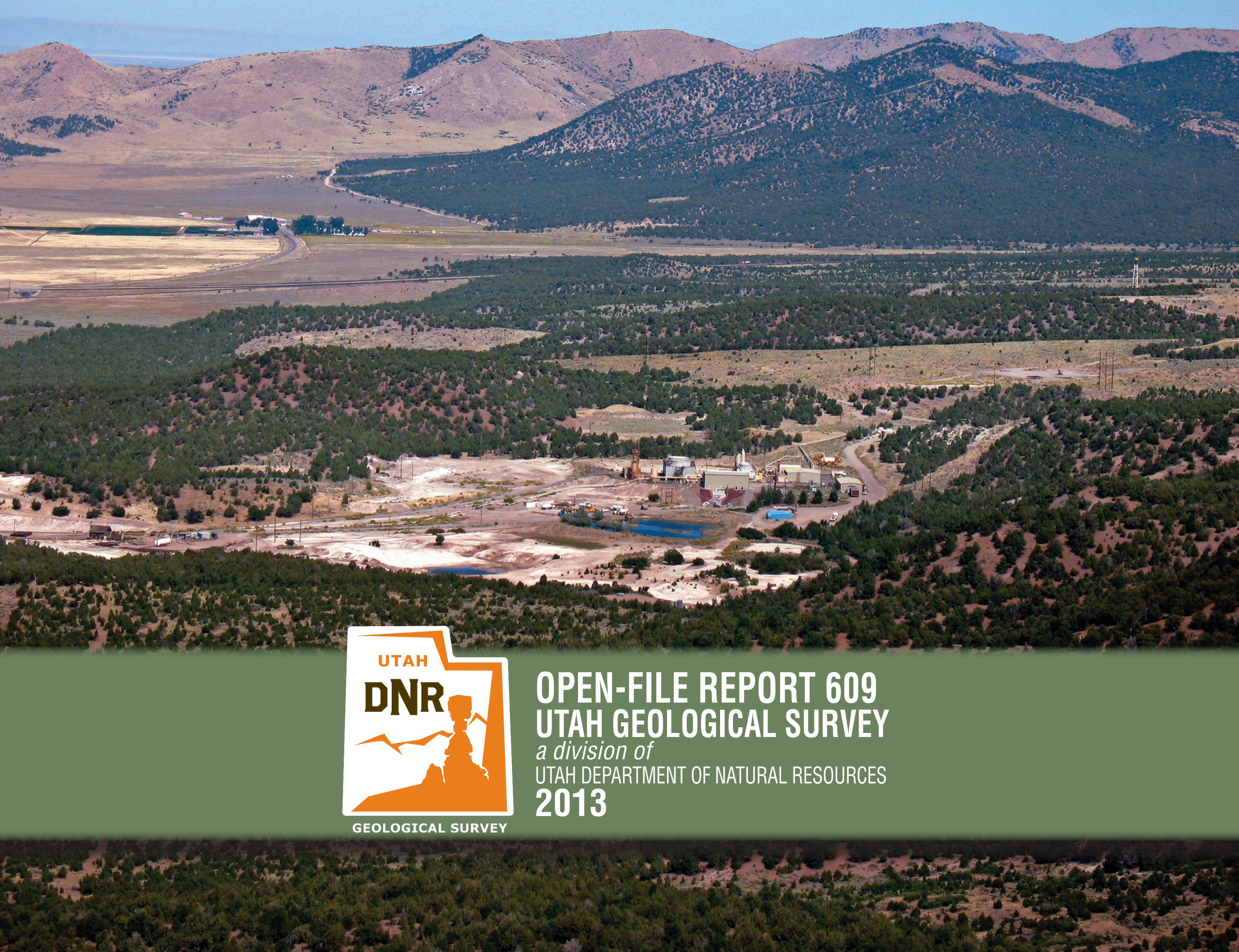
GEOLOGY OF THE SULPHURDALE GEOTHERMAL-RESOURCE AREA, BEAVER AND MILLARD COUNTIES, UTAH

Peter D. Rowley, Edward F. Rutledge, David J. Maxwell, Gary L. Dixon, and Chester A. Wallace



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Peter D. Rowley[1], Edward F. Rutledge[2], David J. Maxwell[3], Gary L. Dixon[4], and Chester A. Wallace[5]

[1]***Consulting geologist***
Geologic Mapping, Inc.
P.O. Box 651
New Harmony, UT 84757
pdrowley@rushisp.com
www.geologicmappinginc.com

[2]***Consulting geologist***
Route-Ledger GIS
192 North 100 West
Payson, UT 84651
routeledger@hotmail.com

[3]***Program Director***
GIS/GPS Laboratory
Southern Utah University
351 West Center
Cedar City, UT 84720
Maxwell@suu.edu

[4]***Consulting geologist***
Southwest Geology, Inc.
323 West 200 North
Blackfoot, ID 83221
dixong22@gmail.com

[5]***Consulting geologist***
Windy Point Exploration, LLC
7294 South Sourdough Drive
Morrison, CO 80465
cawallace.geologist@att.net

Cover photo: *View north of the former Sulphurdale power plant, which is the cluster of large buildings in the foreground. The north-trending road just to the right of the buildings is underlain by a down-to-the-west Quaternary fault that continues south to where the photographer is standing. The sulfur pit (solfatara) is the area underlain by the nearest white acid-leached surficial sediments and by two ponds. Several buildings of old Sulphurdale are near the left side of the image, where west-draining Sulphur Creek is seen. The buildings and trees in the left middle ground belong to the community of Cove Fort; the old fort is just left of the highway. All tree-covered hills belong to the foothills of the Tushar Mountains; its main north-striking range-front fault passes just left of all these foothills and just right of Cove Fort.*

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PUBLICATIONS
contact
Natural Resources Map & Bookstore
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website: mapstore.utah.gov
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UTAH GEOLOGICAL SURVEY
contact
1594 W. North Temple, Suite 3110
Salt Lake City, UT 84116
telephone: 801-537-3300
website: geology.utah.gov

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GEOLOGY OF THE SULPHURDALE GEOTHERMAL-RESOURCE AREA, BEAVER AND MILLARD COUNTIES, UTAH

Peter D. Rowley, Edward F. Rutledge, David J. Maxwell, Gary L. Dixon, and Chester A. Wallace

ABSTRACT

The geothermal resource at Sulphurdale, Utah, perhaps the second most important in Utah in terms of the size and heat content of the reservoir, is being developed for electric power by Enel Green Power North America, Inc. The geothermal resource underlies the ghost town of Sulphurdale and its adjacent active solfatara, which was formerly mined for native sulfur. The area lies within the western range-front faults of the northern Tushar Mountains. Most previous studies have suggested that the source for the heat is rapid rise along these faults of groundwater heated by the geothermal gradient. This water boiled to steam when it reached fractured Permian Queantoweap Sandstone at about 1200 feet (400 m) depth, where it is overlain by a cap of volcanic rocks largely dewatered by the heat. However, the heat is spread over an equidimensional area of about one square mile that is only partly defined by mapped faults. Accordingly, in an effort to understand better the geologic framework of the resource, the Utah Geological Survey funded preparation of a digital, 1:12,000-scale geologic map and five cross sections of a 14-square-mile area centered around the old sulfur open-pit mine and the former steam-generated, electric power plant. The new geologic map includes a portrayal of unconsolidated surficial deposits. Attention to surficial deposits enabled us to identify patches of an unwelded, moderately consolidated, partly hydrothermally altered, Quaternary ash-flow and airfall tuff on the southern side of the sulfur pit. This tuff is tentatively correlated with the ash-flow tuff in Ranch Canyon (K-Ar ages of 0.79 to 0.50 Ma; Lipman and others, 1978), at the western base of the Mineral Mountains about 15 miles (24 km) southwest of Sulphurdale. The Pleistocene tuff of Ranch Canyon was derived from volcanic domes capping the crest of the Mineral Mountains. This correlation of the tuff at Sulphurdale, however, is tenuous because of the tuff is altered and because the phenocryst abundance in the tuff is higher than that of the tuff of Ranch Canyon. Our study of Sulphurdale included an analysis of the likely source of the sulfur at the solfatara based on comparing the local geology with other sulfur occurrences. We conclude that the sulfur came from reduction of sulfates in evaporites in the Permian Kaibab Limestone and Toroweap Formation following their deep burial (hypogene karstification). Cenozoic plutons, some of which were sources for volcanic rocks, were later emplaced in the Cove Fort–Sulphurdale area. Hydrogen sulfide and sulfur derived from reduction of the sulfates were carried in pluton-driven plumes of heated groundwater toward the surface, where they were oxidized to the sulfur and to sulfuric acid, which seeped vertically downward, entirely removing the Kaibab and Toroweap carbonates in the area and providing secondary porosity to the underlying geothermal aquifer made up of the Queantoweap Sandstone and a carbonate section below it. The new map shows a much greater density of high-angle basin-range faults, and interprets some faults differently, than the structural picture given by a previous 1:24,000-scale map (Moore and Samberg, 1979). The new map showed that the producing steam area that drove the former power plant lies within a north-trending graben whose bounding faults have displacement as young as middle to late Pleistocene. A buried east-trending, down-to-the-north fault recognized by Moore and Samberg (1979) passes through the steam area near the plant and apparently provides additional structural control on the thermal reservoir. Mapping suggests that the geothermal resource extends north and east of where it has been defined by previous exploration. A subtle radial pattern is suggested by the faults east of the main range-front fault, which is just east of Highway I-15. These radial faults converge near the solfatara and are interpreted to represent offset during doming of roof rocks by a young buried intrusion, perhaps partly molten. We interpret that this intrusion, whose top is well beneath the level (7700 feet [2300 m] depth) of drilling to date and beneath the level of the cross sections of plate 2, supplies the geothermal heat at Sulphurdale.

INTRODUCTION

The Sulphurdale geothermal-resource area lies among the mostly north-trending, western frontal basin-range faults of the northwestern Tushar Mountains, in the northwestern part of the Marysvale volcanic field. The Tushar Mountains form the highest range in south-central Utah, rising to 12,173 feet (3710 m) at Delano Peak and 12,139 feet (3700 m) at Mount Belknap (figure 1). Therefore, these range-front faults are major structures, with cumulative vertical displacement probably well in excess of 10,000

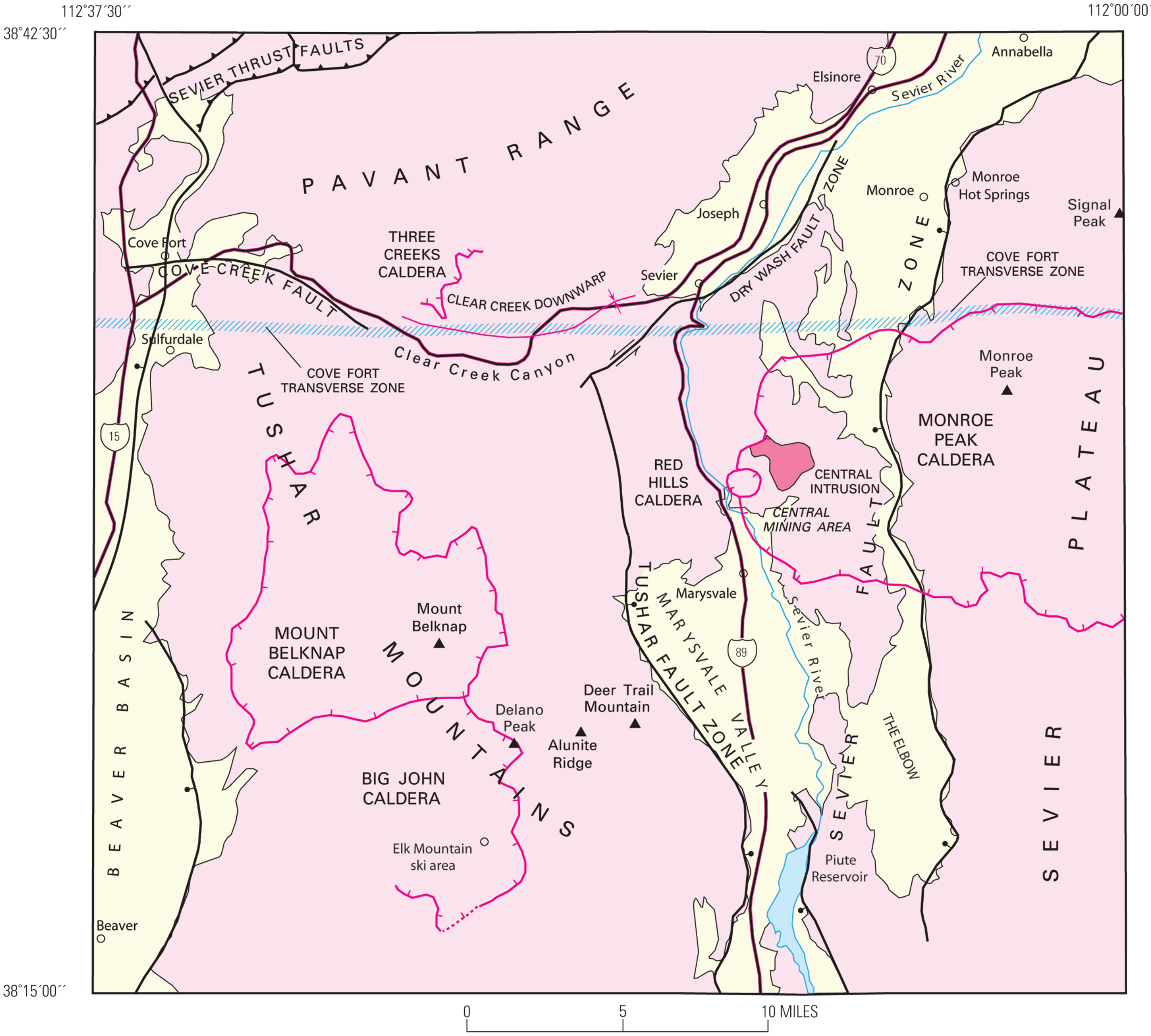

__Figure 1.__ Major features in the north-central part of the Marysvale volcanic field, after Rowley and others (2002b). Bedrock areas in pink; valleys of surficial deposits in yellow.

feet (3000 m). The Sulphurdale/Cove Fort area was rated by Mabey and Budding (1987, 1994) to be second in Utah in importance for geothermal energy potential, after the Roosevelt geothermal area west of the Mineral Mountains, about 20 miles (32 km) southwest of Sulphurdale. To date, the geothermal resources have been defined largely by geophysics and drilling (Mabey and Budding, 1987; Huttrer, 1994; Ross and Moore, 1994). Despite a high potential for generating significantly more electricity than in the past, Sulphurdale has been shrouded in a certain amount of mystery because its geology is poorly exposed, most geophysical and drilling data are proprietary, and the source of Sulphurdale's heat is not known. Nonetheless, Enel Green Power North America, Inc., is proceeding with development of the geothermal resource for electric power.

Most of the known Sulphurdale producing geothermal resources are near and within a mile north of the ghost town of Sulphurdale (Moore and Samberg, 1979; Moore, 2003). Deposits of native sulfur had been discovered by Mormon pioneers in the 1850s near and south of what a decade later became Cove Fort, which was founded to protect settlers from Indian raids; Cove Fort is now near the intersection of Interstate Highways I-15 and I-70 (figure 1). Sulphurdale, which is 3 miles (5 km) south of Cove Fort, apparently was founded and occupied during the period of 1883 to 1906, when a processing plant used a thermal process to extract sulfur from a pit adjacent to the town and from other mines in the Cove Fort area (Lee, 1906; Rodriguez, 1960). Shortly after this period, Sulphurdale was abandoned, and although several other ventures processed sulfur up into the 1950s, their production figures are unknown (King, 1953). The Sulphurdale pit is the site of an active solfatara, which is a type of fumarole where the gases are generally sulfurous (hydrogen sulfide, H_2S). The hydrogen sulfide gas apparently oxidized to deposit the sulfur in veins, cylindrical masses, and pore spaces in unconsolidated tuffaceous sediments through which the gases rose (Lee, 1906; Rodriguez, 1960). Historically and today, H_2S and CO_2 gases have issued from the pit, especially along open fractures related to the north-trending basin-range fault zone on the eastern side of the pit (Lee, 1906; King, 1953). H_2S bubbles can be seen rising through small pools of standing water in the pit; some of these pools have a pH of about 1 (Moore and Samberg, 1979).

The Bonnett power plant (plate 1), located along the northeastern edge of the ghost town, began production in 1985 by Mother Earth Industries, Inc., after the property and data were acquired from Union Oil Company (Huttrer, 1994). This plant produced a small amount (4 to 6 megawatts [MW]) of electricity from geothermal steam, but the plant has been shut down for several years. The leases and the plant are currently owned by Enel Green Power North America, Inc., which intends to dismantle the plant and build a new one, using binary technology that does not require steam. Enel's leases extend northwest, north, and northeast of the plant, as far as the latitude of Cove Fort, where additional hot water has been discovered; additional plants may eventually be constructed to utilize those geothermal resources.

Huttrer (1994) provided a brief summary of drilling completed up to 1994. The most useful and most recent discussion to date of the geology of the immediate Sulphurdale area is that in 2003 by Joseph Moore of the Energy and Geoscience Institute of the University of Utah, formerly the University of Utah Research Institute (UURI). Although not published, this report has become widely available and therefore is not considered proprietary by Enel Green Power North America. This report is cited here as Moore (2003). By 2003 at least 25 drill holes, including at least five production wells (dry steam in excess of 300°F [149°C], at least two wells with water yields of at least 1000 gallons per minute [gpm]) and two reinjection wells, had been drilled near the plant (Huttrer, 1994; Moore, 2003). Additional production and reinjection wells have been drilled since then, including several in 2010, but most information on them is proprietary. No boreholes drilled to date include core drilling, and few cuttings have been systematically collected or saved. The most detailed (including thin sections of epoxy blocks of some cuttings) published lithologic logs are those of wells 42-7 (Moore and Samberg, 1979) and BO1-1 (Moore, 2003). For other logs, a lack of familiarity with locally exposed rock units led to difficulties matching rock units at the surface with those encountered in drilling. A new geophysical study, funded by the Department of Energy (DOE), will be done by principal contractor Massachusetts Institute of Technology (MIT), and subcontractors, including New England Research, Inc. (NER). The study will reportedly consist of gathering passive seismic data. Seismic surveys might detect semisolidified magma in the subsurface.

The Sulphurdale area has been geologically mapped many times but most of these maps are insufficiently detailed to provide an understanding—except in the most general terms—of the geothermal resource. The most detailed (1:24,000 scale) geologic map, by Moore and Samberg (1979), is obsolete based on current knowledge, shows relatively few faults, and does not distinguish the various unconsolidated surficial deposits. Consequently, in response to a solicitation by the Utah Geological Survey (UGS) for proposals for research to characterize Utah's energy and mineral resources, this project effort of geologic mapping at 1:12,000 scale was proposed to the Utah Geological Survey (UGS) in June 2010. The Sulphurdale geothermal-resource area mapped here consists of about 14 square miles (36 km^2) centered at the Sulphurdale ghost town. In addition, five cross sections at the same scale were drawn to help interpret the geothermal resource. This report interprets the map and cross-section data. Modal analyses of 45 stained thin sections facilitated the identification of geologic units. The work benefitted from significant cooperation with Enel Green Power North America, although the large number of proprietary reports on the geophysics and drilling were not examined. Nonetheless, one excellent proprietary summary report (Bowers, 2009) was studied (but not here quoted), and six proprietary well logs of new holes were used to help interpret the cross sections, although the locations of these holes are not identified on the map or sections.

GEOLOGIC AND PHYSIOGRAPHIC SETTING

Sulphurdale lies at the eastern edge of the Great Basin part of the Basin and Range physiographic province. To the east of the ghost town is the High Plateaus subprovince of the Colorado Plateau physiographic province. The Great Basin is characterized by alternating, mostly north-trending, basins (valleys) and ranges. The basins and ranges formed largely through relative vertical movement along mostly north-trending normal faults. The High Plateaus are formed by fewer and smaller faults than those in the Great Basin. Specifically, the High Plateaus consists of horsts (blocks upthrown by large range-front faults on their western and eastern sides) such as the Tushar Mountains and, more commonly, gently east-dipping tilt blocks upthrown by large faults on only their western side, such as the Sevier Plateau (figure 1). The subprovince passes eastward into the main mass of the Colorado Plateau, made up of plateaus and mesas formed by erosion of mostly flat-lying rocks.

The oldest rocks exposed in the Sulphurdale map area are Oligocene volcanic rocks, but Paleozoic rocks unconformably underlie these rocks in the subsurface and are penetrated by many drill holes; the Paleozoic rocks are shown on the cross sections. The youngest of the Paleozoic rocks seen in drill cuttings belongs to the Queantoweap Sandstone of Permian age, deposited in shallow-marine, beach, and dune environments. This unit is underlain by the Pakoon Dolomite of Permian age, predominantly dolomite deposited in marine environments, as recorded by drill cuttings. The drill holes indicate that a thick sequence of marine carbonate underlies the dolomite, but not enough information can be ascertained from the cuttings to assign formation names.

Two major episodes of structural deformation took place in the map area, the Sevier orogeny and basin-range extension. Between those two events was an episode of extremely voluminous calc-alkaline magmatism. The Sevier deformation and calc-alkaline rocks formed during relatively rapid subduction, as Pacific tectonic plates to the west were overridden by west-moving North America (Atwater, 1970; Hamilton, 1989, 1995; Severinghaus and Atwater, 1990; Schellart and others, 2010). Subduction at this latitude slowed drastically (Schellart and others, 2010) or ended at about 20 Ma, when basin-range deformation began. Of the two deformational events, the older structural event, the Sevier deformation, affected the Paleozoic to earliest Cenozoic rocks. This compressional event resulted in Late Cretaceous to Paleocene east- and southeast-directed folds, reverse faults, and thrust faults. As shown in figure 1, folds and thrusts are well exposed west and north of Cove Fort (Hintze and others, 2003); there is no information that they exist beneath Sulphurdale. Significantly, rocks as young as the Permian Kaibab Limestone are exposed in and below Sevier thrust sheets northeast of Cove Fort (Hintze and others, 2003). Below the thrusts, the autochthonous section is as young as the Jurassic Navajo Sandstone. In this autochthonous section, the Kaibab Limestone, which includes the Toroweap Formation in its lower part, is as thick as 1160 feet (350 m) as close as 2 miles (3 km) northeast of Cove Fort (Hintze and others, 2003). At this same location, the Kaibab is underlain by the Queantoweap and is unconformably overlain by Tertiary volcanic rocks.

Two regional Cenozoic magmatic episodes took place, resulting first in calc-alkaline igneous rocks (Oligocene to Miocene) and then bimodal igneous rocks (Miocene to present). The older calc-alkaline volcanic rocks range in composition from andesite to low-silica rhyolite, as elsewhere in the West (Lipman and others, 1972). These volcanic rocks consist of extremely voluminous ash-flow tuffs, lava flows, and volcanic mudflow breccia that erupted from large east-trending igneous belts made up of intrusions and eruptive centers (Rowley, 1998; Rowley and others, 1998; Rowley and Dixon, 2001). Parts of one of these belts, the Pioche-Marysvale igneous belt, are within the map area. The calc-alkaline rocks in the map area range in age from about 34 to 20 Ma. The Marysvale volcanic field, at the eastern end of the Pioche-Marysvale igneous belt, was the vent area for the calc-alkaline rocks, derived in turn from stocks and batholiths at depth. The Marysvale field, one of the largest in the West, resulted predominantly from stratovolcanoes, but large caldera-forming eruptions also were common (Cunningham and Steven, 1979a; Rowley and others, 1979, 1998, 2002a; Steven and others, 1979, 1984, 1990; Cunningham and others, 2007).

Some of the igneous belts are bounded by east-trending faults, folds, strings of igneous vents, hot springs, and hydrothermally altered rocks. These east-striking features are parts of transverse zones, which are discontinuous, poorly understood, deep-seated structural features that are the loci of intrusive activity and, therefore, high heat flow. The faults in these zones may have strike-slip (lateral), oblique-slip (lateral and vertical), or normal-slip relative movement. Transverse zones mark boundaries north and south of which are areas characterized by different rates, types, and amounts of east-west deformation. As such, transverse zones are analogous to transform faults, which are especially prominent as the east-trending features in the ocean basins (Ekren and others, 1976, 1977; Rowley and others, 1978, 1998; Rowley, 1998; Rowley and Dixon, 2001). The closest transverse zone to the map area is the east-trending Cove Fort transverse zone, which defines the northern side of the Marysvale volcanic field and several of its calderas and includes east-trending faults and folds that follow Interstate Highway I-70 from just southwest of Cove Fort, then eastward along Clear Creek to the town of Sevier, then continue eastward across the Sevier Plateau (figure 1).

The younger of the two magmatic episodes (20 Ma to present) produced volcanic rocks of bimodal composition, namely basalt and high-silica rhyolite. Bimodal volcanism was prevalent throughout the West but of much smaller volume than the calc-alkaline volcanism (Christiansen and Lipman, 1972). Although not confined necessarily to the calc-alkaline igneous belts, bimodal tuffs and flows are abundant in the Marysvale volcanic field, including one large caldera, the Mount Belknap caldera (figure 1). Bimodal volcanism coincided with the younger of the two major episodes of structural deformation in the map area. This younger episode is basin-range deformation (Mackin, 1960), which began at about 20 Ma and continues to the present.

The basin-range episode resulted from east-west extension, forming north-striking, primarily high-angle normal faults. Most basin-range faulting took place after about 10 Ma and produced the present topography. These normal faults define the alternating series of north-trending basins (grabens and half grabens) and ranges (horsts and tilt blocks) that characterize the Great Basin. As the basins dropped relative to the ranges, they were filled with basin-fill sediments derived from erosion of the ranges; such basin-fill sedimentary deposits are in places thousands of feet thick. Transverse zones continued to form during the episode of basin-range deformation, producing structures at 90 degrees to the predominant northerly ones.

PREVIOUS STUDIES

The geology of the Sulphurdale geothermal area has been discussed in many reports, most of them either old and obsolete, in gray literature, as published summary studies from company files, or in company-confidential documents. The present authors had access to only one proprietary report. Many proprietary geophysical studies were done in the area, but, other than emphasizing the importance of fault control, they have not identified the cause, size, or temperature of the resource. Only summaries of logs of two wells are published (Moore and Samberg, 1979; Moore, 2003); some other wells were shown in interpretive cross sections by Moore (2003; figures 5 and 6) and briefly summarized by Huttrer (1994). The only other detailed drill logs seen in this study were made available by Enel but, being proprietary, their locations are not shown although the logs were interpreted by the authors and used where possible.

The primary tool for understanding complex geologic problems is geologic mapping. Of this work, the only previous detailed geologic map (1:24,000-scale) to define the Sulphurdale geothermal-resource area was by Moore and Samberg (1979) of the University of Utah Research Institute (UURI), under funding from the Department of Energy. At the same time as the UURI study was being done, the U.S. Geological Survey (USGS) had started a large project that eventually mapped virtually the entire Marysvale volcanic field. P.D. Rowley participated in that project for about 10 years in the 1970s and 1980s, and the project was followed by many additional studies and publications by many of us that continue to the present. The USGS map of the Cove Fort 15-minute quadrangle (Steven and Morris, 1983), done with the collaboration of UURI, covered the entire Sulphurdale and Cove Fort sulfur and geothermal resources areas at 1:62,500 scale. A preliminary version of much of the Marysvale field, including most of the same Sulphurdale–Cove Fort area, was published by Cunningham and others (1983) at 1:50,000 scale. A folio of 6 additional maps showed altered areas, geophysics, and metallic geochemistry of the same area at the 1:50,000 scale. A reconnaissance-scale (1:250,000) map of most of the Marysvale field and areas west to nearly the Nevada border, the Richfield 2-degree sheet, was published by Steven and others (1990). Much later, a 1:100,000-scale geologic map of most of the Marysvale field, the area of figure 1, was compiled to take into account new mapping and all previous work (more than 200 publications by then) as Rowley and others (2002b). Gravity and aeromagnetic maps (Campbell and others, 1999) of the same area and scale accompanied the 1:100,000-scale geologic map. This digital geologic-map file was incorporated into, and combined with, new mapping outside the central Marysvale field, as the Richfield (Hintze and others, 2003) and the Beaver (Rowley and others, 2005) 1:100,000-scale quadrangles, which are the two eastern quadrangles of the Richfield 2-degree sheet. All of these geologic maps are either not sufficiently detailed or are too outdated to significantly aid the current exploration at Sulphurdale.

The most useful of all available previous reports are the excellent studies by Moore and Samberg (1979), Ross and Moore (1994), and Moore (2003). These reports showed that the active solfatara at Sulphurdale is the youngest of several hydrothermal events in the Sulphurdale/Cove Fort area that are associated with bimodal volcanism and basin-range faulting; other such events left fluorite deposits associated with the faults near Cove Fort. The overall active Sulphurdale to Cove Fort geothermal area is estimated by Ross and Moore (1994) to cover about 18 square miles (47 km^2). The oldest of the hydrothermal events in this area is middle Tertiary in age, and resulted from intrusions associated with the voluminous calc-alkaline Marysvale volcanism, one buried pluton of which was penetrated by drill holes beneath the steam area at Sulphurdale. Moore and Samberg (1979), Ross and Moore (1994), and Moore (2003) showed that the Sulphurdale steam and hot-water resource is contained in the upper part of a Paleozoic quartzite and carbonate sequence, which underlies the Tertiary volcanic rocks at about 1200 feet (400 m) depth. The buried, quartz monzonite porphyry pluton (Moore, 2003) identified by the drilling, although it long predated the fluorite hydrothermal event and the current solfatara, contact metamorphosed and mineralized the carbonate rocks, but was not in turn significantly altered by the later hydrothermal events. The work of Moore and Samberg (1979), Ross and Moore (1994), and Moore (2003) concluded that the primary steam and hot water conduits are high-angle basin-range faults. Among these faults of late Tertiary age, Moore and Samberg (1979) and Moore (2003) interpreted some of them as gravity-slide blocks emplaced along low-angle to horizontal faults that they suggested overrode the Paleozoic sedimentary sequence and provided an impermeable cap to the geothermal aquifer. We, on the other hand, found no gravity slides or their underlying low-angle normal faults.

Geophysical studies were summarized by Mabey and Budding (1987, 1994), Ross and Moore (1994), and Huttrer (1994). They found that gravity and magnetic studies supported the portrayal of high-angle faults given by Moore and Samberg (1979). A large area of low magnetization between Sulphurdale and north of Cove Fort, which Ross and Moore (1994, figure 5) ascribed to a polarization low from a high magnetic anomaly on intrusive rocks southeast of Sulphurdale, may be explained in part as hydrothermally altered rocks above the active geothermal aquifer. Thermal gradient data based on 24 shallow (100 to 250 feet, 30–75 m) drill holes in the Sulphurdale–Cove Fort area show two pronounced positive thermal anomalies, one centered beneath and extending as much as 0.6 mile (1 km) north of Sulphurdale, and the other extending east-southeast from north of Cove Fort to east of Cove Fort (Ross and Moore, 1994, figure 6). The boundary of the Sulphurdale thermal-gradient anomaly, however, was not closed out by field data to the east, so this anomaly may extend significantly farther to the east. Ross and Moore noted that many of the higher thermal gradients were recorded in drill holes along fractures. Electrical resistivity surveys (Ross and Moore, 1994, figure 7) defined the northern and western edges of the Sulphurdale steam and hot-water production area by low resistivity readings (from thermal brines at and below the 1200-foot-deep water table and hydrothermally altered clay near and above the water table) extending as far as about 5200 feet (1580 m) west of, and 1800 feet (550 m) north of, well 42-7. Water temperatures recorded at 1320 feet (400 m) depth at well 42-7, near the northern part of the Sulphurdale heat anomaly, reached a maximum of 354°F (179°C); and dry-steam temperatures at 1165 feet (350 m) depth at well 34-7, near the center of the anomaly, reached a maximum of 350°F (176°C; Huttrer, 1994). In fact, during its drilling in 1983, well 34-7 blew steam for 24 days before it was successfully capped. Huttrer (1994) noted that 94 samples collected for soil mercury at, north, and east of the sulfur pit defined four N15°E-striking faults east and west of the pit and two N40°W-striking faults on the southwestern side of the pit.

The geology of the sulfur deposits bears on the chemistry of the geothermal fluids and on the location and character of the geothermal aquifer (see chapter on "Origin and Implications of Sulfur" below). Sulfur deposits are associated with all of the geothermal resources in the overall Sulphurdale/Cove Fort area, but the deposits at Sulphurdale are the largest, and only here is sulfur deposition active, as indicated by observations of hydrogen sulfide gas bubbling up through mud in newly excavated trenches and in small pools of water, especially near the Quaternary basin-range fault on the eastern side of the pit (Rodriguez, 1960; Callaghan, 1973). Here, above the water table, elemental sulfur was deposited in Pleistocene deposits, which are mapped here as the waterlaid tuff of Ranch Canyon (Qtrw). The sulfur resulted from partial oxidation of the H_2S (Rodriguez, 1960, p. 48). In the pit, the sulfur was considered by Rodriguez (1960) to be interbedded and enclosed within siliceous sinter, based on his microscope examination of thin sections. He observed small masses of black iron sulfides (fine-grained pyrite and marcasite) in the lower part of the sulfur deposits.

GEOLOGIC MAP OF THE SULPHURDALE AREA

Plate 1 is a 1:12,000-scale digital geologic map of the Sulphurdale geothermal-resource area. It covers the entire area for which production and exploration holes have been drilled to determine the resource. This resource surrounds the active solfatara that produced the sulfur deposits mined at the Sulphurdale open-pit mine. Our study was done with the encouragement of Enel Green Power North America under funding from the Utah Geological Survey. Four generally-east-trending cross sections (Sections A–A′, B–B′, C–C′, and D–D′) and one generally-north-trending cross section (Section E–E′) were done at the same scale, with no vertical exaggeration. Location of cross sections was guided by the location of seven drill holes described by Moore and Samberg (1979) and Moore (2003), and coincides with previous cross sections by these workers. Of the five cross sections, Section B–B′ included nearly the entire length of Section A–A′ of Moore and Samberg (1979), then extended their cross section to the west. Sections C–C′ and E–E′ included the entire length of Sections B–B′ and A–A′, respectively, of Moore (2003), then extended both of them farther on both ends. The reason for duplicating the locations of the previous sections is that all cross sections are tied to a limited number of crucial drill holes and, furthermore, that we sought to contrast our different interpretations, based on our more detailed mapping, with those of Moore and Samberg (1979) and Moore (2003).

Description of Map Units

QTa **Alluvium, fan deposits, and landslide deposits (Holocene to Pliocene)**—Only on cross sections.

Qa **Stream alluvium (Holocene)**—Alluvium in channels, floodplains, and adjacent low terraces of Sulphur Creek and its tributaries; sand, gravel, silt, and clay; grades laterally into young alluvial-fan deposits (Qaf1); locally hydrothermally altered and impregnated by native sulfur; maximum thickness about 15 feet (5 m).

Qaf1 **Young alluvial-fan deposits (Holocene and upper Pleistocene)**—Unconsolidated, poorly to moderately sorted silt, sand, and gravel deposited by streams, sheetwash, debris flows, and flash floods on alluvial fans; includes alluvium and colluvium in upper stream courses; surface is modern and generally undissected; locally hydrothermally altered and impregnated by native sulfur; map unit includes a thin delta at Alkali Flat, where debris from the sulfur pit shows up as a white deposit, although the debris is acidic rather than alkaline; maximum thickness of the map unit at least 30 feet (10 m).

Qaf2 **Middle alluvial-fan deposits (upper and middle Pleistocene)**—Unconsolidated, poorly to moderately sorted silt, sand, and gravel deposited by streams, sheetwash, debris flows, and flash floods on alluvial fans; includes alluvium and colluvium in upper stream courses; surface is moderately dissected; includes a pedogenic carbonate soil about 1.5 feet (0.5 m) thick and 4 feet (1.25 m) below the surface of the pediment in a roadcut 200 yards (200 m) east of the Bonnett power plant; locally hydrothermally altered and impregnated by native sulfur in the vicinity of the Sulphurdale pit; maximum thickness of the unit at least 30 feet (10 m).

QTaf3 **Old alluvial-fan deposits (middle Pleistocene to upper Pliocene)**—Poorly consolidated, poorly to moderately sorted silt, sand, and gravel deposited by streams, sheetwash, debris flows, and flash floods on alluvial fans; upstream parts not preserved; surface is heavily dissected; maximum thickness at least 50 feet (15 m).

Qms **Landslide deposits (Holocene and upper Pleistocene)**—Unsorted, mostly angular, unstratified rock debris moved by gravity from nearby bedrock cliffs; includes talus and colluvium; thickness may locally be about 200 feet (60 m).

Qtrw **Waterlaid tuff of Ranch Canyon (upper and middle Pleistocene)**—Poorly consolidated, light-gray, waterlaid tuff and interbedded stream alluvium, overbank clay and silt, and alluvial-fan deposits, locally cemented by native sulfur and exposed due to excavation during open-pit mining for sulfur in the Sulphurdale ore pit (Rodriguez, 1960); the open pit was developed on an active solfatara that formed during boiling of the groundwater at about 1200 feet (400 m) depth, from which steam and gases rose; hydrogen sulfide oxidized to native sulfur; perhaps in turn, the sulfur oxidized to sulfuric acid, which leached downward to create high secondary permeability in the waterlaid tuff, and left hydrothermally altered material and residues of silica; the primary and secondary pores are partly filled with native sulfur (Moore and Samberg, 1979); although the rocks are altered, they are interpreted here to be largely derived from erosion of the tuff of Ranch Canyon (Qtr) and perhaps from erosion of the Three Creeks Tuff Member (Tbt) of the Bullion Canyon Volcanics, which apparently underlies the map unit and is exposed upstream from it; these water-laid tuffs were deposited in a shallow Pleistocene graben that underlies the Sulphurdale pit and is bounded on both sides by north-trending Pleistocene faults; fractures due to these faults controlled the rise of the hydrogen sulfide and other gases; Lee (1906) reported that some sulfur was deposited in veins resulting from the fault and in cylindrical masses as much as 15 feet (5 m) across that suggest deposition in intersecting fractures; Rodriguez (1960, p. 34) noted that the fault on the eastern side of the pit bounds the ore body and is synchronous with it; several cobbles and boulders of basalt or basaltic andesite were observed in the pit, suggesting that some of the tuff may be derived from Cinder Crater (Qbc) or, as interpreted here, that the basalt clasts were carried in ash flows of the tuff of Ranch Canyon (Qtr); according to observations and test holes in the pit by Rodriguez (1960), maximum thickness of the unit is about 100 feet (30 m) and it is underlain by a "porphyritic latite flow" that is presumed to be the Three Creeks Tuff Member (Tbt); Callaghan (1973), however, noted that many of the test holes did not go entirely through the ore body and that one of those test holes apparently reached a depth of 172 feet (52 m), providing a minimum thickness to the map unit.

Qbc **Basaltic andesite of Cove Fort (middle Pleistocene)**—Resistant, dark-gray and black, vesicular to dense lava flows of basaltic andesite derived from Cinder Crater, which is a cinder cone 3 miles (5 km) west of Sulphurdale, or from the shield volcano on which it lies. Flow contains sparse phenocrysts and microphenocrysts of plagioclase, pyroxene, Fe-Ti oxides, olivine, and rare corroded quartz in a felted matrix of microlites and glass (Clark, 1977; Steven and Morris, 1983); K-Ar age is 0.5 Ma (Best and others, 1980); exposed thickness in the map area about 40 feet (12 m), thickening westward.

Qtr **Tuff of Ranch Canyon (middle Pleistocene)**—Moderately consolidated, partly hydrothermally altered, white, crystal-poor, unwelded, rhyolite ash-flow tuff, bedded airfall lapilli tuff, and bedded waterlaid lapilli tuff, exposed on the southern side of the Sulphurdale pit and as a tiny patch along Sulphur Creek several hundred yards (100 m) to the east; in addition, when trenching a young fault, Anderson (1980, figure 8) noted a tephra bed of the map unit within unconsolidated sediments apparently of the middle alluvial-fan deposits (Qaf2) at a "pit" identified on the Cove Fort 7.5-minute quadrangle just south of Highway I-70 and just east of the Cove Fort exit, in the northern part of the map area; unit at Sulphurdale lithologically resembles, and therefore tentatively correlated with, ash-flow tuff and related ash deposits that are derived from Quaternary rhyolite volcanic domes on the crest of the Mineral Mountains about 13 miles (21 km) west-southwest of

Sulphurdale and that flowed mostly west and are best exposed at the mouth of Ranch Canyon at the western base of the Mineral Mountains south of the Roosevelt geothermal area (Lipman and others, 1978; Mehnert and others, 1978; Rowley and others, 2005); modal analyses of thin sections from Sulphurdale as part of this study shows 6 to 15 percent phenocrysts of mostly quartz, sanidine, and plagioclase with traces of biotite and Fe-Ti oxides, similar to although slightly more crystal rich than modal analyses on rocks from the Mineral Mountains reported by Lipman and others (1978) and Mehnert and others (1978); K-Ar ages of domes, obsidian lava flows, and ash-flow tuff from these domes range from 0.79 to 0.50 Ma (Lipman and others, 1978; Mehnert and others, 1978); thickness 30 feet (10 m).

QTbf **Sedimentary basin-fill deposits (lower Pleistocene to upper Miocene)**—Moderately consolidated, poorly to moderately sorted boulders (clasts as long as 6 feet [2 m]), gravel, sand, and silt deposited by streams, sheetwash, and debris flows in the graben in the western part of the map area; best exposed along Sulphur Creek east of the frontage road and north of the road to Sulphurdale, where most rocks are a bouldery and cobbly pebble conglomerate at least 100 feet (30 m) thick that is locally hydrothermally altered and impregnated by sulfur; in the subsurface, logs for water wells drilled into the graben in Sections 12, 23, and 26, T. 26 S., R. 7 W., as given in the Utah Division of Water Rights website (http://nrwrt1.nr.state.ut.us/), show that the sedimentary rocks are intertongued with basaltic andesite lava flows (Qbc) probably derived from Cinder Crater, which is 3 mi (5 km) west of Sulphurdale; thickness of basin-fill deposits in the subsurface at least 600 feet (200 m) based on the deepest water well given on the Utah Division of Water Rights website, but likely greater than 1000 feet (300 m) thick; gravity data suggested that basin-fill deposits plus intertongued basalt flows and underlying calc-alkaline volcanic rocks are at least 3000 feet (1 km) thick and as much as 4000 feet (1.2 km) thick in the graben west and southwest of Cove Fort (Cook and others, 1980; Ross and Moore, 1994; Kirby, 2012).

Mount Belknap Volcanics (Miocene)—Named by Callaghan (1938, 1939) for many small to large accumulations of mostly high-silica rhyolite in the Marysvale volcanic field; redefined by Steven and others (1979) and Cunningham and Steven (1979a) for rhyolites that were derived from either small local sources or from the large Mount Belknap caldera (figure 1) making up the crest of the Tushar Mountains. Units of the Mount Belknap Volcanics are described below.

Tmr **Rhyolite lava flows (Miocene)**—Resistant, medium-gray, aphyric rhyolite lava flows characterized by locally contorted flow bands of dark-gray, undevitrified glass within light-gray devitrified rock; consist of several small outcrops, less than 3 feet (1 m) thick, that cap the Joe Lott Tuff Member (Tmj) on the top of a low hill east of the frontage road and north of the road to Sulphurdale; this unit was mapped by Steven and Morris (1983) about 5 miles (8 km) southeast of Sulphurdale, on the edge of, and derived from, the Mount Belknap caldera; boulders of the unit are found in the sedimentary basin-fill deposits (QTbf) on the downthrown western side of the same hill containing the rhyolite lava flows.

Tmj **Joe Lott Tuff Member (Miocene)**—Moderately resistant, light-tan, light-gray, and pink, unwelded rhyolite ash-flow tuff (Steven and others, 1979) that is distinctive in part because it is rich in light- to medium-gray aphyric lithic clasts but is poor (generally 1 percent or less) in small phenocrysts, mostly quartz and sanidine (Budding and others, 1987, table 4); it is the largest ash-flow tuff derived from, and leading to the initial collapse of, the Mount Belknap caldera (Cunningham and Steven, 1979a; Steven and others, 1984) in the central Tushar Mountains, and deposited to greatest thickness in Clear Creek Canyon (containing Interstate Highway I-70) north of the range, but also spread widely over other parts of the Marysvale volcanic field; K-Ar age about 19 Ma (Budding and others, 1987); maximum thickness in the mapped area about 120 feet (37 m).

To **Osiris Tuff (Miocene)**—Resistant, light-gray, densely welded, moderately crystal-rich , rhyodacitic ash-flow tuff (Williams and Hackman, 1971; Anderson and Rowley, 1975) that locally contains thin (half inch [1 cm]) vesicular lenticules drawn out to a foot (0.3 m) or more parallel to bedding; contains a black basal vitrophyre at least 5 feet (2 m) thick where this part of the unit is exposed; distinctive in the field for its 1 to 1.5 percent biotite, whose crystals stand out against the light tuff matrix because they are generally black except in the upper part (the vapor-phase part of the tuff) where they are bronze colored (oxidized by fumarole gas passing to the surface through the top of the cooling tuff); also petrographically distinctive because of its markedly variable total-crystal percentage, ranging from about 25 total percent phenocrysts at the base and middle to about 10 percent at the top but always with about the same ratio of minerals, predominantly plagioclase, with lesser sanidine, and much less biotite, clinopyroxene, and Fe-Ti oxides (Anderson and Rowley, 1975, table 1); derived from the Monroe Peak caldera (figure 1), which is the largest caldera in the Marysvale volcanic field, underlying the northern Sevier Plateau and much of the Central uranium district (Steven and others, 1984), from which outflow tuff was spread throughout and east of the Marysvale field; K-Ar age nearly 23 Ma (Fleck and others, 1975; Rowley and others, 1994); probably made up of two cooling units; maximum total thickness in the northeastern part of the mapped area about 300 feet (100 m), thinning southward and westward.

Bullion Canyon Volcanics (Miocene and Oligocene)—Named by Callaghan (1938, 1939) for intermediate-composition (mostly andesite and dacite) lava flows, flow breccia, and volcanic mudflow breccias; by far the volumetrically most important rock unit in the northern half of the Marysvale volcanic field; these rocks were deposited primarily by clustered stratovolcanoes; later studies showed that many mappable ash-flow tuff units and other distinctive units, some of which were defined as members within the Bullion Canyon Volcanics, were intertongued within, and continued outward from, the stratovolcano deposits (Anderson and Rowley, 1975; Steven and others, 1979); the flows and breccias of the Bullion Canyon Volcanics were deposited almost continuously for about 10 million years (Fleck and others, 1975; Rowley and others, 1979, 1994; Steven and others, 1979). Units of the Bullion Canyon Volcanics are described below.

Tb **Intermediate-composition lava flows, flow breccia, and volcanic mudflow breccia (Miocene and Oligocene)**—Soft to resistant, dark-colored (mostly brown, brownish-gray, and reddish-brown), locally vesicular lava flows and subordinate flow breccia and volcanic mudflow breccia (Steven and others, 1979); individual stratovolcano vents were not seen, so all rocks are interpreted to be alluvial facies, that is rocks deposited on the flanks of the stratovolcanoes and thickening eastward and southward toward their central vent facies (terminology from Anderson and Rowley, 1975); most rock units listed below are intertongued with the intermediate-composition flows and breccia; an attempt was made in this study to distinguish the different parts of the flow and breccia section by field and petrographic methods, but these attempts, which included visiting and sampling well-exposed stratigraphic sections outside the study area, indicated that all parts of the section have more similarities than dissimilarities, and therefore parts of the rock column mapped previously as the volcanics of Wales Canyon, volcanics of Dog Valley, and other informal names (Steven and Morris, 1983; Rowley and others, 2002b; Hintze and others, 2003) are here lumped as intermediate-composition flows and breccia (Tb); a detailed stratigraphic study of the flows and breccia in the different levels of the entire stratigraphic column, using chemical and isotopic methods, might yield distinctive characteristics for different levels, but this was considered beyond the scope of the present study; in many parts of the study area, the unit is poorly exposed because such mafic rocks are more weathered or because they are buried by talus and slopewash from overlying resistant units, but in the ridges in the southwestern part of the map area, south of the landslide (Qms), individual flows are well exposed and commonly consist of flows each about 20 to 40 feet thick (6 to 12 m) characterized by vesicular tops and both flow-breccia and dark-vitrophyre bases; flow breccia and volcanic-mudflow breccias are subordinate to flows in volume in the study area; flow breccia consists of angular clasts in contact with each other with little matrix, having formed as the noses of moving flows roll over themselves, whereas volcanic mudflow breccia consists of angular clasts of flow rock not supported by direct contact with each other in a muddy matrix, having formed as mudflows; modes of flow rocks or clasts in the breccias are characterized by 0 to 30 percent phenocrysts (mostly plagioclase with as much as several percent each of pyroxene, hornblende, and Fe-Ti oxides, locally including biotite) in an aphanitic or devitrified-glass matrix; although in the heart of the Marysvale volcanic field, the Bullion Canyon Volcanics is thousands of feet (at least one thousand meters) thick (Steven and others, 1979), the study area is near the northwestern edge of the stratovolcano sequence, so thicknesses are less: the thickness of the flows and breccia between the Osiris Tuff (To) and the Leach Canyon Formation (Tql) is about 100 to 300 feet (30 to 90 m), between the Leach Canyon Formation and the tuff of Albinus Canyon (Ta) is almost 200 feet (60 m); between the tuff of Albinus Canyon and the Three Creeks Tuff Member (Tbt) is about 0 to more than 400 feet (120 m), between the Three Creeks Tuff Member and the Wah Wah Springs Formation (Tnw) is between 50 and 400 feet (15 to 120 m), and beneath the Wah Wah Springs Formation is about 200 feet (60 m).

Tbt **Three Creeks Tuff Member (Oligocene)**—Moderately resistant, light- to medium-gray and locally pink, moderately welded, crystal-rich, dacitic ash-flow tuff that contains at least several percent each of lithic clasts and collapsed pumice; outside the study area, contains a basal dark-gray vitrophyre at least 10 feet (3 m) thick, but this rock was spotted only in one place in the southern part of the area; probably the most voluminous tuff in the Marysvale volcanic field, derived from the Three Creeks caldera (figure 1) on the northern side of Clear Creek Canyon (Steven and others, 1979; Steven and others, 1984); probably the most distinctive unit in the study area because hand samples contain 35 to 45 percent phenocrysts, mostly distinctively large (as much as 5 mm long) plagioclase, but also including as much as 10 percent hornblende, less abundant (3 percent) but especially conspicuous biotite, 1.5 percent Fe-Ti oxides, 1 to 2 percent quartz, and trace amounts of sanidine and clinopyroxene (Steven and others, 1979; Best and Grant, 1987, table A1); despite the easy identification of the unit in the field and in well cuttings, mapping it is problematic for several reasons: (1) no good stratigraphic section is exposed in or near the study area, (2) the unit is thick but this thickness can only be approximated based on drill cuttings because of the absence of good or complete sections, and (3) the rock is massive, unbedded, and weathers to grus so the rock is not generally well exposed and its attitude can be estimated based only on foliation of biotite or of clasts of collapsed pumice; moreover, mapping the unit and identifying the unit in well cuttings has further problems because the Wah Wah Springs Formation (Tnw) near the base of the Tertiary volcanic section superficially resembles the Three Creeks Member, so the two can be respectively misidentified; K-Ar age is about 27 Ma (Steven and others, 1979); thickness in the study area, based largely from well cuttings, is crudely estimated to be about 900 feet (275 m).

Tql **Leach Canyon Formation of the Quichapa Group (Oligocene)**—Resistant, light-tan, white, and light-gray, poorly welded, generally crystal-poor, rhyolite ash-flow tuff containing several percent lithic clasts and at least 10 percent pumice (Mackin, 1960; Williams, 1967; Anderson and Rowley, 1975; Rowley and others, 1995); locally contains a dark-gray basal vitrophyre several feet (1 m) thick; mapped by previous workers in the area as the "zeolitic tuff" but here is positively correlated with the regional Leach Canyon Formation, which is widespread across southwestern Utah and southeastern Nevada, on the basis of its distinctiveness in several categories: lithology, modal analyses, and the presence in nearly all outcrops and even nearly all hand specimens of bright red clasts within its component of lithic clasts; generally made up of about 15 to 20 percent total phenocrysts, consisting of about 6 percent plagioclase, 5 percent quartz, 4 percent sanidine, about 1 percent conspicuous biotite, and trace amounts of Fe-Ti oxides and hornblende (Williams, 1967, table 2; Anderson and Rowley, 1975, table 1), but total phenocrysts—although not the ratio of individual minerals—decrease dramatically upward in the tuff, consisting of as little as about 4 percent at exposures in the north-central part of the area, where it was previously mapped as the Joe Lott Tuff Member (Tmj); caldera source not certain but, based on isopachs (Williams, 1967), appears to be the Caliente caldera complex, which is mostly in Nevada but its eastern edge is in Utah (Rowley and others, 1995); isotopic age is about 24 Ma (Rowley and others, 1995); maximum thickness about 200 feet (60 m), but the unit locally becomes thinner as it banks against underlying depositional topography of the Bullion Canyon Volcanics.

Ta **Tuff of Albinus Canyon (Oligocene)**—Resistant, red and medium-salmon, vesicular, densely welded, crystal-poor, trachytic ash-flow tuff containing sparse lithic clasts, about 5 to 10 percent black collapsed pumice, and distinctive light-gray, vesicular lenticules as much as 1.5 inches (3 cm) thick that are drawn out to locally more than a foot (0.3 m) in the plane of bedding; about 5 to 10 percent phenocrysts, primarily plagioclase, with about 1 percent altered ferromagnesian minerals, primarily clinopyroxene; source is unknown but probably a caldera suggested to be buried beneath Sevier Valley in the Joseph to Annabella area (figure 1), near the northern part of its center of distribution in the northern Marysvale volcanic field (Rowley and others, 2002b); K-Ar age is 25.3 ± 1.3 Ma (Rowley and others, 1994); maximum thickness about 100 feet (30 m).

Tnw **Wah Wah Springs Formation of the Needles Range Group (Oligocene)**—Resistant, light- to medium-red and light-purple, moderately welded, crystal-rich, dacitic ash-flow tuff containing several percent lithic clasts and collapsed pumice (Mackin, 1960; Best and Grant, 1987; Best and others, 1989); distinctive because it contains about 30 to 40 percent phenocrysts, most of which are plagioclase (maximum crystal length about 3 mm), followed by hornblende (as much as 8 percent), biotite (3 to 4 percent), quartz (less than 2 percent), Fe-Ti oxides (greater than 1 percent), and traces of sanidine and pyroxene (Anderson and Rowley, 1975, table 1; Best and others, 1989, figure 6); as such, the unit is distinguished from the Three Creeks Member (Tbt) with difficulty, primarily by phenocryst size and abundance and, where available, by stratigraphic position and thickness and perhaps by color; one of the largest ash-flow tuffs in the World, derived from the Indian Peak caldera of the Indian Peak caldera complex along the Utah-Nevada border (Best and others, 1989); isotopic age about 30 Ma (Best and others, 1989); maximum thickness in the mapped area about 200 feet (60 m).

Shown only in the cross sections; descriptions below from Hintze and others (2003), Moore (2003), and published logs of well cuttings:

Ti **Intrusive rocks (Miocene and Oligocene)**—Fresh quartz monzonite porphyry encountered in wells 42-7 and 91-4; described and photographed by Moore (2003, figures 5 and 8), from thin sections made of cuttings, as consisting of equigranular plagioclase and minor potassium feldspar, hornblende, biotite, clinopyroxene, and quartz; interpreted here on the basis of these descriptions to consist of one of the intrusive sources of the calc-alkaline lava flows and breccia (Tb) of the Bullion Canyon Volcanics.

Pq **Queantoweap Sandstone (Permian)**—Resistant, brittle, white, light-gray, and pink, mostly silica-cemented, fine-grained quartzite and sandstone; locally crumbly and heavily fractured in drill holes; called the Talisman Quartzite or Coconino Sandstone, which are units considered roughly correlative with the Queantoweap Sandstone, by previous workers; maximum exposed thickness given by Hintze and others (2003) is 817 feet (250 m) in Sevier thrust plates about 6 miles (10 km) north of Cove Fort, but it is thinner below the thrust plates 2 miles (4 km) north of Cove Fort; about 500 feet (150 m) thick in the Bradshaw Mountain area in the southwestern Mineral Mountains, about 25 miles (40 km) southwest of Sulphurdale (Rowley and others, 2005); drill logs given by Moore (2003) suggest that the unit is about 400 to 700 feet (120 to 210 m) thick at Sulphurdale.

Pp **Pakoon Dolomite (Permian)**—Moderately resistant, light- to medium-gray, sandy dolomite characterized by small, white calcite blebs (Hintze and others, 2003); maximum exposed thickness 445 feet (136 m) north of Cove Fort, apparently thinning southward (Hintze and others, 2003), and about 800 feet (240 m) thick in the Bradshaw Mountain area in the southwestern Mineral Mountain, about 25 miles (40 km) southwest of Sulphurdale (Rowley and others, 2005); some drill logs at Sulphurdale describe this gray dolomite (locally metamorphosed to marble) below the Queantoweap Sandstone and assign its maximum thickness as about 400 feet (120 m), a thickness that is applied here in the cross sections.

lPOu **Callville Limestone (Pennsylvanian), Redwall Limestone (Mississippian), Cove Fort Quartzite (Devonian), Guilmette Formation (Devonian), Simonson Dolomite (Devonian), Sevy Dolomite (Devonian), and Laketown and Fish Haven Dolomites (Silurian and Upper Ordovician), undivided**—Mostly gray carbonate rocks and local fine-grained sandstone; all of the units listed above could have been penetrated by the deepest drill holes, but none of these units was identified in any wells; the drillers recorded many intervals of lost circulation, interpreted to represent fractures and solution cavities in these rocks. In deeper parts of wells, commonly contact metamorphosed to marble and locally mineralized (Moore and Samberg, 1979), probably by the buried body of intrusive rocks (Ti); maximum thicknesses given by Hintze and others (2003) are 538 feet (164 m) for Callville Limestone, 1545 feet (471 m) for Redwall Limestone, 160 feet (49 m) for Cove Fort Quartzite, 575 feet (175 m) for Guilmette Formation), 185 feet (56 m) for Simonson Dolomite, 710 feet (217 m) for Sevy Dolomite, and 1000 feet (300 m) for Laketown and Fish Haven Dolomites.

Map Symbols

Contact

Normal fault- Bar and ball on downthrown side. Dashed where approximately located, dotted where concealed.

Strike and dip of bedding

Horizontal bedding

Strike and dip of foliation

Geothermal well or exploratory hole

THE GEOTHERMAL RESOURCE

Detailed mapping allowed improvements to our understanding of the stratigraphic and structural framework of the area. The following is an analysis of the new mapping as it relates to the geothermal resource and its potential for energy development.

Analysis of the Relevant Stratigraphy

Deep-Seated Magma Body

Previously published consensus was that the source of the heat at Sulphurdale is deep circulation and rapid rise along high-angle basin-range fault zones of groundwater heated by the geothermal gradient (Moore and Samberg, 1979; Mabey and Budding, 1987; Huttrer, 1994; Ross and Moore, 1994, figure 11). These workers, however, acknowledged the alternative possibilities of heat from buried Quaternary magma bodies, either the same basaltic source that erupted the basalt field west of the map area or a blind silicic magma body at depth beneath or north of Sulphurdale. These workers also recognized that the geothermal reservoir at Sulphurdale has unusually high heat spread over a relatively large equidimensional area of about one square mile underlying and extending northward and westward from the solfatara and the power plant. The high temperatures, large size, and equidimensional shape of the heat anomaly tend to argue against an origin from the geothermal gradient. Of the two alternatives for magmatic heat, a buried basaltic body would seem to be the least likely even though Quaternary basaltic rocks (unit Qbc; 0.5 Ma) are mapped directly west and northwest of Sulphurdale because most basaltic rocks are derived from deep magma chambers and erupt along narrow fissure dikes, which provide a limited source for heat. More plausible would be a rhyolite/granitic magma body, at the other end of the bimodal magmatic spectrum that accompanies basin-range faulting, because such a magma chamber would be shallower and larger and, if Quaternary, would be expected to remain partly molten, thereby heating overlying groundwater. The closest known exposed young rhyolite rocks to Sulphurdale are large volcanic domes in the Woodtick Hill–Gillies Hill area, nearly 6 miles (10 km) south-southwest of Sulphurdale, but these rocks are 9 Ma (Evans and Steven, 1982), probably too old to remain molten.

Regarding the alternative of a blind rhyolite magma body, it would seem possible that such a pluton might have erupted rhyolite volcanic rocks at the surface, whose presence was overlooked in the previous, less detailed mapping. As a result, one of our highest-priority objectives during our mapping was to look for a young, undiscovered high-silica rhyolite mass near Sulphurdale.

A nearby analogue to guide our ideas at Sulphurdale is provided by the Roosevelt geothermal-resource area on the western flank of the Mineral Mountains, which is the next range to the west of Sulphurdale. This heat source was developed in 1984 into Utah's largest and hottest (reservoir temperature about 500°F [260°C]) geothermal power source (Atkinson, 1981; Ross and others, 1982; Kerna and Allen, 1984; Mabey and Budding, 1987, 1994; Moore and Nielson, 1994; Yearsley, 1994). At the Blundell geothermal power plant (36 MW capacity; owned by PacifiCorp) 15 miles (29 km) southwest of Sulphurdale, geothermal fluid from production wells is flashed to steam that is directed to a 26 MW steam turbine; the remaining liquid phase of the fluid (at 350°F [177°C]) is then directed to a 10 MW binary power plant also at the site. The northern end of the Mineral Mountains is capped by six rhyolite volcanic domes, which overlie a granite batholith that appears on the surface as craggy white spires extending southward along the crest and sides of most of the rest of the range (Sibbett and Nielson, 1980; Nielson and others, 1986; Rowley and others, 2005). The domes erupted obsidian lava flows and ash-flow tuffs whose K-Ar ages range narrowly from 0.79 to 0.51 Ma, middle Pleistocene, and therefore are sufficiently young to be underlain by a partly molten source magma chamber (Lipman and others, 1978; Mehnert and others, 1978). Roosevelt hot springs (Petersen, 1973; Ross and others, 1982) is at the western base of the range, west of the rhyolite domes. Exploration drilling, geophysics, and geologic mapping at and south of Roosevelt hot springs suggested that the magma source for the domes remains partly molten (Sibbett and Nielson, 1980; Nielson and others, 1986). Additional evidence came from gravity data (Carter and Cook, 1978) and teleseismic data (Robinson and Iyer, 1981), which supported a conceptual model proposed by Becker and Blackwell (1993) for a roughly cylindrical magma body with a diameter of 9 miles (15 km) extending upward from perhaps as deep as the Moho to within 2.5 to 3.7 miles (4 to 6 km) of the surface. The molten material at Roosevelt is interpreted to be the last remaining remnant of a huge magma body (the granite) that underlies and forms the core of the Mineral Mountains. That granite, which is the largest exposed batholith in Utah, was largely emplaced at about 18 to 17 Ma (Nielson and others, 1986; Rowley and others, 2005), which is unusually young for such a large intrusive mass. That such a large, young batholith is now exposed capping a major mountain range, yet was originally emplaced deep in the crust, indicates that the Mineral Mountains have undergone great (several miles) vertical uplift. The range is a horst, with major north-striking, basin-range fault zones on its eastern and western sides.

At Sulphurdale, the analogue to the granite body in the Mineral Mountains is the 20- to 18-Ma Mount Belknap caldera, the largest bimodal sequence of high-silica rhyolite flows and ash-flow tuffs in the Marysvale volcanic field and as close as 6 miles (10 km) southeast of Sulphurdale. Two eruptive products from the caldera, the rhyolite lava flows (Tmr) and the Joe Lott Tuff Member (Tmj), were mapped in the study area. Furthermore, one or two unexposed 14-Ma stocks of presumed granite have been interpreted by Cunningham and Steven (1979b) and Cunningham and others (1984) to lie beneath Deer Trail Mountain and Alunite Ridge (figure 1), on the southeastern flank of the Mount Belknap caldera and 17 miles (27 km) southeast of Sulphurdale. These 14-Ma stocks created a dome in the overlying Paleozoic and Mesozoic sedimentary rocks and Tertiary volcanic rocks, resulting in a series of radial faults whose center is on Alunite Ridge, where the extended, fractured top of the intrusive dome allowed deposition of vein-type alunite in a solfatara environment (Cunningham and others, 1984, figure 13). Other rhyolites of older and younger age are present at greater distances from Sulphurdale, within the Marysvale volcanic field. Therefore, younger vestiges of magma bodies would seem to be possible elsewhere in the volcanic field, including at Sulphurdale.

In the course of our mapping, we discovered patches of white, high-silica rhyolite tuffs on the southern side of the Sulphurdale pit, previously undocumented at Sulphurdale. Although we initially hoped that these rocks were locally derived, their resemblance to tuffs in Ranch Canyon, on the western flank of the Mineral Mountains and several miles south of the Blundell power plant, suggested that they instead were derived from the Pleistocene (as young as 0.5 Ma; Lipman and others, 1978; Mehnert and others, 1978) domes on the crest of the Mineral Mountains. Petrography of the rocks suggested a strong similarity in phenocryst types and phenocryst abundances to some of the tuffs from the domes on the Mineral Mountains, although the tuffs at Sulphurdale have been hydrothermally altered by the active steam.

The Geothermal Aquifer

Paleozoic rocks beneath the volcanic section are not exposed at Sulphurdale but are present in the subsurface, where they form the main aquifer for dry steam and hot water. Although thousands of feet of these sedimentary rocks have been penetrated by drill holes, their stratigraphy is poorly known. To the west and northwest, these Paleozoic rocks, along with Mesozoic rocks, were thrust during the Mesozoic to earliest Tertiary Sevier orogeny, but no thrust sheets were demonstrated beneath the Sulphurdale area even though drill holes have reached total depths of more than 7500 feet (2300 m). Instead, in drill holes where younger nearby basin-range faults have not been interpreted to remove parts of the stratigraphic section, the stratigraphy is straightforward and apparently generally conformable with the overlying Tertiary volcanic rocks. In descending order, the Paleozoic strata consist of (1) Permian Queantoweap Sandstone with a thickness of 400 to 700 feet (120–210 m); (2) mostly dolomites to a thickness of about 400 feet (120 m) that have been interpreted to be the Permian Pakoon Dolomite; and (3) thick limestone and perhaps dolomite with a thickness of at least 4000 feet (1200 m) that probably represent the rest of the expected Pennsylvanian through Upper Ordovician carbonate section.

The primary geothermal resource at the Bonnett power plant was a field of dry steam, developed by drill holes near the plant and sulfur pit and within one mile to the north. Most of the steam is hosted by the Queantoweap Sandstone, and the steam is first encountered as the holes pass from volcanic rocks into the Queantoweap. High-temperature water is first encountered near the lower contact of the Queantoweap in the main production area. This water resource extends somewhat farther west and east of the steam area.

Where mapped at the surface in adjacent areas, the Queantoweap Sandstone is generally a hard, thoroughly silica-cemented but brittle quartzite. At Sulphurdale, however, due to the close proximity of young basin-range faults, the unit is highly fractured and it forms an aquifer. This sandstone may be friable where intergranular cement has been removed by hot, acidic geothermal fluid, and this secondary porosity improved the quality of the aquifer. The logs of well 42-7 and most other logs examined note that in many places cavities are created, circulation of fluids in the boreholes is lost, and recovery of borehole geophysical data and cuttings is commonly prevented or impaired. The carbonate rocks below the Queantoweap, as one would expect for rocks subject to initially acidic, hot water, are even more permeable; dissolution cavities and open fractures were noted by Moore (2003). In some drill holes, there is little recovery of data or cuttings throughout the carbonate part of the section. In contrast, the andesitic lava flows of the Bullion Canyon Volcanics that overlie the Queantoweap are hydrothermally altered to clays; these rocks may act as confining units (aquitards) to the rising heated water and steam. However, at the sulfur pit where sulfur is oxidized to sulfuric acid, which then seeps downward, secondary permeability allows groundwater to boil off.

Analysis of the Structural Geology

Basin-Range Faults

The detailed mapping done in this study revealed that basin-range normal faults are far more abundant in the Sulphurdale area than has been suggested by previous mapping. These mostly north-trending faults, of the middle Miocene to present basin-range episode of extensional deformation, created the present topography. The faults enhance water recharge and circulation in the thermal groundwater reservoir. Most of the major faults in the area are down-to-the-west faults that formed the western range front of the Tushar Mountains. The unnamed valley containing Interstate Highway I-15 represents the adjacent graben to the west. The Tushar Mountains is a huge horst block that experienced large amounts of vertical uplift along its faults on both sides of the range (figure 1). Yet, as with the similarly large horst of the Mineral Mountains, both the Roosevelt and Sulphurdale geothermal areas are controlled by their broad western range-front fault zone.

Previous workers have stressed that basin-range faults play an important role in both controlling and limiting the extent of the geothermal reservoir (Moore and Samberg, 1979). Rodriguez (1960) stressed that the basin-range fault on the eastern side of the sulfur pit controlled the sulfur mineralization. Ross and Moore (1994, figure 11) showed groundwater heated by the geothermal gradient moving upward along basin-range faults. Under this concept, broad fault zones and their parallel joints provide pathways (conduits) that allowed rapid rise of water heated by deep circulation. Currently the concept has not been disproved, even though many forms of geophysics (Mabey and Budding, 1987) have been applied to the area to evaluate the alternative means of supplying heat, especially buried magma bodies. Yet the geothermal reservoir extends east and west of the large faults that are east and west of the power plant, indicating that stratigraphic control (in the Queantoweap Sandstone and underlying carbonate rocks) is more important than control by faults alone.

Some of the basin-range faults in the Sulphurdale area cut Quaternary volcanic rocks and surficial sediments and are themselves Quaternary. Where these faults are Holocene to late Pleistocene in age, they are classified as active. The youngest of the Quaternary faults at Sulphurdale strikes northeast and extends northeastward from south of the Sulphurdale pit parallel to, and southeast of, an old water aqueduct (now a plastic pipe) identified on the topographic map. Aerial photographs show that the fault creates a strong lineament that maps as a sharp 5- to 10-foot (1.5–3 m), northwest-facing scarp that cuts not only bedrock but unconsolidated surficial deposits. Most deformed rocks belong to the middle alluvial-fan deposits (Qaf2), making the fault at least as young as middle Pleistocene and probably late Pleistocene.

Because of its height, the most spectacular of the Quaternary faults at Sulphurdale is the north-striking, down-to-the-west fault 300 feet (100 m) east of the power plant. The scarp that this fault created is almost 200 feet (60 m) high. Although this fault also displaces the same middle alluvial-fan deposits (Qaf2), the fault is older than the northeast-trending one because it is buried by slopewash from the scarp and does not form such a youthful, sharp lineament. The scarp probably predates the tuff of Ranch Canyon (Qtr) because a patch of this tuff was noted in the shallow canyon of Sulphur Creek, eroded into the scarp. The fault continues north, with the same morphology, to the northern boundary of the map area, displacing middle alluvial-fan deposits. Most movement on this fault is probably middle Pleistocene, and in part this fault controls the access for gas and the steam that produce both the sulfur and the geothermal resource.

Near the northern edge of the map, the next fault to the west was trenched (at the "pit" on the topographic base about 1000 feet [300 m] east of the Cove Fort exit off Highway I-70) by the U.S. Geological Survey during a study of Quaternary faults along the Wasatch front. On the eastern upthrown side of the fault, Anderson (1980, figure 8) found both the tuff of Ranch Canyon and the underlying Bishop ash (0.74 Ma, middle Pleistocene; Izett and others, 1988) within a fanglomerate that unconformably overlies severely deformed, perhaps early Tertiary sedimentary rocks. Anderson (1980) concluded that the fault was late Pleistocene and had at least 60 feet (18 m) of down-to-the-west displacement.

At the southeastern end of the hill west of the power plant, a small borrow pit in the middle alluvial-fan deposits (Qaf2) exposes several north-striking faults that cut the fan deposits and are interpreted to be part of the down-to-the-east fault that uplifts the hill west of the power plant. This fault thus has displacement that is middle Pleistocene or younger. Therefore, the Sulphurdale sulfur pit, the power plant, and the main part of the underlying steam field north and south of the power plant are within a north-striking Quaternary graben.

The pattern of faults in the map area displays a subtle radial pattern. The faults in the northern and southern parts of the area strike mostly north, those in the northeastern part of the map area strike mostly northeast, some of those in the eastern part of the area strike east or east-northeast, and those in the southeastern part of the area strike mostly north-northwest. The center (bullseye) of this radial pattern is the solfatara and the known steam and hot water area. Only the eastern half of such a pattern is seen; the western half is cut off by the main range-front fault of the Tushar Mountains and therefore it is covered by surficial deposits. We suggest that the area of radial faults formed over a dome that resulted from emplacement of a buried, granitic (bimodal) intrusion that may be partly molten. This granitic intrusion is coaxial with the quartz monzonite porphyry pluton (unit Ti) penetrated by two drill holes (Moore and Samberg, 1979; Moore, 2003; our cross sections B–B′, C–C′, E–E′) but, as would be expected for a younger intrusion, is interpreted to be at far greater depth. The north-trending graben that contains the solfatara and the steam resource may be an axial graben developed on the crest of the dome. The size of the radial pattern is comparable to, but not as well developed as, the domed area at Alunite Ridge in the central Tushar Mountains (Cunningham and Steven, 1979b; Cunningham and others, 1984). At Alunite Ridge, a 14-Ma solfatara formed along the extensional fractures in the crest of the dome, similar to the active solfatara at Sulphurdale.

Our mapping indicates that most of the faults in the study area dip at a high angle, mostly 60 degrees or more. Previous workers, however, have suggested that some of these faults dip at low angles, 30 degrees or less. Steven and Morris (1983) showed some of these faults on their cross sections to be dipping west as little as 20 degrees. Moore and Samberg (1979), Ross and Moore (1994), and Moore (2003) showed some of these faults on their cross sections to be horizontal. In cross section, these workers pictured them as listric faults, that is faults that dip less steeply with depth (spoon shaped). Our mapping of the same faults interpreted them also to be listric faults (see cross sections), but to have a much steeper dip and not to emplace volcanic rocks on top of Paleozoic rocks. Although they are portrayed as listric faults, Moore and Samberg (1979) and Moore (2003) interpreted their faults to represent the basal surface of "gravitational glide blocks," which they suggested effectively covered the Queantoweap Sandstone and partly or entirely created an impermeable seal (confining unit) to the underlying geothermal reservoir. A "gravitational glide block," better known as a gravity-slide block, represents a large rock mass or giant landslide that has moved downhill under the force of gravity. These gravity-slide blocks would be larger and thicker than a classic landslide (Qms), which is the only evidence of gravity sliding in the map area. It is our experience, from mapping in the Iron Springs mining district and Pine Valley Mountains west and southwest of Cedar City, Utah (e.g., Hacker and others, 2002; Rowley and others, 2006) that even huge Miocene gravity-slide blocks, shed off highly uplifted areas and riding down the topographic slope, are relatively thin (less than 300 feet [100 m] thick) so that the rocks making up the slide block are almost always shattered to a breccia, a rock type of high permeability that is unlikely to provide an impermeable roof seal to the top of the Paleozoic section even if there were evidence that it was emplaced on top of these sedimentary rocks.

Transverse Zones

Transverse zones, named because they are 90° to the prevailing structural grain of basin-range faults, are east-striking structures that are abundant in, and in some places span, the Great Basin (Rowley, 1998; Rowley and Dixon, 2001). Transverse zones, although perpendicular to basin-range faults, are similarly the product of east-west extension because—like transform faults that occur mainly in the ocean basins—they represent zones north and south of which extension was at different rates, amounts, or mechanisms. Transverse zones formed not only during basin-range tectonism, but also during previous tectonic events in the area in which compression (Sevier deformation) and light extension (during the episode of calc-alkaline magmatism that predated basin-range deformation) were similarly oriented east-west. Transverse zones appear to be deep-seated features that controlled many Tertiary hydrothermal mineral deposits (that is, ancient geothermal systems), central and caldera vent areas, and plutons in the Great Basin, and they control many current hot springs and geothermal systems. A major transverse zone, the Cove Fort transverse zone, was mapped (Rowley, 1998; Campbell and others, 1999; Rowley and Dixon, 2001; Rowley and others, 2002b) eastward from south of Cove Fort. Steven and Morris (1983) and Rowley and others (2002b) showed it to include, from west to east, the east-striking Cove Creek fault, the southern side of the Three Creeks caldera, the Clear Creek downwarp, and the northern side of the Monroe Peak caldera (figure 1). Some of the most intense earthquake activity within the Intermountain Seismic Belt occurs where the Cove Fort transverse zone crosses the main range-front fault zone of the Tushar Mountains (figure 8 in Mabey and Budding, 1987).

The Cove Fort transverse zone may bear on the geothermal resources in the Cove Fort area, but east-striking structures are hardly common in the Sulphurdale area. Few east-west structures were found in outcrop despite our search. However, a down-to-the-north, east-striking fault was mapped by most workers on the southern side of the large hill west of the power plant, and we noted a minor east-striking fault of unknown relative separation that cuts an outcrop of the Three Creeks Tuff Member (Tbt) about 30 feet north and east (across the road) of the power plant. Despite the elusive nature of east-trending faults at Sulphurdale, Moore (2003) called upon a buried major, east-striking, down-to-the-north fault shown on his figure 13 and on his north-south cross section (his figure 5) to explain why rocks north of about the latitude of the power plant are about 1500 feet (500 m) downthrown relative to those south of the power plant (compare our Cross Section B–B′ with our Cross Section C–C′). Although initially skeptical of this interpretation, we were unable to complete our north-south cross section (E–E′) without similarly resorting to such a fault, and it is interpreted on our map to be offset by the younger north-striking faults in the vicinity of the power plant. The offset east-striking fault thus appears twice in Cross Section E–E′ as a linear, steeply north-dipping, down-to-the-north fault to distinguish it from basin-range faults, most of which are shown to be listric. Furthermore, Moore and Samberg (1979) and Ross and Moore (1994) invoked intersections of north-striking and east-striking faults to explain the distribution of geothermal resources. Clearly the narrow graben that contains the sulfur pit and the main steam area is a heavily fractured area, as demonstrated by well 34-7 that blew out during drilling operations in October 1983. This well, the first drilled by Mother Earth Industries, penetrated a 100-psi, 350°F (177°C) dry steam resource at 1165 feet (355 m) depth and blew for 24 days until it was successfully capped (Huttrer, 1994).

Origin and Implications of Sulfur

Lee (1906) and Moore and Samberg (1979, p. 25–26) proposed that H_2S gas rising in the sulfur open pit oxidizes to form native sulfur (plus H_20), and that further oxidation, perhaps aided by bacterial action, of the sulfur produces sulfuric acid. The sulfuric acid migrates downward toward the deep water table, resulting in acid leaching of the rocks along the way. Moore and Samberg (1979, p. 25) noted that "siliceous residues of pre-existing rocks form above the water table by continuous downward migration of sulphuric acid dissolved in rain water and condensed water vapor." These siliceous residues probably include those beds in the pit considered to be siliceous sinter by Rodriguez (1960) and Callaghan (1973). Moore and Samberg (1979) proposed that downward movement of acid solutions affected rocks to at least the 1200-foot (400 m) depth to the water table. Of more significance with respect to the geothermal resource is the effect when the acid enters the underlying groundwater to create secondary porosity. The presence of sulfur at Sulphurdale, as well as at the other geothermal-resource areas near Cove Fort where sulfur is associated with gypsum, raises the question as to where the sulfur came from.

We suggest here that the sulfur came from evaporites. Native sulfur probably was derived from sulfide or, more likely, sulfate minerals. Of sulfates, gypsum (hydrous calcium sulfate, including the crystallized form, selenite) and anhydrite (anhydrous calcium sulfate) are abundant in Paleozoic and Mesozoic evaporite-bearing rock units in central Utah. Replacement alunite (basic hydrous sulfate of aluminum and potassium) is abundant in the Marysvale area, mainly from alteration of silicic volcanic rocks at high temperatures in the presence of sulfuric acid (Callaghan, 1973; Cunningham and others, 1984, 2005). Near Sulphurdale, the Permian Kaibab Limestone and Toroweap Formation contain abundant gypsum, and Hintze and others (2003) mapped the Kaibab both in thrust sheets and below the thrusts just north of Cove Fort, with thick, east-dipping, autochthonous Kaibab as close as 5 miles (8 km) north-northeast of Sulphurdale. The Kaibab Limestone is reported to be 1160 feet (350 m) thick, including rocks equivalent to the Toroweap Formation in its lower third. The unit overlies the Queantoweap Sandstone. Kaibab Limestone or Toroweap Formation has not been identified in the subsurface near and south of Cove Fort; instead, deep geothermal exploration and production wells drilled between Cove Fort and Sulphurdale find that the uppermost Paleozoic unit below the volcanic rocks is the Queantoweap Sandstone. This, in turn, raises another question as to why the evaporite-bearing Kaibab Limestone and Toroweap Formation are absent.

Our interpretation is that evolution of the Sulphurdale geothermal field consisted of two main stages that involved fundamentally different geochemical regimes: (1) an early event of thermochemical sulfate reduction that created hypogene karst (that is, karst formed at depth, as opposed to the better known phreatic karst formed by groundwater in the saturated zone) at a significant burial depth in the Kaibab Limestone and Toroweap Formation, where migrating, warm, reduced, organic, basinal fluids destroyed interbedded gypsum ($CaSO_4 \cdot 2H_2O$); and (2) one or more later oxidizing events caused by emplacement of Miocene calc-alkaline plutons and/or upper Tertiary to Quaternary granitic plutons. Emplacement of these plutons may have introduced O_2 into the system by either or both of the following methods: (a) plutonism that took local temperatures much higher than temperatures of normal geothermal gradients attained during progressive burial of sediment (see, for example, Wallace and Jacobs, 2012) and thus heated the groundwater by convection cells whose upwelling limbs carried the groundwater toward oxidizing conditions near the water table; and (b) upward migration through the reduced zone of juvenile magmatic fluid, which is oxidizing. The two-stage evolution of this geothermal field is suggested by the fundamental chemical differences between reduced and oxidized chemical systems.

Stability constraints of the five forms of $CaSO_4 \cdot XH_2O$ and principles of thermochemical sulfate reduction provide insights into the chemical composition of the fluids generated during the early thermochemical reduction event. The products of endothermic alteration of gypsum to anhydrite produces two forms of anhydrite, one of which becomes insoluble above 482°F (250°C) (Christensen and others, 2008; Melis, 2008). Therefore, the products of thermochemical sulfate reduction, namely S^0, H_2S, H_2O, and CO_2, were likely to have been produced prior to intrusion of the plutons that fuel the geothermal field.

The early event of thermochemical reduction destroyed gypsum and anhydrite interbedded within the Kaibab Limestone and Toroweap Formation and created hypogene karst and associated dissolution features. Descriptions of the Harrisburg Member of the Kaibab Limestone by Higgins and Willis (1995), Willis and Higgins (1995), and Higgins (1998), plus field observations from the Harrisburg Member at Washington Dome, about 110 miles (180 km) southwest of Sulphurdale, highlight the presence of karst in this unit. Bedded limestone breccias, coarsely recrystallized limestone, boxwork structure, and chert stringers and nodules are indications of former gypsum or anhydrite interbeds in the limestone. Although Higgins and Willis (1995) and Higgins (1998) interpreted that the karst was phreatic and occurred during an erosional period of 20 million years at the end of Permian time, the presence of sulfide minerals in bedded and brecciated limestone suggests that the karst is hypogene in origin and that dissolution occurred under reducing chemical conditions at nearly the maximum burial depth. In contrast, iron-oxide minerals are common in phreatic karst. At places where the Kaibab Limestone is absent from the stratigraphic sequence in southwestern Utah, creation of hypogene karst and dissolution of limestone by acidic, warm, reduced brine could have entirely removed the unit. Restoration of eroded Mesozoic strata above the Kaibab Limestone, using the Cedar City–Iron Mines stratigraphic section of Hintze (1993, Chart 95) and Hintze and Kowallis (2009, Chart 101), suggests that the Kaibab was buried between about 8200 and 11,200 feet (2500 to 3400 m) by the end of Cretaceous time, which equates to burial temperatures of about 167° to 221°F (75° to 105°C). This temperature range is within the stability field of gypsum and is within the endothermic range in which heat would have been adsorbed as water was exsolved from the crystal structure. Reduced, warm, basinal brine probably contained hydrocarbons in gaseous or liquid form (Wallace and Jacobs, 2012); hydrocarbons are powerful reductants that attack the oxidized gypsum ($CaSO_4 \cdot XH_2O$). The main chemical reactions involved in sulfate reduction by hydrocarbons are:

$$4CaSO_4 + 3CH_4 + 8HCl \rightarrow 4S^0 + 3CO_2 + 4CaCl_2 + 10H_2O \quad (1)$$

and

$$4S^0 + 1CH_4 + 2H_2O \rightarrow 4H_2S + 1CO_2 \quad (2)$$

Hydrochloric acid in equation (1) results from elevated chloride concentrations common in formation brine

(Hanor, 1987). Anhydrite is the sulfate mineral shown in equation (1) above, and the chemical reaction produced significant water. Gypsum, because it is a hydrated sulfate, would liberate significantly more water than anhydrite alone. Methane (CH_4) in equation (1) is used as a representative organic molecule that occurs in gas and liquid petroleum.

The later event that accompanied magmatic intrusion clearly elevated rock and fluid temperatures locally, including elevating the temperatures of the formation fluids that were created during oxidation-reduction reactions of hypogene karst. This event also may have introduced juvenile magmatic fluids. Elevated temperatures caused by nearby intrusions could not have produced the reduction products from gypsum interbedded in the Kaibab Limestone and Toroweap Formation because: (1) siliceous magma and attendant hydrothermal fluids have a positive O_2 pressure, and oxygenated fluids are not capable of causing significant redox chemical reactions with gypsum or anhydrite; and (2) high temperatures attendant to igneous intrusion would have preserved sulfate as anhydrite and would not have produced S^0, H_2S, and H_2SO_4 products of thermochemical reduction because at temperatures above 482°F (250°C) a completely anhydrous form of anhydrite (β anhydrite) forms that does not react with water (Christensen and others, 2008). These thermal relations indicate that S^0, H_2S, and H_2SO_4 could not have formed as a result of igneous intrusions into gypsum-bearing carbonate beds of the Kaibab Limestone and Toroweap Formation. However, elevated temperatures could have driven convection plumes of hot groundwater upward, as at Marysvale (Cunningham and others, 1984, 2005), where sulfur and hydrogen sulfide in the groundwater were interpreted to become oxidized near the water table to produce sulfuric acid.

The early oxidation-reduction event produced native sulfur (S^0), hydrogen sulfide (H_2S), water (H_2O), and carbon dioxide (CO_2), but later oxidation of H_2S by either upward movement of heated groundwater to the water table or upward migration of juvenile magmatic fluids produced sulfuric acid (H_2SO_4) in an aqueous medium, where:

$$H_2S + 2O_2 \rightarrow H_2SO_4 \quad (3)$$

In phreatic karst deposits, the acid H_2SO_4 attacks $CaCO_3$ aggressively (Warren, 2006), as shown in the following equation:

$$H_2SO_4 + CaCO_3 \rightarrow CaSO_4 + H_2O + CO_2\uparrow \quad (4)$$

In chemical reaction (4), the reaction is forced to the right because the gypsum is removed by later reduction caused by continuing migration of organic compounds into the system, and the gas CO_2 is altered to HCO_3^- (carbonic acid). These compounds and acids form the characteristic chemical association found in solfataras.

Geologic relations among sulfate minerals, hypogene karst, native sulfur, hydrogen sulfide, and sulfuric acid have been described from many sedimentary basins world-wide. A sampling of these study areas from the literature discussed below in order are in (1) Spain, (2) Italy, (3) Yellowstone National Park (4) New Mexico/West Texas, (5) Marysvale, and (6) the Mormon Mountains of Nevada.

Alonso-Azcarate and others (2001) described epithermal veins in Spain that included native sulfur, plus a gas phase that included H_2S, formed from redox reactions involving thermochemical sulfate reduction by organic matter during “low-grade metamorphism” (about 437°F [225°C]) of gypsum evaporites. They ascribed additional younger sulfur deposition to partial re-oxidation of some H_2S to SO_4^{2-}.

Eastman (2007) described the relationship between sulfur and karst in a study of huge caves at Frasassi, Italy. She noted that, whereas most phreatic caves result from carbonic acid (from atmospheric CO_2 reacting with water) acting on limestone, sulfuric acid will cause greater effects and more spectacular caves. She also noted that the presence of gypsum within caves is indicative of sulfuric-acid cave formation; equation (4) shows the reactions involved in late formation of gypsum. In the Frasassi caves, it appears that the reduction of gypsum mineral deposits at burial depth in the subsurface dissolved sulfate into the groundwater that was flowing through limestone beds, where it interacted with organic compounds in the rocks that further reduced it to sulfide. As the sulfidic groundwater moved to the surface, it was oxidized by near-surface water and atmospheric oxygen in the presence of sulfur bacteria to form sulfuric acid, which then dissolved limestone to form caves (Eastman, 2007). The Frasassi caves contain gypsum crystals on the cave walls. At Frasassi, the reduction of gypsum at burial depth can result in hypogene karst, but the near-surface action of sulfuric acid to form these caves represents phreatic karst.

A connection with solfataras was noted by Schoen and Rye (1970) at Yellowstone National Park. Here fumarolic hydrogen sulfide discharged in most Yellowstone hot springs oxidizes abiologically to form sulfur, which in turn oxidizes biologically to form large quantities of sulfuric acid. The hydrogen sulfide may be baked out of underlying sedimentary rocks, at least some of which contain marine gypsum.

A tie between sulfur, hydrocarbons, and karst was noted by Hill (1995) in New Mexico and West Texas. Here sulfur redox reactions led to a genetic relationship between hydrocarbons, native sulfur, Mississippi Valley-type Pb-Zn deposits, and sulfuric-acid karst in and adjacent to the Delaware basin of southeastern New Mexico and West Texas (Hill, 1995). According to Hill, hydrocarbons in the basin reacted with sulfate ions from evaporites to form H_2S, which then oxidized to produce economic native sulfur deposits locally along faults that formed the Delaware basin graben. Later in the cycle, H_2S reacted with oxygenated water to produce sulfuric acid, which entered the water cycle and dissolved (as phreatic karst) the major limestone caves (Carlsbad Cavern and Lechuguilla Cave) in the mountains bounding the basin. The back-and-forth redox reactions continued: massive gypsum blocks formed on the floors of the caves from chemical reactions that produced the karst, and H_2S produced native sulfur in the caves that in turn oxidized to gypsum in the presence of drip water (Hill, 1995). However, the commonly held concept that sulfur needs to result from oxidation of H_2S—as suggested by Schoen and Rye (1970) at Yellowstone, Hill (1995) in New Mexico/West Texas, and Lee (1906) and Moore and Samberg (1979) at the Sulphurdale open pit—may not be necessary or may be in reverse order, as suggested by equations (1) and (2) above.

Near Marysvale, Utah, Cunningham and others (1984, figure 5; 2005, figure 2) recognized map patterns of subcircular cells of replacement alunite and surrounding kaolinite that are as much as 2 miles (3 km) across in map diameter and spaced about 2 to 3 miles apart around the periphery of the 21- to 22-Ma Central intrusion (figure 1). The Central intrusion is an intracaldera quartz monzonite pluton near the western margin of the Monroe Peak caldera (Rowley and others, 1988a, b, 2002b). Its exposed diameter is about 5 miles (8 km), increasing in diameter downward. The cells are interpreted to represent the product of maximum fluid flow within upwelling convective hydrothermal plumes of groundwater heated by the intrusion. Two cells, at the Yellow Jacket alunite deposit (Cunningham and others, 1984) and at Big Rock Candy Mountain (Cunningham and others, 2005), were studied. The replacement alunite formed at or just below the paleo water table, where oxidizing, steam-heated conditions produced sulfuric acid. In finer detail, the cell core of alunite passes outward, respectively, into kaolinite, dickite, and propylite envelopes. Upward, the alunite passes—above the paleo water table—into a jarosite layer, then a hematite layer, then a silica cap deposited at the paleosurface (Cunningham and others, 1984, figure 9; Cunningham and others, 2005, figure 8). The silica cap consists of replacement ("flooded") silica that replaced (silicified) volcanic rocks and alluvium, above which is hot-spring siliceous sinter that was deposited at the surface; the cap includes silicified hydrothermal breccia that formed as geyser deposits. In the Yellow Jacket cell, an absence of pyrophyllite, which forms in hydrothermal systems above about 536°F (280°C), may provide an upper temperature limit to the Yellow Jacket alunite deposit (Cunningham and others, 1984). The cells, between which volcanic rocks are propylitically altered, replace a thick sequence of Tertiary volcanic rocks that lie unconformably on Mesozoic and Paleozoic rocks that contain gypsum, specifically in the Jurassic Arapien Formation and the Permian Kaibab Limestone and Toroweap Formation (Cunningham and others, 1984, figure 8; Cunningham and others, 2005). Evaporites are generally rich in organic matter (Cunningham and others, 1984). Among several suggested scenarios regarding the evolution of the alunite deposits, probably the most likely given by Cunningham and others (1984, 2005) was for total reduction, in the presence of this organic matter and perhaps aided by intrusive heat, of the evaporite sulfate at its source in the Mesozoic and Paleozoic rocks. This reduction produced hypogene native sulfur and hydrogen sulfide. Sulfur isotopes in alunite are nearly identical with those in Jurassic and Permian evaporites from the area. As the heated groundwater rose in convection plumes toward the water table, the water became richer in oxygen, which oxidized the hydrogen sulfide to sulfuric acid. Boiling at the water table, which further degassed hydrogen sulfide, was followed by additional oxidation to more sulfuric acid, causing the low-pH environment necessary to form alunite near or below the water table. As alunite formed, iron and silica were released, to be carried upward and deposited below the surface as the hematite zone and at the surface as the hot-spring silica sinter. With current erosion into, and supergene destruction of, the Big Rock Candy cell, gypsum is being deposited in fractures and as surficial crusts.

In addition to the replacement alunite deposits at Marysvale, Cunningham and others (1984) also studied the origin of vein-type alunite deposits on Alunite Ridge, nearly 5 miles (8 km) southwest of Marysvale (figure 1). Here, the alunite formed as open-space fillings in open extension fractures above the roof of a concealed 14-Ma stock. The origin of these deposits was interpreted to be similar to those of the replacement alunite, although the sulfur may have been derived from the stock.

Another part of the puzzle at Sulphurdale is addressed by a vast literature, which we will barely touch on, concerning dissolution in the subsurface of large volumes of bedded carbonate. A recently described, but more controversial, aspect of this dissolution is the work of Anderson and others (2010) and Diehl and others (2010) in the Mormon Mountains and surrounding areas near Mesquite, Nevada. Much of the literature on carbonate dissolution is based on the evidence from diagenetic structures, notably stylolites, associated with carbonate sedimentary rocks. Among stylolites, those produced by pressure dissolution and therefore that formed perpendicular to maximum compressive stress are the most studied. However, stylolites are more commonly oriented parallel to bedding and therefore ascribed to overburden pressure. Another diagenetic structure, solution cleavage, indicates that locally, large parts (as much as 50 percent) of some carbonate formations have been shortened in northern Italy and, by analogy, large parts of the sedimentary section elsewhere, have been dissolved (Alvarez and others, 1976, 1978); the parts of the formations remaining, which resemble a type of cleavage, consist of much less soluble chert concretions and stringers that stack up, separated by cleavage planes, when the carbonate between them is dissolved.

Following more than a decade of work (e.g., Diehl, 2000) on dissolution features along the Mormon detachment fault in and off the structural dome of the Mormon Mountains, much of it spent getting the message past skeptical technical reviewers, Anderson and others (2010) and Diehl and others (2010) proposed a model that has considerable merit. They proposed that the entire Paleozoic section (Cambrian to Permian age) of mostly carbonate rocks in the upper plate of the Mormon detachment was thinned a generally unspecified, but locally large (60 percent in some units) percentage. Their mechanism of dissolution was meteoric water, containing weak carbonic acid from atmospheric CO_2, that moved vertically downward along many high-angle faults that feed into one or more, low-angle, outwardly dipping detachment faults off the Mormon Mountains extensional dome. Their photographs of karstic breccia, previously interpreted as fault breccia, as well as stylolites and collapse features, are particularly compelling for a dissolution mechanism. As at Sulphurdale, the Kaibab Limestone and Toroweap Formation are missing in the Mormon Mountains, although they are mapped (Page and others, 2005) to a thickness of 1000 to 1800 feet (300–550 m) in all ranges surrounding the Mormon Mountains. However, the Lower Permian Pakoon Dolomite, which also contains evaporites, is present in the Mormon Mountains.

At Sulphurdale, we conclude that what remained of the entire subsurface carbonate and evaporite section of the Permian Kaibab Limestone and Toroweap Formation, perhaps 1160 feet (350 m) thick, was dissolved by sulfuric-acid phreatic karstification. The process probably took place in several—if not many—redox-reaction steps, beginning with reduction of sulfate (gypsum and anhydrite) in the evaporites (hypogene karstification) in the presence of organic matter in warm, reduced brine that migrated through the Mesozoic (?) and Paleozoic section at burial depths, including the Permian evaporites. Sulfuric acid in large amounts formed later in the groundwater under oxidizing conditions, probably at multiple extended times, and dissolved away Kaibab and Toroweap carbonate beds at or below the water table (phreatic karst). Thin karst breccia, perhaps interpreted by Moore and Samberg (1979) from well cuttings to be detachment- or glide-plane breccia, likely remains between the volcanic rocks and the underlying Queantoweap Sandstone. Karst breccias have been interpreted from widely separated exposures of the Kaibab Limestone elsewhere in Utah.

We also suggest that the extensive dissolution Anderson and others (2010) and Diehl and others (2010) proposed in and adjacent to the Mormon Mountains is more likely if sulfuric acid is the culprit. If so, the sulfuric acid likely formed near the water table long after chemical redox reactions in evaporite in the Kaibab Limestone and Pakoon Dolomite at depth. This sulfuric acid resulted in phreatic karstification and thinning of significant parts of the Paleozoic section, as Anderson and others (2010) and Diehl and others (2010) proposed, and perhaps in dissolution of the missing part (Kaibab and Toroweap) of the top of the Permian section. R.E. Anderson (verbal commun., August 2011) confirmed that some gypsum remains in the karst areas, as at Frasassi.

Analysis of the Hydrogeology

Surface and groundwater conditions

Surface water at Sulphurdale is abundant, as one would expect at the western base of one of the highest and most massive ranges in Utah. The Tushar Mountain front east of Sulphurdale can be expected to supply large amounts of water recharge as western storms hit its abrupt west-facing scarp. Many streams flow into the Sulphur Creek area of Sulphurdale, although there are no significant perennial streams in the map area. Cold-water springs issue from faults in the area, as is common in the Great Basin; these include North Spring, South Spring, and many others east of Sulphurdale. Cattle troughs supplied by pipes or by developed springs are common. A pond supplied by an aqueduct exists directly south of the power plant. The sulfur pit also holds one or more ponds, some of which—not unexpectedly—contain perched meteoric water with a pH of 1 (Moore and Samberg, 1979).

Abundant surface water indicates a high water table, as confirmed by well data (Kirby, 2012, figure 11). Water wells drilled in alluvium and basin-fill deposits in the graben that contains Interstate Highway I-15, west of the main range-front fault, hit the water table at 200 to 300 feet depth. Springs to the east, such as North Spring and South Spring, indicate a high water table in the eastern part of the area as well. However, groundwater is at great depth in the steam-resource area at and north of the power plant. As Moore and Samberg (1979) and Moore (2003) noted, cold- or hot-spring deposits such as siliceous or calcareous sinter have not been documented, although Rodriguez (1960) suggested siliceous sinter at the sulfur pit that is more likely to be siliceous residues from leaching by sulfuric acid. Therefore, there is no unequivocal evidence that geothermal waters discharged at the surface. Instead, the native sulfur at the pit is the product of an active, ongoing solfatara that releases H_2S gas, which combines with CO_2 gas and steam that result from boiling at and above the water table (Rodriguez, 1960; Moore and Samberg, 1979). Drilling in the general area of Sulphurdale indicates that the steam resource issues primarily from and below the upper contact of the Queantoweap Sandstone, at 800 to 1000 feet (240 to 300 m) depth, and the hot water resource is below this, at about 1200 to 1300 feet

(365–400 m) depth, commonly near the lower contact of the Queantoweap (Moore and Samberg, 1979; Moore, 2003, figure 5). This might be interpreted to be an incredibly deep water table beneath the area of highest heat, but this is not a water table in the normal sense. Instead, water is absent only because of the extreme heat. Furthermore, downward-migrating sulfuric acid has increased—likely by orders of magnitude—the secondary porosity and permeability in the Queantoweap Sandstone and volcanic rocks, allowing escape upward of liquid water as steam. A shallow aquifer for cold water is present well above the Queantoweap Sandstone, but generally outside the area of highest heat. Cold water was noted in some drilling, although it was interpreted by drillers to be perched in favorable thin volcanic aquifers.

The direction of groundwater flow (piezometric surface) in the area is westward off the mountain front, then northward in the graben of Cove Fort (Kirby, 2012, figure 9). Presumably the water level for the deep geothermal aquifer also slopes westward and northward, for injection of spent water from the plant is scheduled to be in these directions.

Fracture Flow

The main concept in understanding the movement of groundwater in the Great Basin, where faults are abundant, is that groundwater flows through rock fractures associated with high-angle basin-range fault zones. This concept is known as fracture flow or fracture-dominated flow, as opposed to porous-media flow in which groundwater moves through pore spaces, such as between grains in clastic sedimentary rocks. Recognition, understanding, and documentation of the concept of fracture flow have increased for decades, motivated by fracture flow's important role in such topics as isolation of radioactive waste in underground repositories, groundwater transport of radionuclides, cleanup of toxic waste, exploitation of petroleum and geothermal reservoirs, and movement of groundwater (Haneberg and others, 1999; Faybishenko and others, 2005; Wibberley and others, 2008). The implications of fracture-flow concepts have not generally been applied to Sulphurdale or to many other geothermal-energy projects, yet understanding fracture flow bears on siting wells to maximize yields and on understanding directions and volumes of flow of hot groundwater.

Most of what we know about fracture flow began with U.S. Department of Energy-funded studies, primarily by the U.S. Geological Survey, on the Nevada Test Site to trace movement of contaminated groundwater resulting from hundreds of above- and below-ground nuclear tests (Winograd and Thordarson, 1968, 1975; Laczniak and others, 1996; Rowley and Dixon, 2004). The most useful study specific to the conceptualization of the role of faults on flow is that of Caine and others (1996). This report classified high-angle faults into (1) a central core zone, which is generally of low permeability across it because of gouge and foliation in clay minerals formed along the axis of fault deformation; and (2) outer damage zones on each side of the core that are likely to be of high permeability across and along them because they consist largely of joints and small faults that are generally parallel to the core zone. Caine and others found that faults therefore generally provide conduits to flow laterally along (parallel to) them but may retard or be local barriers to flow across (perpendicular to) them. Because portrayal of faults is the work of geologists, who use geologic maps, the concept of fracture flow is not generally applied by hydrologists (Rowley and Dixon, 2004; Dixon and others, 2007; Rowley and others, 2009).

Results from siting production water wells provide the most practical application of fracture flow, and these results apply also to geothermal production and monitoring wells. In the Mesquite basin of Nevada, geologic mapping allowed geologists to locate basin-range faults that cut the basin-fill deposits (Muddy Creek Formation) and carry groundwater southward by conduit flow from a broad recharge area in the Clover Mountains to the north (Dixon and Katzer, 2002). Then the downthrown sides of the faults were drilled for production water wells, with yields that average about 1500 gpm (Johnson and others, 2002).

In the St. George area of Utah, the main aquifer is the Jurassic Navajo Sandstone (2000 to 3000 feet [600 to 900 m] thick), and most production well fields for the St. George metropolitan area are drilled in the Navajo. The Gunlock well field, one of St. George's largest, is drilled in the Navajo Sandstone. The well field is just downgradient (south) from where the south-flowing Santa Clara River is dammed to create the Gunlock Reservoir, which supplies artificial recharge to the well field. However, most of the yield in the wells results from southward conduit flow of recharge from the high Pine Valley Mountains in fractures of the large, north-striking Gunlock fault, almost a mile east of the well field; the best yields (1400 gpm) are in the wells on the eastern side of the well field (Rowley and Dixon, 2004). The Sand Hollow Reservoir southwest of Hurricane, Utah, although now a State Park, was developed by the Washington County Water Conservancy District (WCWCD) to artificially recharge the Navajo Sandstone for a well field that surrounds the reservoir. As the reservoir was being filled, additional wells were sited for the well field, following detailed geologic mapping at 1:12,000 scale to locate faults on which to site the new wells (Rowley and others, 2004); the first of these new wells to be drilled, on a newly discovered fault (Rowley and others, 2004; Biek and others, 2009), was pump tested at 2500 gpm (Corey Cram, WCWCD, oral communication, 2006). The same concept, using geologic mapping at 1 inch equals 500 feet, was used for the planned WCWCD Anderson Junction artificial-recharge reservoir and well field in the Navajo Sandstone south of Pintura, Utah (Rowley and Dixon, 2010). Although reservoir or well construction has not yet started, production wells were proposed by drilling the downthrown sides of basin-range faults identified by the mapping; as with the other examples, the wells will be drilled to a depth below the water table so as to intercept the fault zone.

The method used to site wells (see Rowley and Dixon, 2004) requires us to map the normal fault, hopefully also determining the dip of the fault plane. Then, using trigonometry, we site the well on the downthrown side of the fault at a horizontal distance from the fault that allows the driller to intersect the fault at 50 to 100 feet (15–30 m) below the water table. If the fault plane is not exposed, we presume a dip of 60° toward the downthrown side, typical for normal faults in this area.

On the basis of studies at two geothermal-energy fields in Japan, Pritchett (2005) made conclusions that fracture flow may apply to all geothermal fields. He noted that “fracture zones” (what we call faults) provide the mechanism for fluid flow in geothermal fields. Furthermore, when these underlying fracture zones are intersected by production wells, the sharp permeability contrast between relatively impermeable rock and the fractures that cut it allow hot liquid water to boil to steam. He concluded (p. 178) that “[w]ells that do not intersect permeable fractures are non-productive ‘dry holes’ and are usually abandoned.”

The geologic map and cross sections of this report provide the geologic framework for the Sulphurdale geothermal field. The most important part of this framework is the fault architecture, inasmuch as it will control delivery of hot fluids. Based on our experience, drilling the downthrown side of faults so as to intersect the fault zone will produce the highest water yield. The map should be useful to guide future exploration and to help explain heat and volume distributions within the geothermal aquifer.

CONCLUSIONS

The geothermal resource at Sulphurdale, Utah, is an important economic asset under development for electric power by Enel Green Power North America, Inc. However, the geologic framework of the area and the origin of the geothermal heat were poorly understood, even though significant company-confidential geophysical and geologic studies have been completed by Enel and previous owners. Accordingly, detailed geologic mapping at 1:12,000-scale was proposed, funded by the Utah Geological Survey. This product, consisting of a digital geologic map, five cross sections at the same scale, and a text analysis, represents the most detailed geologic coverage of the Sulphurdale geothermal-resource area to date.

Compared to previous geologic maps of the Sulphurdale area, our new map is more detailed and makes many different assignments in structural geology and the stratigraphic sequence in the Sulphurdale area, as is always the case where more detailed mapping supersedes previous, less detailed mapping. The new geologic map also shows all relevant Quaternary and Pliocene unconsolidated surficial units, which had not previously been mapped. Mapping surficial deposits allowed us to identify patches of a poorly consolidated, hydrothermally altered, Quaternary(?) ash-flow tuff on the southern side of the sulfur pit. At first we thought that this was a locally derived deposit, perhaps from an eruptive vent in the pit that was occupied later by the solfatara. That interpretation would surely explain the origin of the Sulphurdale heat source as the molten magma chamber that erupted the tuff. However, a lithologic similarity of the tuff to the middle Pleistocene (0.79 to 0.50 Ma) tuff of Ranch Canyon (Lipman and others, 1978) on the western flank of the Mineral Mountains, led us to correlate the tuff at the sulfur pit with this unit. If so, the tuff would have erupted from a relatively crystal-rich dome on the crest of the Mineral Mountains and flowed east down the mountain side and up the drainages off the Tushar Mountains; the tuff at the sulfur pit, farther east in the canyon of Sulphur Creek, and farther north in an excavation made by the USGS are all that remains. This correlation is still tenuous, but it is beyond the scope of the present study to do additional chemical and isotopic studies that would be needed to verify our interpretation.

Basin-range faults provide a critical control for the geothermal heat at Sulphurdale, but our mapping showed more faults and interpreted their type and significance differently. The steam resource originally developed by Mother Earth Industries underlies the sulfur pit and power plant and extends as far north as drill hole 47-6 (Huttrer, 1994; Moore, 2003). The eastern side of this resource area appears to be near, but east of, a north-striking, down-to-the-west fault that was mapped just east of the power plant by Moore and Samberg (1979). The western side of the resource area is near, but west of, a north-striking, down-to-the-east fault located just west of the plant. The steam resource area thus is partly in a graben. Geothermal-fluid migration will be as conduit flow northward along those faults.

Moore and Samberg (1979) and Moore (2003) suggested that a buried east-trending, down-to-the-north fault passes through the steam area just north of the plant. We agree with their interpretation. In the graben, depth to the main Paleozoic aquifer in the area south of the east-striking fault is nearly 1000 feet (300 m) less than north of the fault. Moore and Samberg (1979) and Moore (2003) also proposed that intersection of this east-west fault with the north-south graben faults may be a further control on the heat. The eastern extent of the east-west fault, east of the graben, enables recharge from the mountain front to move westward to the heat source. The northeast-striking Pleistocene fault farther south also is a likely conduit for recharge from the mountain front.

Our attention to the young surficial deposits enabled us to assign ages with more accuracy than previously done to the youngest rocks deposited during this active geothermal system. Our mapping therefore refined the Quaternary assignment by Moore and Samberg (1979) of the age of latest movement on the eastern fault of the graben containing most of the steam resource to be middle to late Pleistocene. The western fault to the graben is middle Pleistocene, if not younger. Our mapping also notes that this young graben extends northward, as does groundwater flow along it, and therefore that the geothermal resource likely extends farther north than currently identified.

According to fracture-flow concepts, the graben faults should be barriers to the lateral (east and west) flow of geothermal water across them, at the same time as being conduits to flow northward along them, so wells drilled east of the eastern fault in the graben and west of the western fault should yield cooler water. But we know that hot water occurs within Paleozoic rocks both east and west of the graben. One explanation may be that relative displacement on the Paleozoic rocks was not sufficient to juxtapose confining units against aquifers, so carbonate and sandstone aquifers connect with each other on both sides of the faults. This explanation seems to be true according to the cross sections: the primary control on the steam and water aquifers is stratigraphic, with steam generally in the Queantoweap Sandstone and hot water in the underlying Pakoon Dolomite and older carbonate units. Another explanation of the equidimensional shape (in map plan) of the geothermal resource is that an equidimensional, partly molten magma body underlies the resource area.

At a “prospect” (exploratory pit dug by someone looking for metallic minerals) shown on the topographic map and intersected by Cross Section D–D′, we found exposed rock that was the most severely hydrothermally altered and silicified of any outcrop seen during our mapping. This silicified rock, tentatively identified as the Leach Canyon Formation, appears in a graben and is located about a mile southeast of the sulfur pit. The bounding faults of the graben that underlies the prospect dropped the brittle Leach Canyon Formation, a good fractured aquifer, below the water table where it was altered by geothermal water. The highest part of the thermal-gradient anomaly (Ross and Moore, 1994, figure 6) that underlies the existing steam-production area at Sulphurdale was not constrained by field data to the east and therefore may extend into this area.

Many faults on the geologic map appear to radiate north, northeast, east, southeast, and south from a center defined by the sulfur pit and the main part of the steam-resource area. The symmetry is only on the east because any western half of the pattern was cut off by the main range-front fault of the Tushar Mountains. This main fault is seen as the westernmost fault of cross-sections A–A′, B–B′, C–C′, and D–D′ and places basin-fill deposits of unknown thickness against the Paleozoic aquifer east of the fault. This fault therefore probably provides the western extent of the hydrothermal resource. The radial pattern is similar to a more pronounced, better displayed radial pattern mapped by Cunningham and Steven (1979b) in the Deer Trail Mountain–Alunite Ridge mining area in the east-central part of the Tushar Mountains. They interpreted the pattern to result from a dome caused by a buried intrusion of 14 Ma that created skarn deposits at the Deer Trail Mine and that formed vein alunite in fissures that developed in the extended roof of the dome. H_2S gas arose in heated groundwater, and the gas was oxidized to H_2SO_4 at the surface. By analogy, we suggest that at Sulphurdale, the radial pattern suggests a buried intrusion centered beneath the sulfur pit and steam-resource area. Inasmuch as the sulfur pit is an active solfatara, the buried intrusion probably contains either cooling magma or a molten magma (active) component that supplies the heat at Sulphurdale. The hypothetical intrusion, likely granite, is coaxial with much older (quartz monzonite) buried intrusions penetrated by two drill holes. The maximum water reservoir temperature now found at Sulphurdale, about 350°F (177°C), is significantly less than those reservoir temperatures (about 500°F [260°C]) at the Blundell power plant in the Roosevelt geothermal area, where magma is projected to be at 2.5 to 3.7 miles (4 to 6 km) depth. The lesser reservoir temperature at Sulphurdale indicates that any partly molten Quaternary magma body would be far deeper than existing drill holes, and probably deeper than the depth to magma at Roosevelt.

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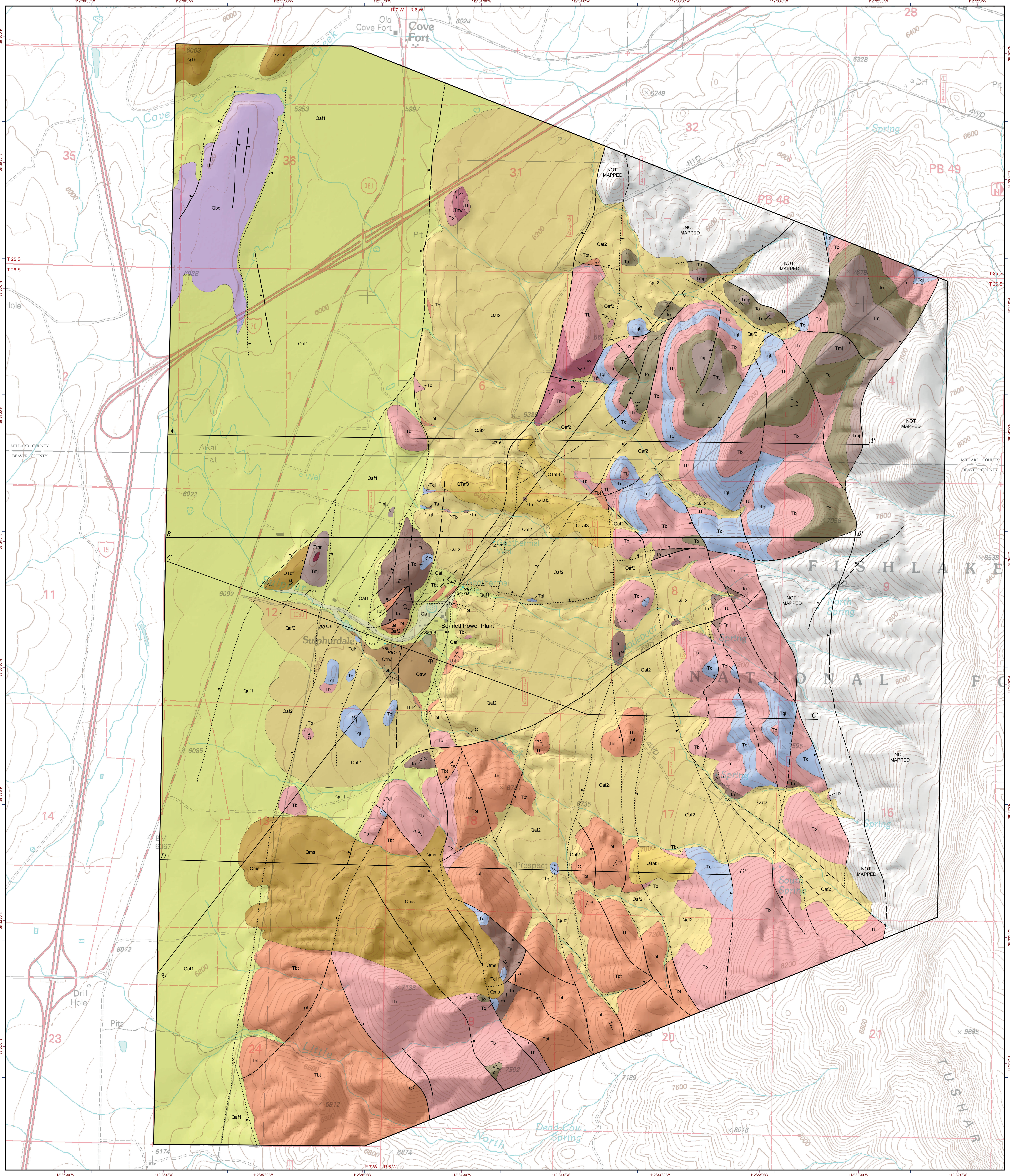
Plate 1
Utah Geological Survey Open-File Report 609
Geology of the Sulphurdale Geothermal-Resource Area

Utah Geological Survey
a division of
Utah Department of Natural Resources

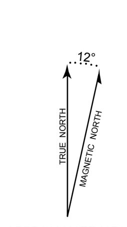


SCALE 1:12 000

CONTOUR INTERVAL 40 FEET
SUPPLEMENTAL CONTOUR INTERVAL 20 FEET
NATIONAL GEODETIC VERTICAL DATUM OF 1929

This geologic map was funded by the Utah Geological Survey Energy Grants for Research Pertaining to: Characterization of Utah's Hydrocarbon Reservoirs, Metals, and Industrial Minerals - FY 2011.
The views and conclusions contained in this document are those of the author, and should not be interpreted as necessarily the official policies, either expressed or implied, of the U.S. government.

Utah Geological Survey
1594 W. North Temple
PO Box 146100
Salt Lake City, Utah 84114-6100
ph: 801-537-3300; fax 801-537-3400
geology.utah.gov

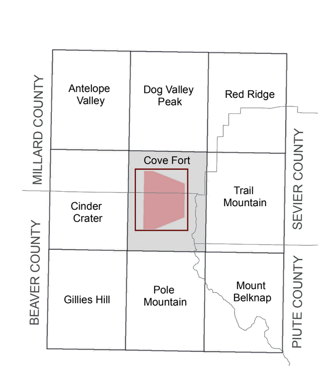


APPROXIMATE MEAN DECLINATION, 2006

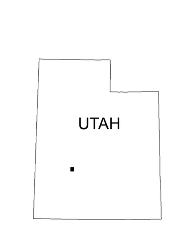
Measured Grid 1000 Meter
North American Datum 1983.

GEOLOGIC MAP OF THE SULPHURDALE GEOTHERMAL-RESOURCE AREA, BEAVER AND MILLARD COUNTIES, UTAH

Peter D. Rowley, Edward F. Rutledge, David J. Maxwell, Gary L. Dixon, and Chester A. Wallace
2013



ADJOINING 7.5' QUADRANGLES



MAP LOCATION

BASEMAP:
Topography compiled 1956.
Produced by the United States Geological Survey 1986
Planimetry derived from imagery taken 1998 and other sources.
Revised by USDA Forest Service 2001.
Public Land Survey and survey control current as of 2001

Managed by:
Utah Geological Survey
Robert E. Blackett and Craig D. Morgan

Digital Cartography by:
GIS Services & Consulting, LLC
November 11, 2011

Utah Geological Survey
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