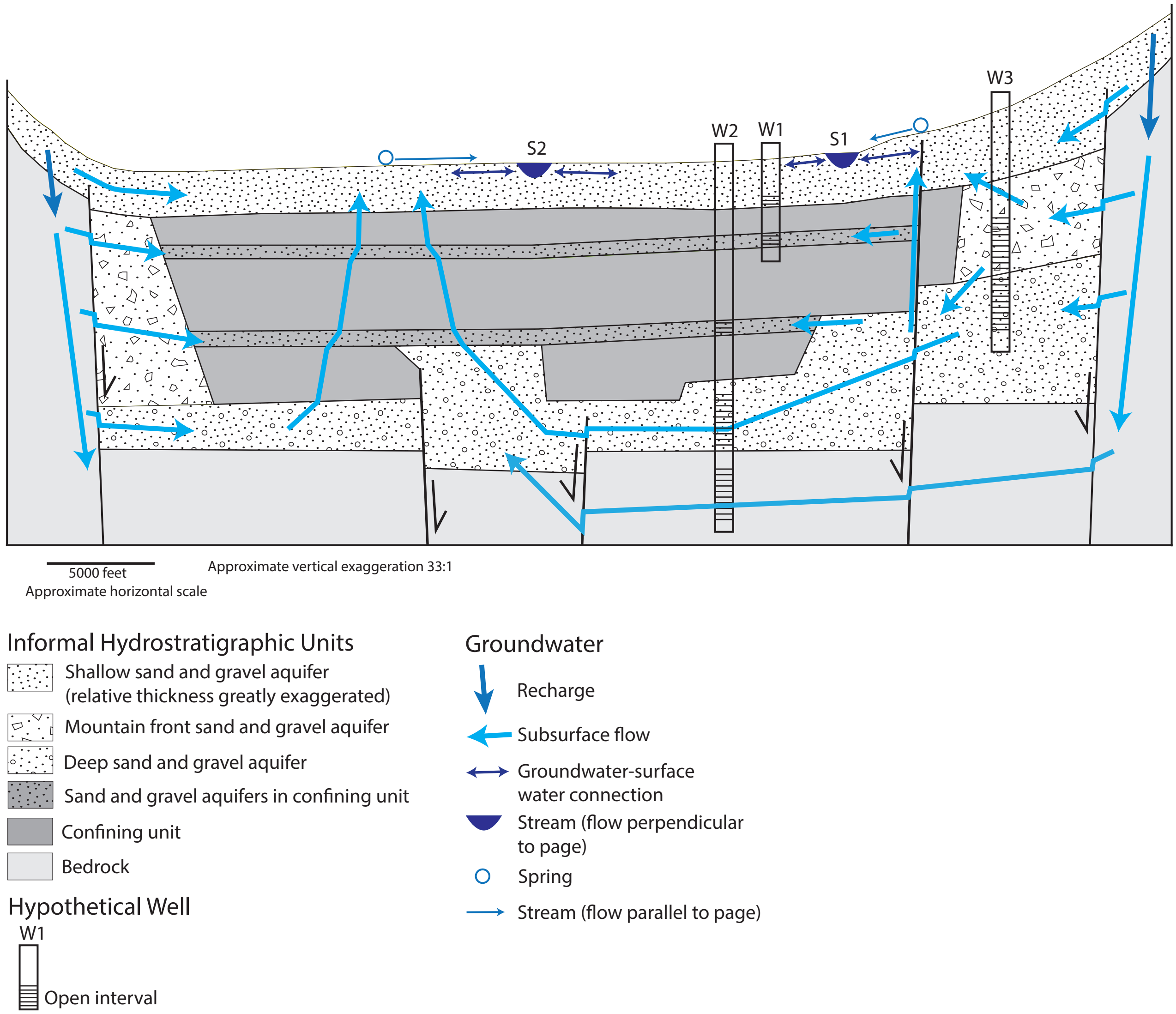


Figure 18. *Schematic cross section showing a simplified version of the informal hydrostratigraphic units defined in figure 17, schematic groundwater flow, and hypothetical streams and wells. The section provides a conceptual framework to consider possible streamflow depletion by wells in a variety of locations and depths.*

2012) and, therefore, may be hydraulically connected with the younger basin fill where they are in contact or along faults.

Potential for Streamflow Depletion by Wells

Current and new groundwater pumping in the Malad–Lower Bear River basin may deplete streamflow. The time response of streamflow depletion is described by the elapsed time between the beginning of pumping and the initiation of depletion, and by the rate of change of the transition from removal from storage to depletion as the dominant source of flow to the well(s). Barlow and Leake (2012, p. 13) stated that "The factors that control the time response of streamflow depletion to pumping are [1] the geologic structure, dimensions, and hydraulic properties of the groundwater system; [2] the locations and hydrologic conditions along the boundaries of the groundwater system, including the streams [*i.e., the degree of hydraulic connection between the stream and the aquifer(s) being pumped*]; and [3] the horizontal and vertical distances of wells from the streams" (bracketed italicized text added in this report). The magnitude of depletion at a particular time and place depends on the magnitude and duration of pumping.

Streamflow data summarized in the "Hydrogeologic Setting" section indicate that the Malad River and Bear River are hydraulically connected with shallow groundwater and are, therefore, potentially susceptible to streamflow depletion by groundwater pumping. The hydraulic connection between the shallow and deep sand and gravel aquifers indicates that pumping from the deep sand and gravel aquifer may cause streamflow depletion.

The stratigraphy and structure of the younger basin fill in the Malad–Lower Bear River basin, as summarized on figure 18, affect the time response of streamflow depletion due to groundwater pumping. Pumping from well W1 would produce the most rapid streamflow depletion because it is screened in the shallow sand and gravel aquifer and is close to a stream (S1). Depletion of stream S1 due to pumping well W1 from the thin sand and gravel aquifer in the composite confining unit may be delayed compared to pumping from the upper screen, but the upper predominantly clay layer would not completely insulate the shallow sand and gravel aquifer from the effects of pumping from the lower aquifer (Barlow and Leake, 2012). Groundwater flow due to pumping from the lower screen in well W1 would propagate laterally due to the confined conditions and small aquifer thickness (Barlow and Leake, 2012, p. 47), and could capture groundwater flowing upward along the normal fault (right side of figure 18).

Pumping from well W2 in the deep sand and gravel aquifer would draw groundwater from a greater aquifer volume than is available in the overlying aquifers (particularly in southern Bear River Valley where the deep sand and gravel aquifer is thickest), and the well is separated from the streams by the composite confining unit and is farther from the streams, all of which would result in later initiation of depletion and slower transition to depletion-dominated flow compared to well W1. Flow from the Salt Lake Formation and/or bedrock aquifers may also delay the transition to depletion by providing a closer source of water to the well. The response time for streamflow depletion by pumping well W2 would be longer where the composite confining unit is thicker, and shorter where the confining unit is thinner. Faults in the basin fill may partition groundwater into smaller aquifer volumes accessible to the well, or increase hydraulic communication between the principal sand and gravel aquifer and the surface or underlying aquifers due to flow along their surfaces.

Pumping from well W3 would draw groundwater from the mountain-front sand and gravel aquifer, where groundwater is moving from the recharge areas to the basin fill. Depression of groundwater levels due to removal of groundwater from storage would decrease the hydraulic head that drives the flow into the aquifers below the valley floor. The well screens are below the shallow sand and gravel aquifer and are farther from stream S1 than well W1, so the time response for depletion of the stream would be longer than for pumping of the shallow sand and gravel aquifer.

Pumping near major springs or on strike with the faults that localize the springs would reduce spring flow because pumping would reduce flow along the faults to the surface or induce hydraulic gradients away from the springs. Springs such as Woodruff Warm Springs, Uddy Hot Springs, and Crystal Hot Springs would be vulnerable to pumping from the bedrock or basin fill near their localizing faults. Some of the larger springs in the main study area, such as Woodruff Warm Springs, Uddy Hot Springs, and the spring near Fielding, Utah, produce streams that flow into the Malad or Bear River. Reducing flow from these springs by pumping would, therefore, also reduce flow in the larger streams.

SUMMARY AND CONCLUSIONS

The Malad–Lower Bear River basin in eastern Box Elder County, north-central Utah, and Oneida County, south-central Idaho, is expected to experience continued growth of population and industry and, consequently, water use for the next several decades. This report delineates the hydrogeologic framework of the basin in Utah, an important part of evaluating potential impacts of current and possible future increases in groundwater development.

The study area is a generally north-trending intermontane basin near the eastern margin of the Basin and Range physiographic province. Average annual precipitation ranges from 13 inches on the valley floor in southwestern Bear River Valley to 30 to 40 inches on the eastern bounding mountains. The Bear River enters the east-central part of the basin at Cutler Dam and flows south to the northeastern arm of Great Salt Lake in the southeastern part of the study area. The Malad River originates from springs in the northern part of the basin in Idaho and flows south to its confluence with the Bear River about 8 miles north of Great Salt Lake. Both streams are hydraulically connected with groundwater, are used extensively for agriculture, and support wetland environments on the margins of Great Salt Lake.

The Malad–Lower Bear River basin lies between north-south striking, Quaternary- to late Tertiary-age Basin and Range normal-fault zones that define the range-valley transition. The hanging wall of the basin-bounding normal-fault zones is a subsiding sedimentary basin composed of alluvial sediment eroded from the adjacent mountains interbedded with lacustrine deposits. Quaternary to late Tertiary unconsolidated deposits, referred to here as the "younger basin fill," overlie the Tertiary Salt Lake Formation. The Salt Lake Formation is unconsolidated to consolidated gravel, sand, mud, conglomerate, sandstone, mudstone, limestone, and volcanic rocks which formed in fluvial, lacustrine, and volcanic depositional environments during an episode of low- and high-angle normal faulting that predated the Basin and Range faulting. Bedrock units exposed in the mountain ranges and that underlie the basin fill are mainly Paleozoic limestone and dolomite and early Paleozoic to late Neoproterozoic quartzite. These rocks were tilted, fractured, and folded during late Mesozoic to early Tertiary regional thrust faulting.

Analysis of well logs in this study delineated the lithologic composition and variation of the younger basin fill. Based on previous work in the Utah part of Malad Valley and northern Bear River Valley by Oaks (1998, 2000, 2008) and in Cache Valley by Williams (1962), Robinson (1999), and Oaks (2000), analysis of the well logs in serial sections yielded eight lithologic units in the younger basin fill and a facies transition near the valley floor-mountain front boundary. The facies transition marks the lateral transition from a well-defined stratigraphic succession of alternating predominantly fine- and coarse-grained units below the valley floor to mixed coarse and fine-grained deposits beneath the mountain fronts. The transition corresponds to an abrupt change from interbedded lacustrine and alluvial deposits below the valley floor to mainly alluvial-fan and deltaic deposits along the mountain front, and approximately coincides with the normal-fault zones that bound the valley. Lithologic units on the valley-floor side include, from youngest to oldest, gsf1, f1, gsf2, f2, gsf4, f3, and gsf5, where the f (fine) units are mainly clay, the gsf (gravel, sand, fine) units are predominantly gravel and sand with variable amounts of intermixed or interbedded clay and silt, and the numbers increase with increasing age and depth below the land surface. On the mountain-front side of the facies transition, lithologic unit gsf3 is laterally equivalent to the units beneath the valley floor.

Isopach maps (figures 7 through 14) show that, on the valley-floor side of the facies transition, the individual lithologic units vary from 5 to as much as 250 feet thick in most of the main study area, but thicken markedly beneath southern Bear River Valley to 250 to 950 feet. The younger basin fill as a whole is less than 300 feet thick in the northern two-thirds of the main study area, but thickens to nearly 1200 feet in the southern one-third. Thickness variations are geologically reasonable and correspond with likely areas of subsidence in the hanging walls of normal faults, particularly with southward-increasing displacement on the Wasatch fault zone.

The lithologic units in the younger basin fill were combined into informal hydrostratigraphic units. The shallow sand and gravel aquifer includes lithologic unit gsf1, and the uppermost parts of unit f1 that are adjacent to streams and may store and transmit groundwater. The composite confining unit includes lithologic units f1, gsf2, f2, gsf4, and f3. The composite confining unit is 5 to nearly 225 feet thick in the northern two-thirds of the main study area and increases to nearly 375 feet thick in southern Bear River Valley. The composite confining unit accommodates slow vertical groundwater movement as demonstrated by the large groundwater-discharge area in the broad, flat part of the valley in the southern one-third of the study area. The underlying deep sand and gravel aquifer (gsf5) is confined, very thick in the south, and overall has the highest transmissivity in this area based on comparison to Cache Valley (Inkenbrandt and Lachmar, 2012). Parts of the Salt Lake Formation and carbonate bedrock are aquifers having lower average transmissivity than the principal sand and gravel aquifer.

The informal hydrostratigraphy characterized in this study provides a conceptual physical framework for evaluating possible regional flow patterns and impact of groundwater pumping on surface water and shallow groundwater. Groundwater recharges to surficial deposits and bedrock on the mountain block and mountain front, and moves to the mountain-front sand and gravel and Salt Lake Formation aquifers. Groundwater in the mountain-front sand and gravel aquifer moves to either the shallow or the principal sand and gravel aquifers. Groundwater in most of the study area must cross the basin-bounding fault zones to move toward the valley centers and some moves vertically along the high-transmissivity fault planes to form springs at the surface. Groundwater in the deep sand and gravel aquifer moves below the composite confining unit toward the valley centers. At the valley center, the hydraulic head forces groundwater upward through the composite confining unit toward the surface, where it sources springs and diffuse seepage into the shallow sand and gravel aquifer.

Pumping groundwater from wells completed in the shallow sand and gravel aquifer would result in streamflow depletion by virtue of their strong hydraulic connection. Existing or future wells that pump groundwater from the deep sand and gravel aquifer beneath the thickest parts of the composite confining unit have the longest time to initial streamflow depletion and transition to depletion as the dominant supply of pumped groundwater, due to the comparatively low hydraulic conductivity of the composite confining unit. These conditions are met in the southern one-third of the main study area. Some streamflow depletion would occur due to reduction in spring flow that is sourced by the deep sand and gravel aquifer, particularly springs that provide surface flow to the Malad River in the northern part of the study area. Areas most vulnerable to potential streamflow depletion by groundwater pumping include (1) any part of the shallow sand and gravel aquifer that is hydraulically connected to streams, (2) the sand and gravel units within the composite confining unit, and (3) where the composite confining unit is thinnest, i.e., along the mountain fronts and in the northern third of the study area.

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APPENDIX

Table A1. Records of wells used to construct serial sections.

Well/Map Number[1]	Location				Elevation[5]	Diameter (in)	Depth (ft)	Source[6]
	Longitude[2]	Latitude[2]	PLSS[3]	USGS[4]				
1	-112.03552	41.44852	S 1200 E 2150 NW 11 8N 2W SL	(B-8-2)11bad-1	4378	10	298	DWRi
2	-112.05053	41.45609	N 1580 W 1812 SE 03 8N 2W SL	(B-8-2)03dbd-1	4272	8	206	DWRi
3	-112.04399	41.45219	N 137 W 38 SE 03 8N 2W SL	(B-8-2)03ddd-1	4326	12	105	DWRi
4	-112.04230	41.44721	S 1705 E 405 NW 11 8N 2W SL	(B-8-2)11bcb-1	4321	9	65	DWRi
5	-112.04031	41.44232	S 850 E 950 W4 11 8N 2W SL	(B-8-2)11cbd-1	4292	8	107	DWRi
6	-112.04399	41.45360	N 652 W 32 SE 03 8N 2W SL	(B-8-2)03ddd-2	4329	20	83	DWRi
12	-112.06086	41.50224	S 2773 E 640 NW 22 9N 2W SL	(B-9-2)22cbb-1	4222	10	665	DWRi
13	-112.07147	41.52445	N 47 W 2160 SE 09 9N 2W SL	(B-9-2)09dcc-1	4224	8	461	DWRi
16	-112.06021	41.53116	N 2453 E 953 SW 10 9N 2W SL	(B-9-2)10cba-3	4224	4	16	DWRi
17	-112.05245	41.50276	N 50 E 2350 W4 23 9N 2W SL	(B-9-2)23bdd-1	4224	6	238	DWRi
18	-112.03469	41.52744	N 970 E 2600 SW 11 9N 2W SL	(B-9-2)11cda-1	4248	10	606	DWRi
19	-112.03646	41.53094	N 2250 E 2130 SW 11 9N 2W SL	(B-9-2)11caa-1	4234	6	455	DWRi
20	-112.14002	41.51062	S 988 W 574 E4 14 9N 3W SL	(B-9-3)14dad-1	4224	6	572	DWRi
21	-112.06116	41.61135	S 20 E 860 NW 15 10N 2W SL	(B-10-2)15ccd-1	4281	7	50	DWRi
22	-112.04594	41.59897	N 750 W 275 SE 15 10N 2W SL	(B-10-2)15dda-1	4287	6	100	DWRi
23	-112.04255	41.59312	S 1390 E 625 NW 23 10N 2W SL	(B-10-2)23bcb-1	4324	8	95	DWRi
24	-112.04432	41.59007	N 170 E 140 W4 23 10N 2W SL	(B-10-2)23bcc-1	4259	7	41	DWRi
25	-112.04236	41.58430	N 727 E 662 SW 23 10N 2W SL	(B-10-2)23ccd-1	4239	6	72	DWRi
26	-112.04145	41.59645	S 180 E 940 NW 23 10N 2W SL	(B-10-2)23bba-1	4390	6	204	DWRi
27	-112.04089	41.59564	S 480 E 1090 NW 23 10N 2W SL	(B-10-2)23bba-2	4404	6	200	DWRi
28	-112.06021	41.62351	S 900 E 1150 NW 10 10N 2W SL	(B-10-2)10bbd-1	4456	6	338	DWRi
29	-112.17404	41.59905	S 872 E 920 W4 15 10N 3W SL	(B-10-3)15cbd-1	4251	6	400	DWRi
31	-112.14792	41.62781	N 930 W 2430 SE 02 10N 3W SL	(B-10-3)02dcb-1	4259	6	170	DWRi
32	-112.12493	41.61730	S 3000 W 1450 NE 12 10N 3W SL	(B-10-3)12dba-1	4261	6	50	DWRi
33	-112.14039	41.63323	N 250 W 360 E4 02 10N 3W SL	(B-10-3)02add-1	4261	6	120	DWRi
34	-112.13000	41.56289	S 687 W 333 N4 36 10N 3W SL	(B-10-3)36bad-1	4238	8	55	DWRi
35	-112.13960	41.63692	S 1090 W 120 NE 02 10N 3W SL	(B-10-3)02aad-1	4263	6	69	DWRi
37	-112.08075	41.69137	N 0 E 1000 W4 16 11N 2W SL	(B-11-2)16bcd-1	4345	7	185	DWRi
38	-112.08486	41.67364	N 795 E 30 SW 21 11N 2W SL	(B-11-2)21ccb-1	4327	6	100	DWRi
39	-112.07577	41.66819	S 1220 E 2540 NW 28 11N 2W SL	(B-11-2)28abc-1	4294	16	365	DWRi
40	-112.09022	41.67262	N 1093 W 1600 SE 20 11N 2W SL	(B-11-2)20dca-1	4303	5	83	DWRi
42	-112.16063	41.68242	S 180 W 130 NE 22 11N 3W SL	(B-11-3)22aaa-1	4294	6	60	DWRi
43	-112.19861	41.69897	N 960 E 185 SW 09 11N 3W SL	(B-11-3)09ccb-1	4303	6	30	DWRi
44	-112.15070	41.68298	S 43 W 87 N4 23 11N 3W SL	(B-11-3)23baa-1	4287	6	200	DWRi
45	-112.15928	41.66196	N 368 E 50 W4 26 11N 3W SL	(B-11-3)26bcc-1	4278	6	160	DWRi
46	-112.18965	41.71046	S 285 W 2584 NE 09 11N 3W SL	(B-11-3)09abb-1	4323	6	30	DWRi
48	-112.29540	41.68733	S 100 E 100 W4 15 11N 4W SL	(B-11-4)15bcc-1	4319	6	95	DWRi
49	-112.29442	41.67369	N 175 E 200 W4 22 11N 4W SL	(B-11-4)22bcc-1	4302	6	100	DWRi

Table A1. continued

Well/Map Number[1]	Location				Elevation[5]	Diameter (in)	Depth (ft)	Source[6]
	Longitude[2]	Latitude[2]	PLSS[3]	USGS[4]				
50	-112.29770	41.68796	N 140 W 525 E4 16 11N 4W SL	(B-11-4)16add-1	4356	6	80	DWRi
52	-112.29455	41.67078	S 884 E 148 W4 22 11N 4W SL	(B-11-4)22cbc-1	4303	-	136	DWRi
53	-112.28721	41.69205	S 1025 W 200 N4 15 11N 4W SL	(B-11-4)15bad-1	4302	8	91	DWRi
54	-112.27726	41.68706	S 250 W 200 E4 15 11N 4W SL	(B-11-4)15daa-1	4290	8	160	DWRi
55	-112.28706	41.69409	S 280 W 150 N4 15 11N 4W SL	(B-11-4)15baa-1	4306	6	79	DWRi
56	-112.08597	41.78225	S 1300 W 100 NE 17 12N 2W SL	(B-12-2)17aad-1	4583	6	300	DWRi
57	-112.08520	41.78473	S 400 E 120 NW 16 12N 2W SL	(B-12-2)16bbb-1	4536	7	60	DWRi
58	-112.09251	41.77213	N 350 E 720 S4 17 12N 2W SL	(B-12-2)17dcc-1	4464	6	380	DWRi
59	-112.09365	41.78076	N 840 W 2200 E4 17 12N 2W SL	(B-12-2)17acb-1	4432	6	100	DWRi
60	-112.18706	41.77112	N 450 W 1379 SE 16 12N 3W SL	(B-12-3)16dcd-1	4775	6	558	DWRi
61	-112.16235	41.77266	N 900 E 100 SW 14 12N 3W SL	(B-12-3)14ccb-1	4371	6	85	DWRi
62	-112.16420	41.75615	N 150 W 525 SE 22 12N 3W SL	(B-12-3)22ddd-1	4358	8	128	DWRi
63	-112.18084	41.74993	S 2025 E 100 NW 27 12N 3W SL	(B-12-3)27bcc-1	4451	6	160	DWRi
64	-112.14562	41.77018	S 133 W 650 NE 23 12N 3W SL	(B-12-3)23aab-1	4342	2	30	DWRi
65	-112.15942	41.74955	S 2400 E 480 NW 26 12N 3W SL	(B-12-3)26bcd-1	4337	6	32	DWRi
67	-112.17177	41.74246	N 624 W 103 S4 27 12N 3W SL	(B-12-3)27cdd-1	4355	6	53	DWRi
68	-112.19138	41.73974	S 160 W 190 N4 33 12N 3W SL	(B-12-3)33baa-1	4521	6	240	DWRi
69	-112.19222	41.73921	S 350 W 420 N4 33 12N 3W SL	(B-12-3)33baa-2	4533	6	285	DWRi
70	-112.19132	41.73786	S 842 W 183 N4 33 12N 3W SL	(B-12-3)33bad-1	4486	6	104	DWRi
71	-112.28362	41.76406	S 1320 W 1220 NE 22 12N 4W SL	(B-12-4)22adb-1	4535	20	397	DWRi
72	-112.27847	41.75243	S 225 E 81 NW 26 12N 4W SL	(B-12-4)26bbb-1	4469	6	240	DWRi
74	-112.26353	41.74804	N 725 W 1200 E4 26 12N 4W SL	(B-12-4)26adc-1	4442	6	275	DWRi
75	-112.28491	41.73817	S 50 W 1770 NE 34 12N 4W SL	(B-12-4)34aba-1	4410	12	310	DWRi
76	-112.10316	41.85590	S 920 E 980 NW 20 13N 2W SL	(B-13-2)20bbd-1	4482	10	440	DWRi
77	-112.10818	41.85811	S 94 W 376 NE 19 13N 2W SL	(B-13-2)19aaa-1	4489	6	100	DWRi
78	-112.10848	41.85816	S 75 W 460 NE 19 13N 2W SL	(B-13-2)19aaa-2	4489	8	100	DWRi
79	-112.09127	41.87348	N 120 W 960 SE 08 13N 2W SL	(B-13-2)08ddc-1	4776	6	138	DWRi
81	-112.15829	41.85694	S 250 W 800 N4 23 13N 3W SL	(B-13-3)23bab-1	4332	8	143	DWRi
83	-112.18996	41.88370	S 1346 W 1180 NE 09 13N 3W SL	(B-13-3)09adb-1	4406	10	828	DWRi
84	-112.16687	41.88580	S 233 W 233 NE 10 13N 3W SL	(B-13-3)10aaa-1	4497	8	185	DWRi
85	-112.14178	41.87220	S 92 E 1189 NW 13 13N 3W SL	(B-13-3)13bba-1	4473	6	232	DWRi
96	-112.18258	41.96196	N 915 E 1365 SW 10 14N 3W SL	(B-14-3)10cdb-1	4393	7	63	DWRi
97	-112.18106	41.96250	N 1114 W 854 S4 10 14N 3W SL	(B-14-3)10cdb-2	4433	6	140	DWRi
98	-112.17377	41.92231	S 326 W 1820 E4 27 14N 3W SL	(B-14-3)27dba-1	4406	6	140	DWRi
99	-112.22786	41.94431	N 315 W 550 SE 18 14N 3W SL	(B-14-3)18ddd-1	4456	6	88	DWRi
100	-112.23955	41.97932	N 2600 E 1760 SW 06 14N 3W SL	(B-14-3)06cab-1	4455	6	145	DWRi
101	-112.23814	41.98025	S 2400 E2365 NW 06 14N 3W SL	(B-14-3)06bdd-2-1	4427	5	85	DWRi
102	-112.23927	41.97439	N 190 W 565 S4 06 14N 3W SL	(B-14-3)01cdd-1	4445	7	88	DWRi

Table A1. continued

Well/Map Number[1]	Location				Elevation[5]	Diameter (in)	Depth (ft)	Source[6]
	Longitude[2]	Latitude[2]	PLSS[3]	USGS[4]				
106	-112.23240	41.99409	S 50 W 1250 E4 31 15N 3W	(B-15-3)31adc-1	4390	10	300	DWRi
108	-112.25496	41.99924	S 775 E 3150 NW 36 15N 4W SL	(B-15-4)36abb-1	4545	6	250	DWRi
109	-112.03265	41.46575	N 1272 E 534 S4 02 8N 2W SL	(B-8-2)02abb-1	4358	12	334	Bjorklund (1973)
110	-112.05639	41.46216	S 1566 E 1850 NW 03 8N 2W SL	(B-8-2)03bdb-8	4234	4	77	Bjorklund (1973)
111	-112.03524	41.43211	S 1969 W 300 N4 14 8N 2W SL	(B-8-2)14bda-1	4325	12	332	Bjorklund (1973)
112	-112.06866	41.42201	S 330 W 1600 NE 21 8N 2W SL	(B-8-2)21aab-1	4221	2	567	Bjorklund (1973)
113	-112.00135	41.50379	N 2970 E 1060 SW 9N 1W SL	(B-9-1)19bcd-1	4550	12	412	Bjorklund (1973)
117	-112.02559	41.49516	S 140 W 225 NE 26 9N 2W SL	(B-9-2)26aaa-1	4333	10	412	Bjorklund (1973)
118	-112.26914	41.48051	S 100 E 1640 NW 35 9S 4W SL	(B-9-4)35bab-1	4208	6	860	Bjorklund (1973)
119	-112.07120	41.62840	N 900 W 1860 04 10N 2W SL	(B-10-2)04dda-1	4353	12	366	Bjorklund (1973)
120	-112.10216	41.60672	S 1650 E 200 NW 17 10N 2W SL	(B-10-2)17bcb-1	4255	2	609	Bjorklund (1973)
121	-112.02355	41.56518	S 950 E 470 NW 36 10N 2W SL	(B-10-2)36bbc-3	4290	10	66	Bjorklund (1973)
122	-112.12614	41.63143	N 2170 E 905 S4 01 10N 3W SL	(B-10-3)01dba-1	4269	4	220	Bjorklund (1973)
123	-112.17815	41.62421	N 275 W 175 SE 04 10N 3W SL	(B-10-3)04ddd-1	4265	2	510	Bjorklund (1973)
124	-112.34331	41.62383	N 550 E 2330 SW 06 10N 4W SL	(B-10-4)06cdd-1	4259	4	104	Bjorklund (1973)
125	-112.35701	41.63576	S 165 W 1250 NE 01 10N 5W SL	(B-10-5)01aab-1	4560	8	325	Bjorklund (1973)
126	-112.12134	41.71350	N 340 E 190 SW 06 11N 2W SL	(B-11-2)06ccc-1	4307	6	178	Bjorklund (1973)
127	-112.11419	41.65434	N 4030 W 20'50" E4 31 11N 2W SL	(B-11-2)31bab-1	4255	8	461	Bjorklund (1973)
128	-112.16935	41.71053	S 400 W 2350 NE 10 11N 3W SL	(B-11-3)10abb-4	4322	6	705	Bjorklund (1973)
129	-112.19935	41.68609	N 1600 W 200 SW 17 11N 3W SL	(B-11-3)17dad-2	4284	2	410	Bjorklund (1973)
130	-112.22532	41.69542	S 130 W 1900 NE 18 11N 3W SL	(B-11-3)18aba-1	4289	6	308	Bjorklund (1973)
131	-112.29677	41.70936	N 80 E 25 SW 03 11N 4W SL	(B-11-4)03ccc-1	4433	12	430	Bjorklund (1973)
132	-112.24387	41.70959	S 150 W 1515 NE 12 11N 4W SL	(B-11-4)12aba-1	4318	2	240	Bjorklund (1973)
133	-112.27574	41.67310	S 2590 E 125 NW 23 11N 4W SL	(B-11-4)23bcc-1	4275	-	393	Bjorklund (1973)
134	-112.07674	41.79004	N 1860 E 2395 SW 09 12N 2W SL	(B-12-2)09cad-1	4547	6	95	Bjorklund (1973)
135	-112.09972	41.77541	N 1580 E 100 SW 17 12N 2W SL	(B-12-2)17cac-1	4391	4	198	Bjorklund (1973)
136	-112.10849	41.77017	S 295 W 980 NE 19 12N 2W SL	(B-12-2)19aab-1	4247	2	280	Bjorklund (1973)
137	-112.14446	41.79093	N 2130 E 1535 SE 11 12N 3W SL	(B-12-3)11daa-1	4362	6	68	Bjorklund (1973)
138	-112.17519	41.77048	N 175 E 1860 SW 15 12N 3W SL	(B-12-3)15cdc-1	4471	12	277	Bjorklund (1973)
139	-112.14674	41.75150	S 1605 W 1180 NE 26 12N 3W SL	(B-12-3)26adb-1	4344	4	290	Bjorklund (1973)
140	-112.28301	41.74268	N 1485 W 1320 SE 27 12N 4W SL	(B-12-4)27bdb-1	4422	16	500	Bjorklund (1973)
141	-112.29198	41.74824	S 1750 E 1630 NW 27 12N 4W SL	(B-12-4)27dbd-1	4500	16	478	Bjorklund (1973)
142	-112.29309	41.73484	S 1320 E 1210 NW 34 12N 4W SL	(B-12-4)34bbd-1	4431	12	306	Bjorklund (1973)
143	-112.29256	41.72741	N 1280 E 1300 SW 31 12N 4W SL	(B-12-4)34cbd-1	4428	12	292	Bjorklund (1973)
144	-112.27698	41.73502	S 20 W 1320 NE 35 12N 4W SL	(B-12-4)35bbc-1	4380	12	668	Bjorklund (1973)
145	-112.17175	41.87255	N 255 W 1700 SE 10 13N 3W SL	(B-13-3)10dcd-1	4418	6	202	Bjorklund (1973)
146	-112.14170	41.87835	N 2155 E 1190 SW 12 13N 3W SL	(B-13-3)12cba-1	4543	6	100	Bjorklund (1973)
147	-112.16338	41.82877	N 120 E 235 SW 26 13N 3W SL	(B-13-3)26ccc-1	4404	6	131	Bjorklund (1973)

Table A1. continued

Well/Map Number[1]	Location				Elevation[5]	Diameter (in)	Depth (ft)	Source[6]
	Longitude[2]	Latitude[2]	PLSS[3]	USGS[4]				
148	-112.14542	41.81648	N 830 W 270 SE 35 13N 3W SL	(B-13-3)35dda-1	4374	10	237	Bjorklund (1973)
151	-112.19853	41.97522	N 800 E 2405 SW 04 14N 3W SL	(B-14-3)04cda-1	4373	5	105	Bjorklund (1973)
152	-112.24222	41.97533	N 1250 E 1145 SW 06 14N 3W SL	(B-14-3)06cca-1	4484	6	135	Bjorklund (1973)
153	-112.21964	41.94469	N 400 E 1615 SW 17 14N 3W SL	(B-14-3)17cdc-1	4395	5	323	Bjorklund (1973)
154	-112.24605	41.98690	N 215 E 240 SW 31 15N 3W SL	(B-15-3)31ccc-1	4443	12	160	Bjorklund (1973)
155	-112.00364	41.50305	N 65 E 458 W4 19 9N 1W SL	(B-9-1)19bcc-1	4558	16	620	DWRi
158	-112.06486	41.63305	S 350 W 150 E4 04 10N 2W SL	(B-10-2)04daa-1	4570	14	319	DWRi
159	-112.23116	41.69535	S 50 W 1170 NE 18 11N 3W SL	(B-11-3)18bab-1	4294	6.7	380	DWRi
160	-112.11813	41.76729	S 1340 E 1510 NW 19 12N 2W SL	(B-12-2)19bac-1	4331	6	260	DWRi
161	-112.16352	41.83386	S 670 E 220 W4 26 13N 3W SL	(B-13-3)26cbb-1	4410	7	105	DWRi
162	-112.19200	41.97337	N 10 W 1100 SE 04 14N 3W SL	(B-14-3)04ddc-1	4388	16	415	DWRi
163	-112.05047	41.43448	S 1075 W 1844 NE 15 8N 2W SL	(B-8-2)15abd-1	4244	6	170	DWRi
164	-112.04692	41.42898	S 3020 W 882 NE 15 8N 2W SL	(B-8-2)15dab-1	4260	8	200	DWRi
165	-112.04987	41.42855	N 2010 E 845 S4 15 8N 2W SL	(B-8-2)15dba-1	4250	10	294	DWRi
167	-112.01402	41.54017	N 387 E 169 S4 01 9N 2W SL	(B-9-2)01dcc-1	4281	8.8	150	DWRi
168	-112.08209	41.53857	S 130 E 170 NW 09 9N 2W SL	(B-9-2)09bbb-1	4223	8	40	DWRi
169	-112.07329	41.50961	S 50 E 2620 NW 21 9N 2W SL	(B-9-2)21baa-1	4221	12	555	DWRi
170	-112.02424	41.50962	S 200 E 50 24 9N 2W SL	(B-9-2)24bbb-1	4357	8	65	DWRi
171	-112.02311	41.48433	N 1165 E 419 SW 25 9N 2W SL	(B-9-2)25ccb-1	4300	12	316	DWRi
172	-112.04501	41.47383	S 710 W 415 E4 34 9N 2W SL	(B-9-2)34daa-1	4256	4	142	DWRi
173	-112.03440	41.47811	S 1051 W 425 N4 35 9N 2W SL	(B-9-2)35bad-1	4268	6	363	DWRi
174	-112.03353	41.46757	N 400 W 2500 E4 35 9N 2W SL	(B-9-2)35dcc-1	4337	8	270	DWRi
175	-112.09793	41.58890	S 2750 W 4000 NE 20 10N 2W SL	(B-10-2)20cba-1	4224	6	300	DWRi
176	-112.02988	41.57441	S 2900 W 1250 NE 26 10N 2W SL	(B-10-2)26dab-1	4294	6	79	DWRi
177	-112.11607	41.55482	N 1850 E 875 SW 36 10N 2W SL	(B-10-2)31cdb-1	4224	6	170	DWRi
178	-112.08779	41.71340	N 121 W 864 SE 05 11N 2W SL	(B-11-2)05ddc-1	4448	6	200	DWRi
179	-112.08654	41.71398	S 2300 W 520 E4 05 11N 2W SL	(B-11-2)05ddd-1	4489	10	352	DWRi
180	-112.08500	41.70167	S 1520 W 200 E4 08 11N 2W SL	(B-11-2)08dda-1	4358	8	78	DWRi
181	-112.08900	41.70012	N 600 E 50 SW 09 11N 2W SL	(B-11-2)09ccc-1	4331	8	110	DWRi
182	-112.08574	41.65987	N 1745 W 425 SE 29 11N 2W SL	(B-11-2)29dad-1	4306	8	126	DWRi
183	-112.08496	41.65846	N 1220 W 200 SE 29 11N 2W SL	(B-11-2)29dda-1	4323	12	120	DWRi
184	-112.10403	41.67510	N 2100 W 150 SE 19 11N 2W SL	(B-11-2)19daa-1	4300	6	260	DWRi
185	-112.08336	41.64734	S 200 W 150 W4 33 11N 2W SL	(B-11-2)33cbb-1	4291	6	290	DWRi
186	-112.12913	41.71964	N 2581 E 814 S4 01 11N 3W SL	(B-11-3)01dba-1	4329	12	80	DWRi
187	-112.18250	41.72409	S 794 W 551 NE 04 11N 3W SL	(B-11-3)04aad-1	4336	6	120	DWRi
188	-112.20021	41.71621	N 1950 W 150 SE 05 11N 3W SL	(B-11-3)05dad-1	4331	4	125	DWRi
189	-112.23772	41.71520	N 1840 E 180 06 11N 3W SL	(B-11-3)06cbc-1	4330	6	180	DWRi
190	-112.22086	41.72332	S 680 W 400 NE 06 11N 3W SL	(B-11-3)06aad-1	4468	6	250	DWRi

Table A1. *continued*

Well/Map	Location							
Number[1]	Longitude[2]	Latitude[2]	PLSS[3]	USGS[4]	Elevation[5]	Diameter (in)	Depth (ft)	Source[6]
191	-112.23317	41.69584	N 50 E 1240 SW 07 11N 3W SL	(B-11-3)07ccd-1	4294	2	246	DWRi
192	-112.23485	41.71001	N 50 E 946 NW 07 11N 3W SL	(B-11-3)07bba-1	4318	6	350	DWRi
193	-112.15586	41.71107	S 325 E 1320 NW 11 11N 3W SL	(B-11-3)11bab-1	4318	12	52	DWRi
194	-112.16085	41.64740	S 2240 W 600 NE 34 11N 3W SL	(B-11-3)34add-1	4268	12	70	DWRi
195	-112.25493	41.71686	N 2060 E 850 SW 01 11N 4W SL	(B-11-4)01cba-1	4330	8	140	DWRi
196	-112.25745	41.71607	S 350 E 120 W4 01 11N 4W SL	(B-11-4)01cbb-1	4329	6	170	DWRi
197	-112.26329	41.71741	N 145 W 1400 E4 02 11N 4W SL	(B-11-4)02acd-1	4331	10	110	DWRi
198	-112.27573	41.71739	N 220 E 525 W4 02 11N 4W SL	(B-11-4)02bcc-1	4334	6	103	DWRi
199	-112.29699	41.71909	S 1700 E 10 NW 03 11N 4W SL	(B-11-4)03bcb-1	4495	6	300	DWRi
200	-112.31663	41.70927	N 167 W 173 SE 05 11N 4W SL	(B-11-4)05ddd-1	4786	8	580	DWRi
202	-112.29826	41.70820	S 975 W 200 NE 09 11N 4W SL	(B-11-4)09aad-1	4435	6.6	175	DWRi
203	-112.31572	41.70457	S 1535 W 100 NE 09 11N 4W SL	(B-11-4)09bb-1	4692	10	215	DWRi
204	-112.29306	41.69487	N 160 E 909 SW 10 11N 4W SL	(B-11-4)10ccd-1	4333	8	100	DWRi
205	-112.27624	41.69905	N 1540 E 210 SW 11 11N 4W SL	(B-11-4)11cbc-1	4307	8	151	DWRi
206	-112.27575	41.68639	S 460 E 200 W4 14 11N 4W SL	(B-11-4)14cbb-1	4286	8	307	DWRi
208	-112.31453	41.65336	N 1035 W 260 SE 29 11N 4W SL	(B-11-4)29dda-1	4299	6	160	DWRi
209	-112.29422	41.65070	S 80 E 150 NW 34 11N 4W SL	(B-11-4)34bbb-1	4272	6.6	92	DWRi
210	-112.11419	41.81032	S 1550 E 2900 NW 06 12N 2W SL	(B-12-2)06acb-1	4376	9	99	DWRi
211	-112.11456	41.79363	S 2350 E 2700 NW 07 12N 2W SL	(B-12-2)07acc-1	4364	6	162	DWRi
212	-112.07695	41.79112	N 1886 E 2378 SW 09 12N 2W SL	(B-12-2)09cad-2	4534	6	160	DWRi
214	-112.11564	41.78079	S 1720 W 2300 NE 18 12N 2W SL	(B-12-2)18acb-1	4353	6	201	DWRi
215	-112.09087	41.76336	N 2380 W 1550 SE 20 12N 2W SL	(B-12-2)20dba-1	4511	7	360	DWRi
218	-112.09611	41.74815	N 2199 E 2304 SW 29 12N 2W SL	(B-12-2)29caa-1	4505	8	870	DWRi
219	-112.09749	41.75327	S 1230 W 750 N4 29 12N 2W SL	(B-12-2)29bad-1	4420	8	330	DWRi
220	-112.09705	41.75092	S 2086 E 2093 NW 29 12N 2W SL	(B-12-2)29bdd-1	4451	8	500	DWRi
221	-112.10610	41.74855	S 245 W 420 E4 30 12N 2W SL	(B-12-2)30daa-1	4377	8	180	DWRi
222	-112.09801	41.73881	S 1204 W 994 N4 32 12N 2W SL	(B-12-2)32bac-1	4465	8	540	DWRi
223	-112.09958	41.73729	N 860 E 1270 W4 32 12N 2W SL	(B-12-2)32bca-1	4410	6	165	DWRi
224	-112.16317	41.80934	S 1690 E 140 NW 02 12N 3W SL	(B-12-3)02bcb-1	4418	6.7	140	DWRi
225	-112.16289	41.80468	S 695 E 215 W4 02 12N 2W SL	(B-12-3)02cbb-1	4423	6.5	122	DWRi
226	-112.14505	41.80569	S 400 W 250 E4 03 12N 3W SL	(B-12-3)02daa-1	4368	6	155	DWRi
227	-112.16420	41.81346	S 150 W 90 NE 03 12N 3W SL	(B-12-3)03aaa-1	4418	6.7	142	DWRi
228	-112.12487	41.79582	N 1174 W 106 E4 12 12N 3W SL	(B-12-3)12ada-1	4360	6	90	DWRi
229	-112.13750	41.77024	S 190 W 510 N4 24 12N 3W SL	(B-12-3)24bab-1	4345	6.8	100	DWRi
230	-112.14685	41.74869	S 50 W 1140 E4 26 12N 3W SL	(B-12-3)26dab-1	4343	6	200	DWRi
231	-112.18374	41.74517	S 992 W 782 E4 28 12N 3W SL	(B-12-3)28dac-1	4450	7	167	DWRi
233	-112.21199	41.72579	N 225 E 2000 SW 32 12N 3W SL	(B-12-3)32cdd-1	4476	6	192	DWRi
235	-112.12376	41.83990	S 1390 E 540 NW 30 13N 2W SL	(B-13-2)30bcb-1	4395	6	141	DWRi

Table A1. *continued*

Well/Map	Location							
Number[1]	Longitude[2]	Latitude[2]	PLSS[3]	USGS[4]	Elevation[5]	Diameter (in)	Depth (ft)	Source[6]
236	-112.12342	41.82320	N 500 E 500 W4 31 13N 2W SL	(B-13-2)31bcc-1	4376	6.7	300	DWRi
237	-112.09248	41.81493	N 20 W 1700 SE 32 13N 2W SL	(B-13-2)32dcd-1	4433	8	100	DWRi
238	-112.08458	41.82355	S 2155 W 430 NW 33 13N 2W SL	(B-13-2)33bcc-1	4474	6	145	DWRi
239	-112.06023	41.82933	S 150 E 1800 NW 34 13N 2W SL	(B-13-2)34bab-1	4305	6	218	DWRi
240	-112.06418	41.82669	N 1450 E 700 W4 34 13N 2W SL	(B-13-2)34bbd-1	4401	14	190	DWRi
241	-112.06663	41.82890	S 270 E 50 NW 34 13N 2W SL	(B-13-2)34bbb-1	4464	6	107	DWRi
243	-112.16473	41.89099	N 1650 E 330 SW 02 13N 3W SL	(B-13-3)02cbc-1	4579	8	228	DWRi
244	-112.17739	41.89966	S 409 W 3036 NE 03 13N 3W SL	(B-13-3)03baa-1	4468	19	560	DWRi
245	-112.20765	41.89475	N 2600 W 500 SW 04 13N 3W SL	(B-13-3)04cbb-1	4490	9.5	103	DWRi
246	-112.17051	41.84314	N 100 W 1580 SE 22 13N 3W SL	(B-13-3)22dcd-1	4492	8	185	DWRi
247	-112.12634	41.83577	S 250 W 200 E4 25 13N 3W SL	(B-13-3)25daa-1	4388	8	102	DWRi
248	-112.12718	41.81638	N 680 W 590 SE 36 13N 3W SL	(B-13-3)36dda-1	4372	12	60	DWRi
249	-112.23625	41.96863	S 1300 W 2620 NE 07 14N 3W SL	(B-14-3)07abc-1	4429	12	200	DWRi
250	-112.22689	41.96133	N 1300 W 200 SE 07 14N 3W SL	(B-14-3)07dad-1	4389	16	400	DWRi
251	-112.24521	41.94436	N 500 E 30 SW 18 14N 3W SL	(B-14-3)18ccc-1	4700	8	371	DWRi
252	-112.23227	41.94411	N 315 W 550 SE 18 14N 3W SL	(B-14-3)18ddd-1	4495	6	90	DWRi
253	-112.21072	41.95781	S 100 W 1100 NE 19 14N 3W SL	(B-14-3)17aab-1	4366	8	160	DWRi
254	-112.22540	41.90881	S 50 E 25 W4 32 14N 3W SL	(B-14-3)32cbb-1	4504	10	300	DWRi
255	-112.16866	41.90381	S 4269 W 653 NE 34 14N 3W SL	(B-14-3)34dda-1	4543	12	450	DWRi
256	-112.16981	41.91080	S 1692 W 862 NE 34 14N 3W SL	(B-14-3)34adb-1	4488	12	300	DWRi
259	-112.19008	41.97400	N 340 W 590 SE 04 14N 3W SL	(B-14-3)04ddd-1	4411	6	60	DWRi
260	-112.23642	41.97182	S 100 E 2700 NW 07 14N 3W SL	(B-14-3)07abb-1	4432	4	71	DWRi
261	-112.23625	41.97017	S 730 W 2620 NE 07 14N 3W SL	(B-14-3)07abc-1	4429	12	175	DWRi
263	-112.17181	41.90670	S 520 W 1390 E4 34 14N 3W SL	(B-14-3)34dba-1	4476	6	125	DWRi
264	-112.20421	41.89339	N 2130 W 4929 SE 04 13N 3W SL	(B-13-3)04cbb-2	4460	12	1000	DWRi
265	-112.20861	41.89659	N 3900 W 1000 SW 04 13N 3W SL	(B-13-3)05adb-1	4479	9.5	87	DWRi
266	-112.13421	41.88278	S 1500 W 2000 NE 12 13N 3W SL	(B-13-3)12aca-1	4745	8	240	DWRi
267	-112.13497	41.87329	N 290 W 2280 SE 12 13N 3W SL	(B-13-3)12dcc-1	4496	6.6	78	DWRi
268	-112.13322	41.88096	N 440 W 1760 E4 12 13N 3W SL	(B-13-3)12acd-1	4696	8	240	DWRi
270	-112.19410	41.87758	S 3103 W 2472 09 13N 3W SL	(B-13-3)09dbb-1	4468	11	194	Oaks (2008)
271	-112.14636	41.87702	N 1700 W 76 SE 11 13N 3W SL	(B-13-3)11dad-1	4497	8	100	Oaks (2008)
272	-112.16514	41.87544	N 1300 E 100 SW 11 13N 3W SL	(B-13-3)11ccb-1	4437	16	228	Oaks (2008)
273	-112.13128	41.88238	S 1652 W 1250 NE 12 13N 3W SL	(B-13-3)12adb-1	4749	12	531	Oaks (2008)
274	-112.23725	41.97432	N 815 W 165 S4 06 14N 3W SL	(B-14-3)06cda-1	4445	6	80	Oaks (2008)
275	-112.22332	41.95667	S 450 E 760 NW 17 14N 3W SL	(B-14-3)17bba-1	4379	6	120	Oaks (2008)
276	-112.23431	41.94621	N 1050 E 350 S4 18 14N 3W SL	(B-14-3)18dcb-1	4518	6	450	Oaks (2008)
277	-112.20975	41.93955	N 900 W 950 E4 20 14N 3W SL	(B-14-3)20abd-1	4369	12	151	Oaks (2008)
278	-112.17146	41.90431	N 1279 W 1420 SE 34 14N 3W SL	(B-14-3)34dbd-1	4492	16	320	Oaks (2008)

Table A1. continued

Well/Map Number[1]	Location				Elevation[5]	Diameter (in)	Depth (ft)	Source[6]
	Longitude[2]	Latitude[2]	PLSS[3]	USGS[4]				
279	-112.16616	41.90334	N 900 E 30 SW 35 14N 3W SL	(B-14-3)35ccb-1	4598	13	269	Oaks (2008)
280	-112.15308	41.90485	N 1400 E 930 S4 35 14N 3W SL	(B-14-3)35dbd-1	4942	16	408	Oaks (2008)
281	-112.20678	41.97558	N 1015 E 180 SW 04 14S 3W SL	(B-14-3)04ccb-1	4364	-	180	CH2MHill (2008)
282	-112.22764	41.97450	N 815 W 210 SE 06 14S 3W SL	(B-14-3)06dda-1	4387	-	102	CH2MHill (2008)
283	-112.20677	41.92770	S 555 W 295 NE 29 14N 3W SL	(B-14-3)29aaa-1	4380	-	102	CH2MHill (2008)
284	-112.19160	41.97659	N 1225 W 945 SE 04 14N 3W SL	(B-14-3)04ddb-1	4429	-	33	CH2MHill (2008)
285	-112.19280	41.90108	N 180 W 1955 SE 33 14N 3W SL	(B-14-3)33dcd-1	4383	-	201	CH2MHill (2008)
286	-112.19789	41.90332	N 1025 E 2005 SW 33 14N 3W SL	(B-14-3)33cda-1	4380	-	100	CH2MHill (2008)
287	-112.07458	41.50620	S 660 E 1980 NW 21 9S 2W SL	(B-9-2)21bda-1	4219	-	1035	DOGM
288	-112.12299	41.49848	N 1980 W 820 SE 24 9N 3W SL	(B-9-3)24dda-1	4210	-	6000	DOGM
289	-112.17277	41.48460	N 1995 E 555 SW 27 9N 3W SL	(B-9-3)27bcd-1	4210	-	4600	DOGM
290	-112.29630	41.72003	S 1350 E 250 NW 03 11N 4W SL	(B-11-4)03bcb-2	4485	6	280	DWRi
291	-112.28096	41.72328	S 955 W 685 NE 03 11N 4W SL	(B-11-4)03aad-1	4338	6	205	DWRi
292	-112.27898	41.71322	S 955 W 685 NE 03 11N 4W SL	(B-11-4)03dda-1	4325	7	138	DWRi
293	-112.20287	41.97631	geotechnical test well	-	4366	2	54	Oaks (2008)
294	-112.21277	41.97646	geotechnical test well	-	4361	2	104	Oaks (2008)
295	-112.21728	41.95697	geotechnical test well	-	4367	2	106	Oaks (2008)
296	-112.21005	41.93744	geotechnical test well	-	4365	2	106	Oaks (2008)
297	-112.20362	41.91970	geotechnical test well	-	4378	2	128	Oaks (2008)
298	-112.19444	41.90116	geotechnical test well	-	4350	2	98	Oaks (2008)
299	-112.18556	41.90087	geotechnical test well	-	4417	2	49	Oaks (2008)
300	-112.19310	41.97657	geotechnical test well	-	4400	2	52	CH2MHill (2008)
301	-112.20788	41.97644	geotechnical test well	-	4362	2	114	CH2MHill (2008)
302	-112.22435	41.97596	geotechnical test well	-	4375	2	78	CH2MHill (2008)
303	-112.21310	41.94527	geotechnical test well	-	4368	2	76	CH2MHill (2008)
304	-112.20706	41.92939	geotechnical test well	-	4378	2	62	CH2MHill (2008)
305	-112.20218	41.91435	geotechnical test well	-	4384	2	61	CH2MHill (2008)
306	-112.19702	41.90116	geotechnical test well	-	4380	2	47	CH2MHill (2008)
307	-112.18959	41.90097	geotechnical test well	-	4396	2	113	CH2MHill (2008)
310	-112.19874	41.88849	N 909 E 1678 SW 04 13N 3W SL	(B-13-3)04cdb-1	4422	4	105	CH2MHill (2008)
311	-112.19170	41.87179	N 80 E 818 S 09 13N 3W SL	(B-13-3)09dcd-1	4422	4	87	CH2MHill (2008)
312	-112.19332	41.88192	S 1536 W 2214 NE 09 13N 3W SL	(B-13-3)09acb-2	4425	8	402	CH2MHill (2008)
313	-112.19508	41.88296	N 1700 W 2700 SE 09 13N 3W SL	(B-13-3)09cad-1	4475	10	80	CH2MHill (2008)
314	-112.16496	41.87556	N 1320 E 165 SW 11 13N 3W SL	(B-13-3)11ccb-2	4435	12	300	CH2MHill (2008)
315	-112.14128	41.87925	S 97 E 1340 W4 12 13N 3W SL	(B-13-3)12cab-1	4575	6	93	CH2MHill (2008)
316	-112.19200	41.97715	N 1340 W 1040 SE 04 14N 3W SL	(B-14-3)04dac-1	4435	4	50	CH2MHill (2008)
318	-112.22177	41.96832	N 1170 E 1305 W4 08 14N 3W SL	(B-14-3)08bdb-1	4370	4	118	CH2MHill (2008)
319	-112.21415	41.94467	N 350 W 2111 SE 17 14N 3W SL	(B-14-3)17dcc-1	4370	4	174	CH2MHill (2008)

Table A1. continued

Well/Map Number[1]	Location				Elevation[5]	Diameter (in)	Depth (ft)	Source[6]
	Longitude[2]	Latitude[2]	PLSS[3]	USGS[4]				
321	-112.20963	41.93649	N 1155 W 1015 E4 20 14N 3W SL	(B-14-3)20dab-1	4365	4	80	CH2MHill (2008)
322	-112.22022	41.91470	N 65 E 1245 SW 29 14N 3W SL	(B-14-3)29ccd-1	4480	4	135	CH2MHill (2008)
323	-112.18949	41.87239	N 300 W 1255 SE 09 13N 3W SL	(B-13-3)09ddc-1	4427	-	200	Oaks (2008)
324	-112.09818	41.77414	N 1100 E 1844 SW 17 12N 2W SL	(B-12-2)17cdb-1	4398	2	142	Oaks (1998)
325	-112.10701	41.76535	S 2048 W 580 NE 19 12N 2W SL	(B-12-2)19add-1	4360	2	400	Oaks (1998)
326	-112.09888	41.74223	N 50 E 1450 SW 29 12N 2W SL	(B-12-2)29cdc-1	4400	2	260	Oaks (1998)
327	-112.10637	41.73063	N 1185 W 580 SE 31 12N 2W SL	(B-12-2)31dda-1	4240	2	124	Oaks (1998)
328	-112.07944	41.69352	S 1840 E 1350 NW 16 11N 2W SL	(B-11-2)19cba-1	4385	2	160	Oaks (1998)
329	-112.07766	41.66976	N 25 E 1800 SW 21 11N 2W SL	(B-11-2)21cdc-1	4380	2	188	Oaks (1998)
331	-112.12424	41.79327	S 400 E 300 W4 07 12N 2W SL	(B-12-2)07bcc-1	4360	6	220	Oaks (1998)
336	-112.22085	41.90886	S 1994 E 1335 NW 32 14N 3W SL	(B-14-3)32bdc-1	4505	-	183	Oaks (1998)

Note
- No data

[1] Well identification number on figures and plates of this report.

[2] Projection: NAD27; Horizontal Datum: WGS-84. Location data are for scientific purposes and should not be used for definitions of legal boundaries or other legal purposes.

[3] Public Land Survey Township, Range, and Section relative to Salt Lake Base Line and Meridian.

[4] U.S. Geological Survey location nomenclature. In parentheses are quadrant in Utah as denoted by letter, followed by township and range, followed by section and subsections. See Bjorklund and McGreevy (1974, figure 12), or Burden and others (2015) for detailed explanation of notation.

[5] Land-surface elevations estimated from U.S. Geological Survey topographic maps or Digital Elevation Model from the Utah AGRC.

[6] Source from which well log was obtained. DWRi is Utah Division of Water Rights <http://www.waterrights.utah.gov/wellInfo/wellInfo.asp>, DOGM is Utah Division of Oil, Gas and Mining <http://oilgas.ogm.utah.gov/Data_Center/LiveData_Search/files.htm>, other sources listed in References section.

***Table A2**. Records of petroleum- and geothermal-exploration wells in the study area, from the Utah Division of Oil, Gas and Mining (http://oilgas.ogm.utah.gov/Data_Center/LiveData_Search/files.htm).*

Operator	Well Name	API Number[1]	Latitude[2]	Longitude[2]	Township, Range, Section[4]	Completion Date	Surface Elevation (ft)	Total Depth (ft)	Notes
ADMANTIA CORP OF NEW YORK	1 STANLEY	4300310002	41.56289	-112.21847	10N, 3W, 31	4/4/56	4220	110	
RHINE PETROLEUM	1 KNUDSON	4300310978	41.48537	-112.11529	9N 2W 30	3/16/58	4212	2300	
STACEY, PAUL S & ASSOC	1 NICHOLS	4300311151	41.50805	-112.07537	9N 2W 21	7/15/55	4220	1035	Upper basin fill to 484 ft; Salt Lake Fm to TD
UNKNOWN OPERATOR	3 BRIGHAM CITY	4300316540	41.58901	-112.05275	9N 2W 22	1/20/94	4228	100	
UNKNOWN OPERATOR	4 BRIGHAM CITY	4300316541	41.58895	-112.05268	9N 2W 22	1/20/94	4228	52	
UNKNOWN OPERATOR	5 BRIGHAM CITY	4300316542	41.58961	-112.04785	9N 2W 22	1/21/94	4229	100	
CRISTION & DAVIS	1 BRIGHAM CITY	4300320055	41.58874	-112.05238	9N 2W 22	1/19/94	4230	1250	
CRISTION & DAVIS	2 BRIGHAM CITY	4300320057	41.58885	-112.05259	9N 2W 22	1/23/94	4225	100	
UNKNOWN OPERATOR	1 BRIGHAM CITY	4300320059	41.58524	-112.04413	9N 2W 23	1/18/94	4245	100	
UTAH PENN OIL CO	2	4300320069	41.63493	-112.29165	10N 4W 03	Dec-31	4300	4100	
PROMONTORY OIL CO	1 JENSEN	4300320077	41.87244	-112.34217	13N 4W 07	9/2/50	5100	7321	
NORTHERN OIL CO	1 NORTHERN	4300320079	41.85834	-112.32946	13N 4W 17	Dec-47	5140	2113	
ZEPCO INC	1 LAMAR BOWEN	4300330005	41.80348	-112.03485	12N 2W 02	2/5/79	5080	740	
ZEPCO INC	1 GOLDEN RIGBY	4300330006	41.86320	-112.05938	13N 2W 15	11/12/79	5085	1107	Basin fill to 1000 ft; Oil show in limestone 1065 ft
BURNETT OIL CO INC	1-9 CHRISTENSEN	4300330021	41.50034	-112.12377	9N 3W 24	8/4/81	4226	6000	Upper basin fill to 1300 ft; Salt Lake Fm to 3450 ft
BURNETT OIL CO INC	1 CHESAPEAKE ENERGY	4300330022	41.48646	-112.17399	9N 3W 27	5/18/81	4210	273	
BURNETT OIL CO INC	1-A CHESAPEAKE ENERG	4300330023	41.48645	-112.17363	9N 3W 27	9/2/81	4210	4610	Upper basin fill to 660 ft; Salt Lake Fm to 1625 ft
GEOTHERMAL KINETICS	1 DAVIS JOINT VENTURE[4]	n/a	41.60500	-112.08300	10N 1W 16	not known	4251	11,000	Upper basin fill to 580 or 680 ft; Salt Lake Fm to 4400 ft

Note

[1] American Petroleum Institute number.

[2] Projection: NAD27; Horizontal Datum: WGS-84. Location data are for scientifc purposes and should not be used for definitions of legal boundaries or other legal purposes.

[3] Public Land Survey Township, Range, and Section relative to Salt Lake Base Line and Meridian.

[4] Geologic log from Jensen and King (1999, table 1).

DESCRIPTION OF MAP UNITS

Qcs — **Quaternary coarse-grained sediment** – Sand, gravel, and cobbles with variable amounts of clay and silt

Qfs — **Quaternary fine-grained sediment** – Clay and silt, with minor but variable amounts of sand and gravel

QTs — **Quaternary-Tertiary sediment** – Unconsolidated to semi-consolidated gravel, sand and clay

Ts — **Tertiary Salt Lake Formation & Wasatch Formation** – Semi-consolidated gravel, tuffaceous siltstone, mudstone, conglomerate, limestone, and tephra

Tv — **Tertiary Volcanic Rocks** – Basaltic tuff and flows, and rhyolitic tuff, flows, breccia, and debris flows

UPzs — **Upper Paleozoic siliciclastic rocks** – Sandstone, quartzite, and siltstone in the lower two-thirds, and interbedded limestone, dolomite, and sandstone in the upper third

UPzc — **Upper Paleozoic carbonate rocks** – Limestone, dolomite, and fine-grained sandstone

MPzs — **Middle Paleozoic siliciclastic rocks** – Shale, mudstone, and thin beds of quartzite and limestone

MPzc — **Middle Paleozoic carbonate rocks** – Limestone and sandstone

LPzc2 — **Lower Paleozoic carbonate rocks** – Limestone, dolomite, and minor sandstone

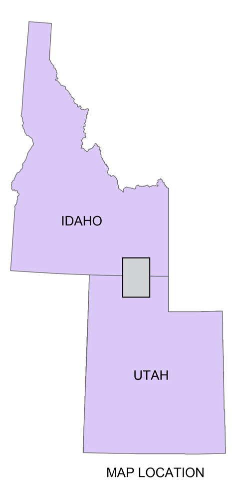
LPzs — **Lower Paleozoic silicilastic rocks** – Quartzite and sandstone

LPzc1 — **Lower Paleozoic carbonate rocks** – Limestone, silty limestone, dolomite, and shale

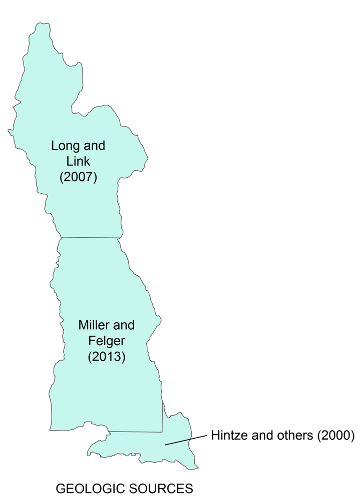
CZs — **Cambrian-Neoproterozoic siliciclastic rocks** – Shale and thinly bedded limestone in the upper one-fourth, and quartzite and shale in the lower three-fourths

MAP SYMBOLS

- Contact
- Normal fault – dashed where approximately located, dotted where concealed
- Normal fault – concealed (from Oaks, 2000)
- Low-angle fault
- Thrust fault – dotted where concealed
- Fault, displacement unknown – dashed where approximately located, dotted where concealed
- Monocline
- Syncline
- Anticline
- Boundary of hydrologic basin
- Strike and dip of bedding
- Spring



MAP LOCATION



GEOLOGIC SOURCES

Scale: 1:100,000

0 0.5 1 2 3 4 5 MILES

0 1.25 2.5 5 7.5 10 12.5 KILOMETERS

N

COMPILED HYDROGEOLOGICAL MAP OF THE MALAD–LOWER BEAR RIVER HYDROLOGIC BASIN, NORTH-CENTRAL UTAH AND SOUTH-CENTRAL IDAHO

by

Hugh Hurlow

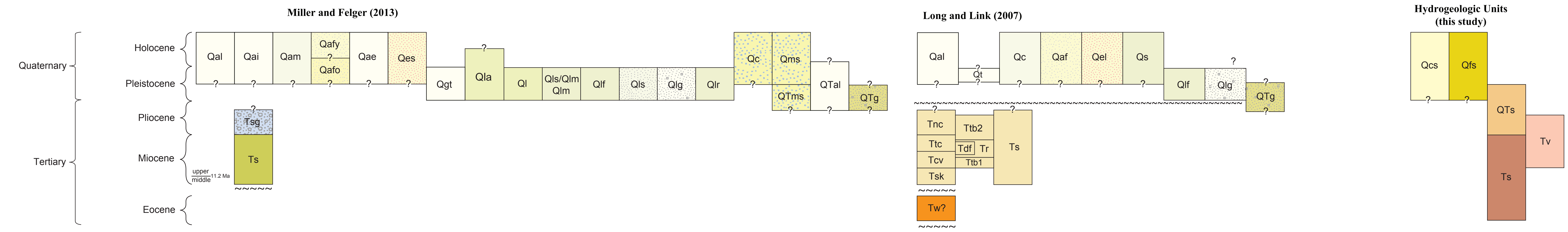
2016

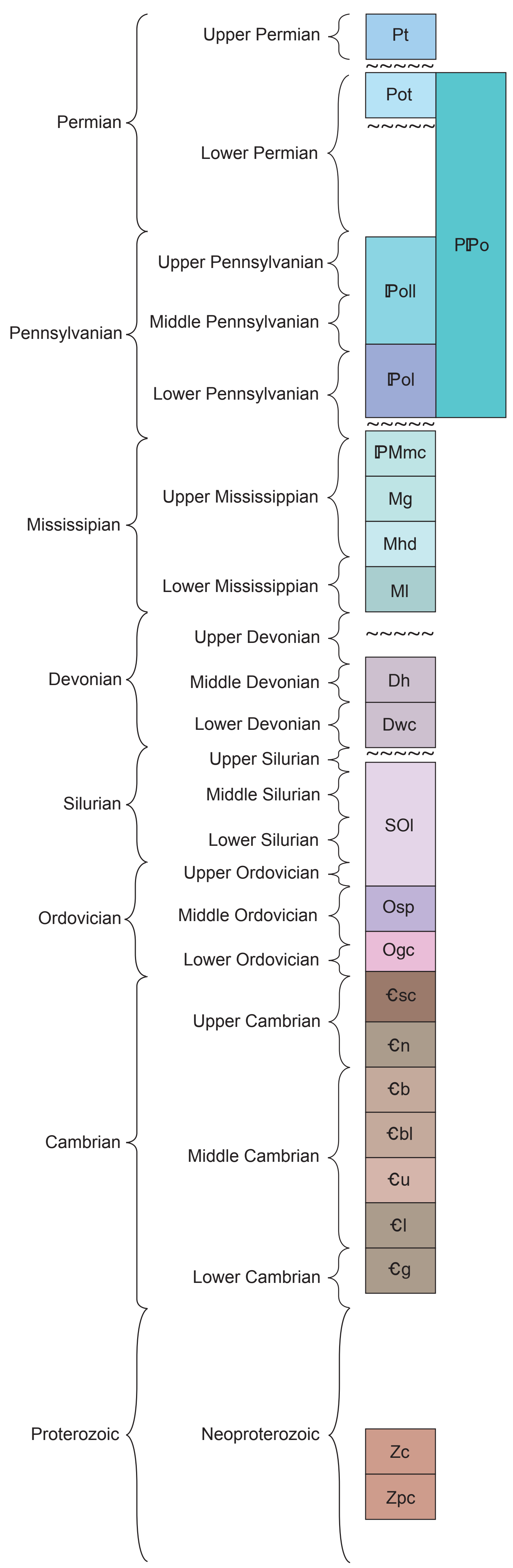
Projection: NAD 83 UTM Zone 12
Units: Meters
GIS by Nathan Payne, Richard Emerson, and Walid Sabbah

UTAH GEOLOGICAL SURVEY
a division of
Utah Department of Natural Resources

Plate 2
Utah Geological Survey Special Study 157
Hydrogeology of the Malad–Lower Bear River Basin,
North-Central Utah and South-Central Idaho

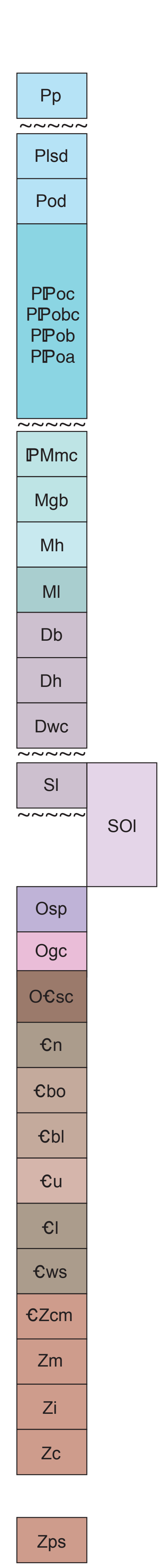
CORRELATION OF GEOLOGIC UNITS ON COMPILED GEOLOGIC MAP





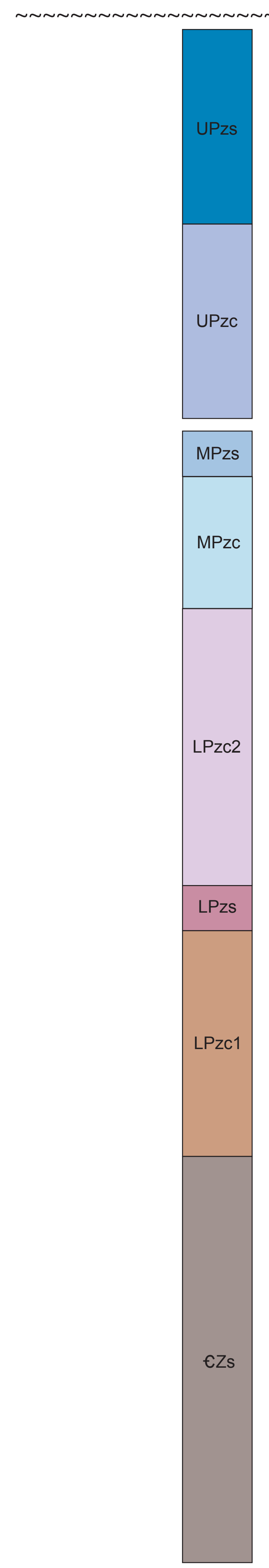
GEOLOGIC UNITS

Qal	Alluvium (Holocene)
Qai	Alluvial silt (Holocene)
Qam	Alluvial mud (Holocene)
Qafy	Alluvial-fan deposits (Holocene)
Qae	Alluvial and eolian deposits (Holocene)
Qes	Eolian sand (Holocene and Pleistocene)
Qc	Colluvium (Holocene)
Qms	Mass–movement slides (Holocene and Pleistocene)
Qgt	Glacial till (Pleistocene)
Qla	Lacustrine and alluvial deposits undivided (Holocene and Pleistocene)
Ql	Lacustrine mud and sand (Holocene)
Qls/Qlm	Lacustrine sand over marl (Pleistocene)
Qlm	Lacustrine marl (Pleistocene)
Qlf	Lacustrine fine–grained sediment (Pleistocene)
Qls	Lacustrine sand (Pleistocene)
Qlg	Lacustrine gravel (Pleistocene)
Qlr	Regressive lake deposits (Pleistocene)
Qafo	Older alluvial–fan deposits (Pleistocene)
QTms	Mass-wasting slumps (Pleistocene or Pliocene)
QTal	Alluvium and loess undivided (Pleistocene to Miocene)
QTg	Gravel deposits (Pleistocene and Pliocene)
Tsg	Salt Lake Formation—gravel member (Pliocene)
Ts	Salt Lake Formation (Miocene)
Pt	Thatcher Mountain Formation (Permian)
Pot	Oquirrh Formation—thinly bedded member (Lower Permian)
PIPo	Oquirrh Formation—undivided (Permian and Pennsylvanian)
IPoll	Oquirrh Formation—bioturbated limestone member (Upper and Middle Pennsylvanian)
IPol	Oquirrh Formation—limestone member (Middle? and Lower Pennsylvanian)
IPMmc	Manning Canyon Shale (Pennsylvanian and Upper Mississippian)
Mg	Great Blue Limestone (Mississippian)
Mhd	Humbug Formation and Deseret Limestone undivided (Mississippian)
Ml	Lodgepole Limestone (Mississippian)
Dbh	Beirdneau Formation and Hyrum Dolomite (Devonian)
Dwc	Water Canyon Formation (Devonian)
SOl	Laketown Dolomite and Fish Haven Dolomite undivided (Silurian and Ordovician)
Osp	Swan Peak Quartzite (Ordovician)
Ogc	Garden City Formation (Ordovician)
€sc	St. Charles Formation (Cambrian)
€n	Nounan Formation (Cambrian)
€b	Bloomington Formation (Cambrian)
€bl	Blacksmith Formation (Cambrian)
€u	Ute Formation (Cambrian)
€l	Langston Formation (Cambrian)
€g	Geertsen Canyon Quartzite (Cambrian)
Zc	Caddy Canyon Quartzite (Neoproterozoic)
Zpc	Papoose Creek Formation (Neoproterozoic)

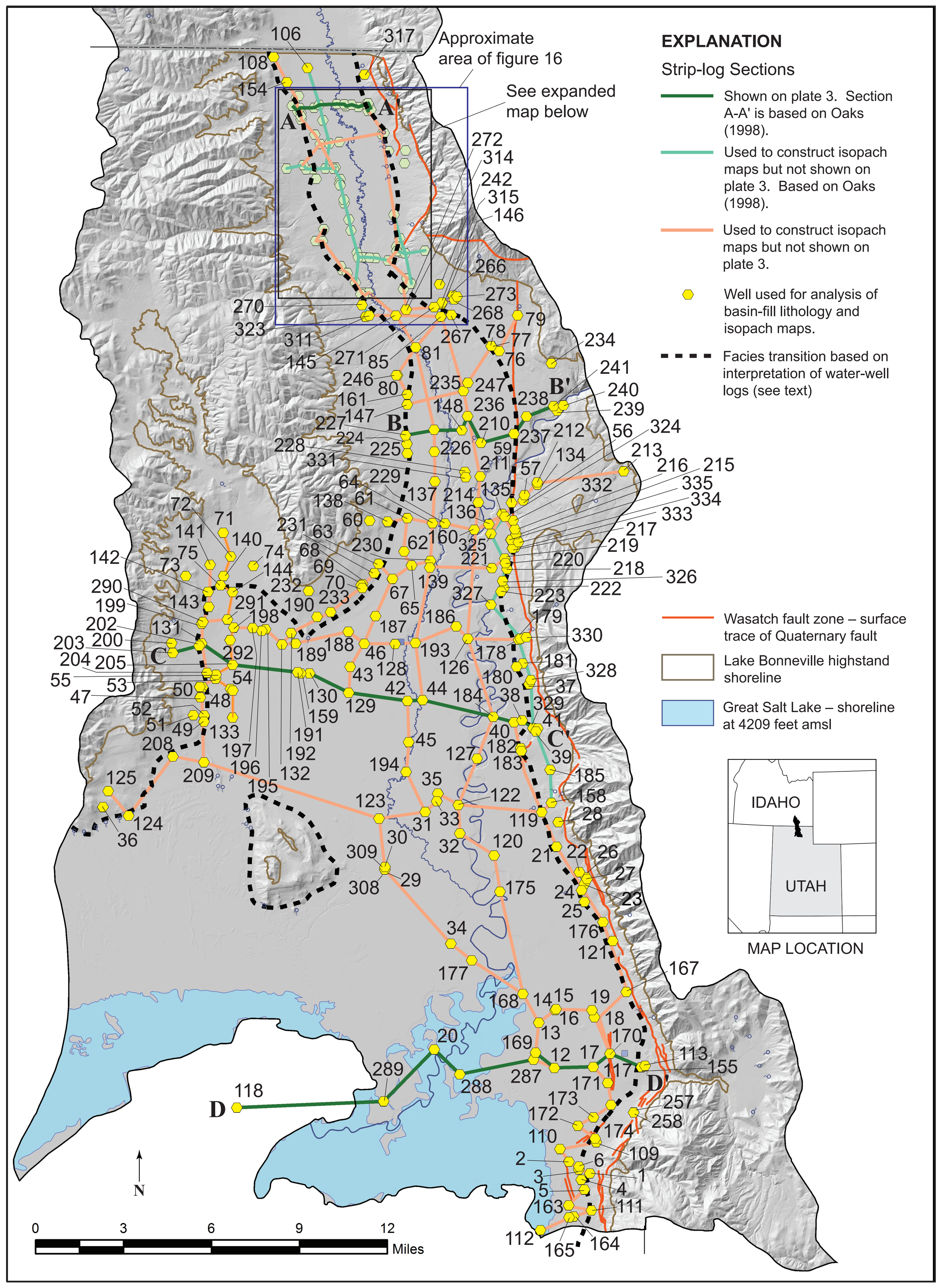


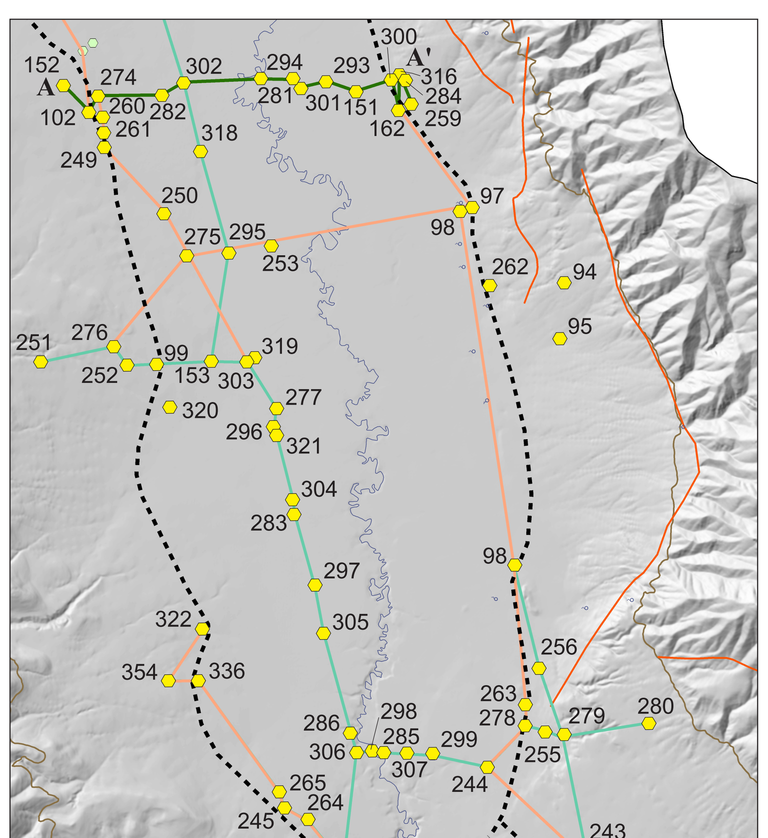
GEOLOGIC UNITS

Qal	Alluvial deposits (Holocene to Pleistocene?)
Qt	Terrace gravels (latest Pleistocene?)
Qc	Colluvium and talus (Holocene to Pleistocene?)
Qaf	Alluvial-fan deposits (Holocene to Pleistocene)
Qel	Eolian loess (Holocene to latest Pleistocene)
Qs	Landslide and slump deposits (Holocene to Pleistocene?)
Qlf	Lacustrine fine-grained sediment (Pleistocene)
Qlg	Lacustrine gravel (Pleistocene)
QTg	Quaternary-Tertiary gravel (Pleistocene to Pliocene?)
Ts	Salt Lake Formation—undivided (Pliocene? to Middle Miocene)
Tnc	Salt Lake Formation—New Canyon Member (Pliocene)
Ttb2	Salt Lake Formation—upper tuff and basalt unit (Pliocene to Upper Miocene)
Ttc	Salt Lake Formation—Third Creek Member (Pliocene to Upper Miocene)
Tr	Salt Lake Formation—rhyolite unit (Upper Miocene)
Tdf	Salt Lake Formation—rhyolite debris flow unit (Upper Miocene)
Ttb1	Salt Lake Formation—lower tuff and basalt unit (Upper Miocene)
Tcv	Salt Lake Formation—Cache Valley Member (Upper to Middle Miocene)
Tsk	Salt Lake Formation—Skyline member (Upper to Middle Miocene)
Tw?	Wasatch? Formation (Eocene?)
Pp	Phosphoria Formation (Lower Permian)
Plsd	Limestone, sandstone, and dolomite (Early to Late? Permian)
Pod	Oquirrh Group—unit d (Early Permian)
PIPoc	Oquirrh Group—unit c (Early Permian to Late Pennsylvanian)
PIPobc	Oquirrh Group—units b and c undivided (Early Permian to Early? Pennsylvanian)
PIPob	Oquirrh Group—unit b (Late to Early? Pennsylvanian)
PIPoa	Oquirrh Group—unit c (Early to Middle? Pennsylvanian)
IPMmc	Manning Canyon Shale (Lower Pennsylvanian and Upper Mississippian)
Mgb	Great Blue Limestone (Upper Mississippian)
Mh	Humbug Formation (Upper Mississippian)
Ml	Lodgepole Limestone (Lower Mississippian)
Db	Beirdneau Formation (Upper Devonian)
Dh	Hyrum Dolomite (Upper and Middle Devonian)
Dwc	Water Canyon Formation (Lower Devonian)
Sl	Laketown Dolomite (Middle and Upper Silurian)
SOl	Laketown Dolomite and Fish Haven Dolomite undivided (Upper Silurian to Upper Ordovician)
Osp	Swan Peak Quartzite (Middle Ordovician)
Ogc	Garden City Formation (Middle and Lower Ordovician)
O€sc	Saint Charles Formation (Lower Ordovician to Upper Cambrian)
€n	Nounan Formation (Upper and Middle Cambrian)
€bo	Bloomington Formation (Middle Cambrian)
€bl	Blacksmith Limestone (Middle Cambrian)
€u	Ute Formation (Middle Cambrian)
€l	Langston Formation (Middle Cambrian)
€ws	Sedgwick Peak Quartzite and Windy Pass Argillite of Brigham Quartzite undivided (Lower Cambrian)
€Zcm	Camelback Mountain Quartzite (Lower Cambrian to Neoproterozoic)
Zm	Mutual Formation (Neoproterozoic)
Zi	Inkom Formation (Neoproterozoic)
Zc	Caddy Canyon Quartzite (Neoproterozoic)
Zps	Pocatello Formation—Scout Mountain Member (Neoproterozoic)



STRIP-LOG SECTIONS





Expanded map of northern part of study area

EXPLANATION OF SYMBOLS IN STRIP-LOG SECTIONS