Implications of Thrust and Detachment Faulting for the Structural Geology of Thermo Hot Springs Region, Beaver County, Utah

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Keywords

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ABSTRACT

This report presents data and conclusions concerning the role of low-angle faulting in the formation of Thermo Hot Springs and the effects it may have on fluid flow and production. The conclusions are that Thermo Hot Springs is formed by a low-angle normal or detachment fault that places Mesozoic and upper Paleozoic sedimentary rock in the upper plate over underlying metamorphic rock and granite. The Mesozoic section is overlain by a sequence of Tertiary to Quaternary volcanic and sedimentary deposits. High-angle normal faults offset the sedimentary and volcanic section, and in some, if not all, cases penetrate and offset the low-angle detachment fault. The high-angle normal faulting has two primary strikes: one is the northern strike of classical Basin and Range faulting, and the other is a roughly east-west striking set of normal faults. These faults may hydraulically compartmentalize the reservoir but also provide pathways for fluids to ascend upwards from beneath the detachment fault.

The low-angle detachment fault model for Thermo Hot Springs structure has regional implications for geothermal prospecting in the Basin and Range terrain of southwestern Utah. This region is underlain by several known detachment faults of Middle to Late Tertiary age, which may act to laterally channel hot fluids at depth over large areas with little surface expression except where the low-angle faults are breached by younger faulting. That is, blind geothermal reservoirs may well occur at depth with few if any surface manifestations such as springs or tufa mounds. We suspect that thrust faults of Mesozoic age may also play a similar role to the Tertiary detachment faults in channeling fluids laterally in the Basin and Range region of southwestern Utah, but this is apparently not the case at Thermo Hot Springs.

1. Geological Background

The Sevier geothermal anomaly of southwestern Utah encompasses a broad region of enhanced heat flow with seven known high-temperature geothermal resource areas (Mabey and Budding, 1987, 1994). The anomaly covers the transition between the Colorado Plateau and the eastern Basin and Range Province, where the Paleozoic miogeocline was collapsed eastward by thrust faulting during the Cretaceous to early Tertiary (Cowan and Bruhn, 1992). The subsequent history included widespread igneous activity, and extension initiated during mid-Tertiary time and continuing to the present. Thrust faults are exposed throughout mountain blocks of the region, but there

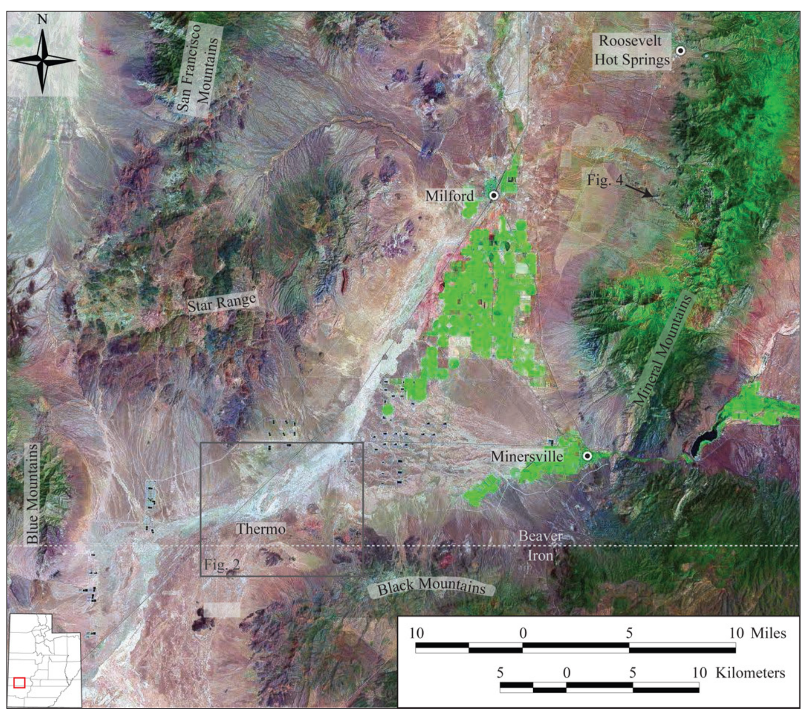


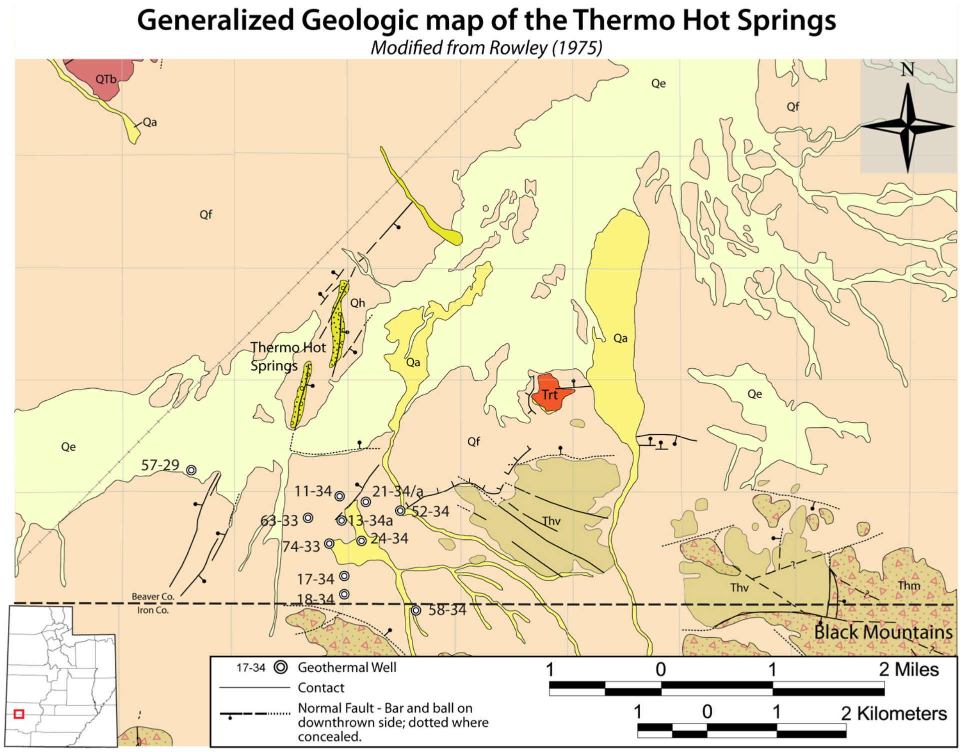
Figure 1. Satellite image of southwestern Utah showing the locations of Thermo Hot Springs and southern Mineral Mountains study areas.

are also both low-angle and high-angle normal faults that occur within the mountain blocks and beneath valleys. The origin of the low-angle normal faults remains controversial, with some geologists arguing that low-angle normal faults formed in their present orientation, or possibly by reactivation of thrust fault surfaces, while others cite evidence for subsequent rotation of high-angle normal faults to gentle dip by isostatic flexure during unloading of the footwall, and/or rotation of originally high-angle faults in a collapsing domino style of deformation. Regardless of the process, the structural geology of southwestern Utah contains both low-angle thrust and normal faults of large areal extent, many of which are cut and offset by younger high-angle normal faults.

The presence of low-angle faults within geothermal reservoir rocks of Paleozoic age is suspected at the Cove Fort – Sulphurdale (Huttrer, 1994; Ross and Moore, 1994), at Thermo Hot Springs (Figure 1), and is likely at Fumarole Butte – Abraham Hot Springs based on geophysical data and regional structural setting (e.g. Figure 6 of Mabey and Budding, 1994). Low-angle normal faults also occur within the Roosevelt Hot Springs (Bruhn and others, 1982), and may reflect footwall deformation caused by flexural uplift and back-rotation in the footwall of the extensive Cave Canyon detachment fault that is exposed in the central part of the Mineral Mountains (Coleman and others, 1997; Anders and others, 2001). Both outcrop and subsurface data (Smith and Bruhn, 1984; Nielson and others, 1986) suggest that the Cave Canyon fault system projects southwestward towards Thermo Hot Springs. Alternatively, Paleozoic rocks are thrust over Mesozoic strata along the Blue Mountain fault to the west of Thermo Hot Springs, which suggests that carbonate and sandstone strata geothermal reservoir may be duplicated by relict thrust faults as inferred by Nash and Jones (2010).

An evaluation of low-angle detachment faulting within the Thermo Hot Springs is our primary focus. Surface manifestation at Thermo is a series of hot spring mounds formed by siliceous sinter and eolian sand and silt located along NNE-trending faults on the Escalante Desert floor (Figure 2; Mabey and Budding, 1987, 1994). Thermo Hot Springs is located in the complex volcanic terrain of the Blue Ribbon plutonic lineament, an E-W trending belt of extensive Mid-Tertiary volcanism and faulting that was subsequently disrupted by younger normal faulting and eruption of basaltic lavas (Rowley and others, 1978). Gravity and magnetic data suggest that Thermo Hot Springs is bounded by both N-S and E-W striking normal faults that dip steeply and presumably offset earlier structures related to thrust faulting or mid-Tertiary extension (Sawyer, 1977). Drill-hole data from a Republic Geothermal well located southwest of the Hot Spring Mounds penetrated 350 m (1148 ft) of alluvium, followed by 610 m (2000 ft) of volcanic rocks, 540 m (1772 ft) of sedimentary and metamorphic rocks, and bottomed in granite at 2220 m (7283 ft) with a maximum temperature of 174° C (345° F) at 2000 m (6562 ft) (Mabey and Budding, 1994).

This stratigraphy is similar to that of the Thermo Hot Springs, described by Nash and Jones (2010). The sedimentary rocks are presumably Paleozoic or early Mesozoic age based on a com-



Qa — ALLUVIUM (HOLOCENE AND PLEISTOCENE)-Sand and less abundant pebble gravel deposited in intermittent stream channels, on bordering flood plains, and in fans of major drainages. Contact transitional with deposits of Escalante Arm of Lake Bonneville (Qe) in some places. As much as 10 m thick.

Qf — FAN AND PEDIMENT DEPOSITS (HOLOCENE AND PLEISTOCENE)-Silt, sand, and minor pebble gravel from local sources deposited in alluvial fans and on pediments. Includes minor colluvium. Locally more than 30 m thick. Contacts approximately located.

Qh — HOT SPRING DEPOSITS OF THE THERMO AREA (HOLOCENE AND PLEISTOCENE)-Hot spring deposits of two echelon mounds nearly 10 m high (sec. 21 and 28, T. 30 S., R. 12 W.) that overlie north-striking fractures, probably faults (Petersen, 1973). The main rock type is resistant bulbous and cavernous growths of tan and pale-green bedded opal (siliceous sinter), containing clasts of windblown quartz sand and silt Travertine also has been reported (Mundorff, 1970), and eolian sand occurs on the tops and flanks of the mounds. About 20 small hot springs, containing water with recorded surface temperatures as high as 90"C. and with an estimated average reservoir subsurface temperature of 200"C. (Howell, 1875; Renner and others, 1976), issue from the tops and eastern sides of the mounds along the main controlling faults. The water is high in hydrogen sulfide and dissolved silica (Lee, 1908).

Qe — DEPOSITS OF ESCALANTE ARM OF LAKE BONNEVILLE (Pleistocene)-Includes clay, silt, sand, and pebble gravel deposited in, and on shorelines of, a Pleistocene lake (Escalante arm of Lake Bonneville). Includes fluvial deposits from streams that emptied into the lake. Much of the unit, however, consists of fluvial deposits formed during terminal drying up of the lake and draining of its water northward to lower parts of the Lake Bonneville topographic basin. Thus most contacts may represent a north-draining channel. Only the most prominent contact is shown; generally, it represents the youngest and lowest shoreline or outlet channel, and has an elevation of 1,530-1,540 m, sloping northward. Locally includes Holocene alluvium. Contact with alluvium (Qa) and fan and pediment deposits (Of) locally transitional (Lee, 1908).

QTb — BASALT LAVA FLOWS (PLEISTOCENE?, PLIOCENE, AND MIOCENE)-Resistant black to medium-gray, commonly vesicular or amygdaloidal lava flows of basalt. Basalt generally contains spots of antigorite(?), an alteration product of olivine. This unit also includes scoria and a 3 m thick white tuff that underlies basalt in sec. 16 and 20, T. 31 S., R. 12 W. Some flows overlie and resemble rocks of the mafic member of the Horse Valley Formation (Thm); in these places, age and genesis of parts of the two mapped units may be closely similar. As much as 15 m thick

Trt — RHYOLITE OF THERMO HOT SPRINGS AREA (MIOCENE)-Light-gray or black resistant flow-foliated, locally spherulitic crystal-poor dome and (or) lava flows of alkalic rhyolite that contain sanidine, quartz, and plagioclase, and traces of biotite, opaque minerals, and hornblende. Mostly devitrified except for a 2 m thick obsidian layer in the southwestern part of the exposure. Has a K-Ar age of 10.3 m.y., and is part of an east-trending alignment of small plugs, domes, and lava flows of alkalic rhyolite (Rowley and others, 1978)

Thv — HORSE VALLEY FORMATION (MIOCENE) – Gray or pink, or less commonly white, red, tan, black, purple, brown, soft to resistant, rhyodacite to dacitic lava flows, volcanic mudflow breccia, plugs, and minor ash-flow tuff. Erupted from numerous clustered central vents, most of which are in the quadrangle. Unit is generally poorly exposed, especially where composed of volcanic mudflow breccia, which weathers to boulder-strewn slopes. Where well exposed, volcanic mudflow breccia consists of angular pebble-to bolder-sized clasts of Horse Valley Formation lithology contained in a mostly light-gray or tan muddy matrix, and unsupported by direct contact with each other. Lava flows and plugs are generally flow-foliated. Most of the unit represents vent facies rock, using the terminology of Parsons (1965, 1969) and Smedes and Prostka (1973).

Thm — Mafic member of the Horse Valley Formation – Soft to resistant mostly black dacitic to andesitic{?) volcanic mudflow breccia and subordinate lava flows. Volcanic mudflow breccia consists of angular pebble-to boulder-sized clasts contained in a light-to medium-gray, tan, or pink muddy matrix and unsupported by direct contact with each other; breccia weathers to boulder-strewn slopes. Clasts in the breccia and lava flows generally are black, red (devitrified rock), or dark-gray and consist of 15-30 percent plagioclase, 2-11 percent pyroxene, 1-3.5 percent opaque minerals, and, in some specimens, small amounts (generally 1 percent or less) of hornblende set in a glass matrix that contains sparse plagioclase microlites.

Figure 2. Geological map of Thermo Hot Springs in the Escalante Desert and descriptions of geologic units (Modified from Rowley 1975), with locations of geothermal wells.

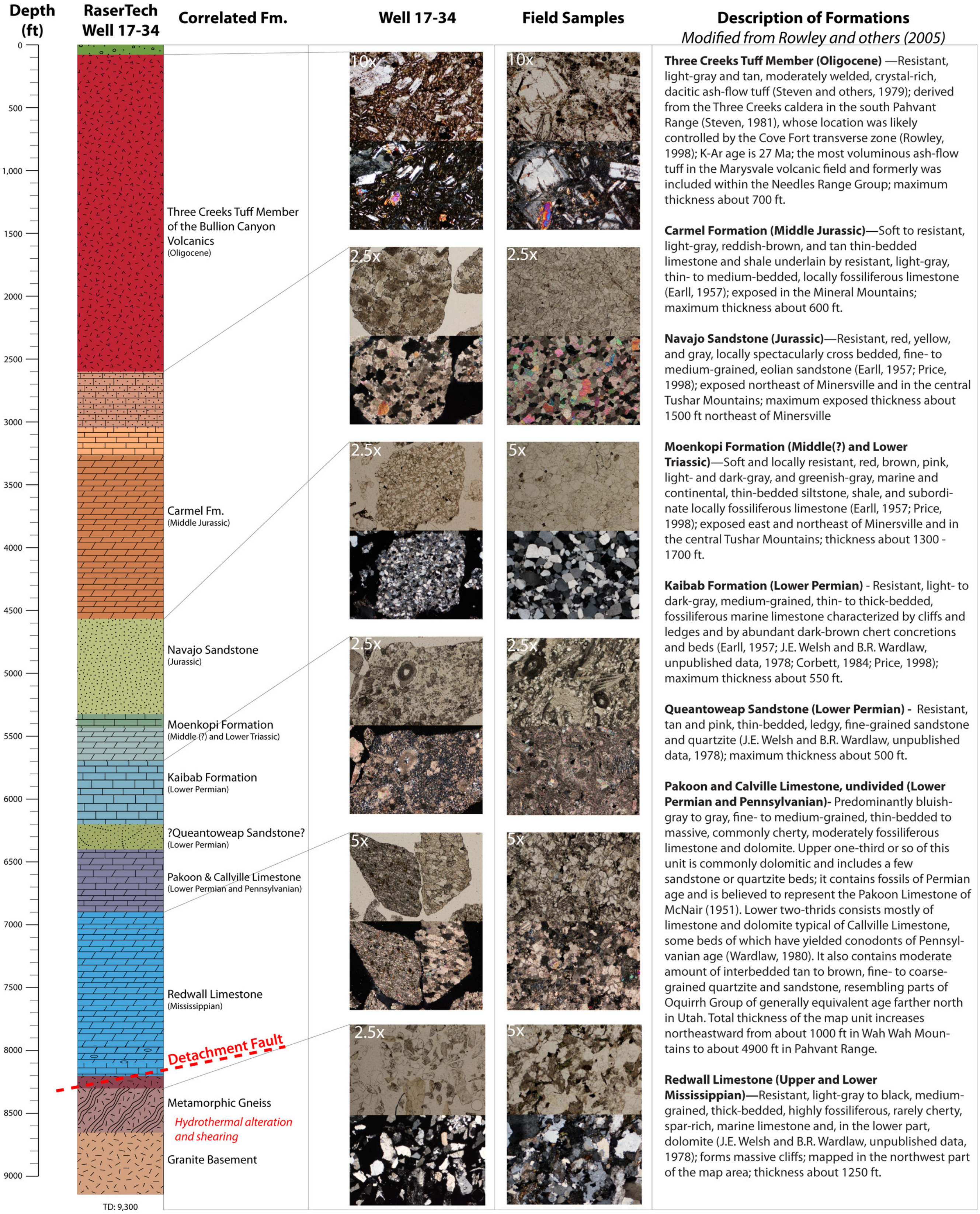


Figure 3. Stratigraphic column of well 17-34 based upon comparing rock fragments and mineralogy in thin sections from samples in well 17-34 with thin sections of rocks exposed in the Mineral Mountains, Utah. Rocks exposed in the Mineral Mountains include Tertiary volcanic and sedimentary rock, Mesozoic and Paleozoic strata, together with metamorphic rock, granite and fault-related cataclasite. Images of representative thin sections from the well and equivalent rocks in outcrop are displayed to the right of the stratigraphic column. The rock unit description in the right column is from Rowely and others (2005) and references cited therein.

parison of well chip samples with stratigraphic descriptions from outcrops in the surrounding mountains. The metamorphic rocks, described as skarn by Nash and Jones (2010), may be contact metamorphic products of the underlying intrusion, but a similar stratigraphy and metamorphic sequence is found in the Cave Canyon detachment fault in the southern Mineral Mountains (Nielson and others, 1986; Coleman and others, 1997).

2. Stratigraphy and Structure of Rasertech Well 17-34

Petrographic thin sections of cuttings from well 17-34 were compared to thin sections of hand samples collected in the southern Mineral Mountains and inspected for fragments of fossils to constrain the age of the limestone units encountered in the borehole. This comparison allows us to correlate units to the various formations penetrated in well 17-34 based on the petrography, composition, and fossil fragment content (Figure 3). This geologic section is very similar to that associated with the Cave Canyon detachment fault in the southern Mineral Mountains (Nielson and others, 1986).

Mesozoic Carbonates

Carbonate rock in well 17-34 from a depth of 914 to 975 m (3000 to 3200 ft) is a clastic light brown to grey micritic limestone composed of fragments of bivalve shells, crinoid, echinoids and bryozoans. This fossil assemblage is similar to those described in outcrop studies of the Middle Jurassic Carmel Formation in Utah by Charette (1998) and De Gilbert and Ekdale (1999). The fossils found in the Carmel Formation are characterized by a low-diversity and confined to the upper part of the formation. Identification of this formation is also confirmed by the presence of the Carmel Formation below the Tertiary volcanic sequence and above the Navajo Sandstone, as seen in the southern Mineral Mountains.

Paleozoic Carbonates

The limestone and sandstone strata between the base of the Lower to Middle Triassic Moenkopi Formation and the top of the metamorphic sequence are upper Paleozoic in age. This age was determined from and assemblage of fossil fragments found in thin section including: hollow brachiopod spines, crinoid stems, echinoderm shells, and trilobites. The fossil assemblage is similar to those described from outcrops of upper Paleozoic rocks elsewhere in Utah (Cheevers and Rawson, 1979; Schubert and Bottjer, 1995). The uppermost limestone unit is the Lower Permian Kaibab Formation. According to McKee, 1938, brachiopods in the Kaibab Limestone constitute the most useful group for correlation purposes because they are usually abundant, and are represented by a number of genera and species. The most abundant species of Strophomenida brachiopod are the Productus and Chonetes whose shells are typified by external hollow, tubular spines that are typically broken off by taphonomic processes (Brunton and Cocks, 1995). These tubular spines are found in the petrographic sections from both well cuttings and hand samples and enable a quick relative age determination. The stratigraphic section beneath the Kaibab Formation then appears to follow the known measured stratigraphic sequence with increasing depth that includes the Queantoweap Sandstone (Lower Permian), the Pakoon Dolomite – Callville Limestone (Lower Permian to Pennsylvanian) and the Mississippian Redwall Limestone.

Structural Interpretations

We find a largely intact stratigraphic section based on the comparison of the lithology and mineralogy of the chip samples from the borehole with samples we collected from the Mesozoic and Paleozoic strata exposed in the southern Mineral Mountains, and find no evidence of down-hole repetition of fossil fragment assemblages that would suggest duplication of the strata by thrust faulting.

We interpret a fault contact at the base of the Redwall Limestone where remnants of contact metamorphic skarn, and the underlying metamorphic and granite show evidence of shearing and hydrothermal alteration with the formation of chlorite, sericite, and epidote that is similar to the low-angle normal faults exposed in the Mineral Mountains (Bruhn and others 1982; 1994), including the large-scale Cave Canyon detachment fault mapped by Nielson and others (1986).

3. Permeability Structure of Analog Outcrops

The effects of faulting and jointing on permeability were documented in the Mineral Mountains where rocks equivalent to those in the Thermo Hot Springs reservoir are exposed in outcrop. For example the low-angle normal fault near Corral Canyon on the western flank of the Mineral Mountains provides insight into the structure and mineralogy of part of the detachment fault system (Figure 4; Bruhn and others, 1982, 1994). This exposure provides field evidence concerning structural controls on fluid permeability that may be of use when evaluating the reservoir at Thermo Hot Springs. The fault strikes north and dips gently to the west and contains a complex assemblage of variably altered granite cataclasite (Figure 9a). Upper Paleozoic limestone and quartzite in the hanging wall are in fault contact and brecciated along the upper part of the fault zone (Bruhn and others, 1982, 1994; Barnett and others, 1996). The granite beneath the cataclasite zone is intensely fractured with linear intensities of 1.2 to 1.5 fractures/m (4 to 5 factures/ft). The fractures strike approximately normal to the slip direction on the low-angle fault zone, and dip steeply into the granite. Where exposed in the wall of stream cuts the fractures are up to several meters or tens of feet long (Figure 9b).

The cataclasite within the fault is comminuted and hydrothermally altered granite with abundant hydrothermal chlorite, epidote, sericite and hematite (Bruhn and others, 1994; Barnett and others, 1996). Stable isotope and geochemical analyses of the cataclasite indicate that alteration occurred during a relatively short time span, and presumably sealed the cataclasite by mineral alteration and precipitation. The implication is the low-angle fault zone sealed rapidly and became a barrier rather than conduit to fluid flow once faulting ceased. This is a typical process in fault zones, and suggests that low-angle faults may become barriers to upward migration of fluids unless breached by younger and more steeply dipping faults. Intense fracturing of granite beneath the cataclasite will create substantial fracture permeability and pathways for lateral migration of fluid over large areas beneath detachment faults.

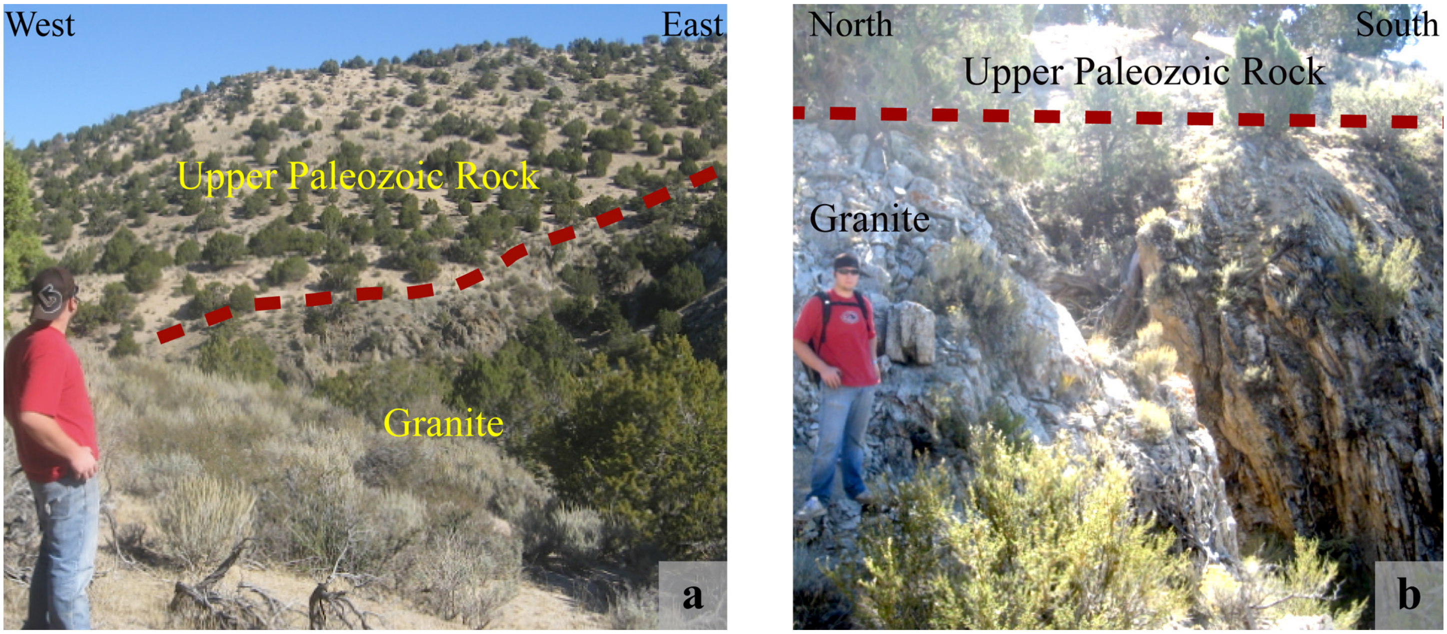


Figure 4. Photographs showing the low-angle detachment fault near Corral Canyon on the western flank of the Mineral Mountains. (a) View of the fault with granite in the footwall and Paleozoic strata in the hanging wall. (b) View of the closely spaced fractures formed in the granite just below the detachment fault. See figure 1 for location.

4. Temperature Survey Comparison

Average temperature gradients observed throughout the Great Basin are typically 35-50 °C/km (1.9-2.8 °F/100 ft), and 40 °C/km (2.2 °F/100 ft) may be considered a typical background value. All other gradients in the area are anomalous and suggest the presence of a shallow thermal groundwater plume within the alluvium. Thermal gradient wells in the Thermo Hot Springs area were drilled throughout Escalante Desert in the 1970s by a number of geothermal companies, including Republic Geothermal, Inc., Phillips Petroleum Co., Geothermal Operations; Amax Exploration, Inc.; and Hunt Energy Co. The gradient wells were widely separated and of varying depths, but they do provide clear indications of a large thermal anomaly in the area surrounding Thermo Hot Springs.

Figure 5 shows surveys run in the two wells graphed on a common sea level datum. The survey from well 17-34 is the solid green line while the two surveys run in well 57-29 are the red and blue lines Note that the surveys of well 57-29 were obtained thirty years ago. Several features are noteworthy in both wells' data. Looking over all the available Republic data, we conclude that the maximum bottom-hole temperature measured in 57-29 is 172 ± 4 °C (341 ± 3 °F).

The surveys of 57-29 on 10 March and 20 April were also run with mechanical Kuster tools. The surveys are important because the well had been heating up since the previous December, and had been flowing to the surface for 20 days at the time of the 10 March run. The well was shut in at that time and the final survey on 20 April followed five weeks of inactivity. These are representative temperatures that confirm the 20-day flow test did not draw in cooler water.

The green line in figure 5 depicts well 17-34 that was surveyed in August 2009. Depths cited in borehole 17-34 are measured along the length of the borehole with the Kelly bushing as datum. The borehole is vertical to a measured depth of about 671 m (2200 ft), below which the hole deviates on average 17.7° from vertical to the Total Depth (T.D.) at 2835 m (9300 ft). The maximum bottom-hole temperature measured in 17-34 is 188 ± 4 °C (371 ± 3 °F). The favorable temperatures in the Republic well were also found in 17-34, but occurred at a much greater depth.

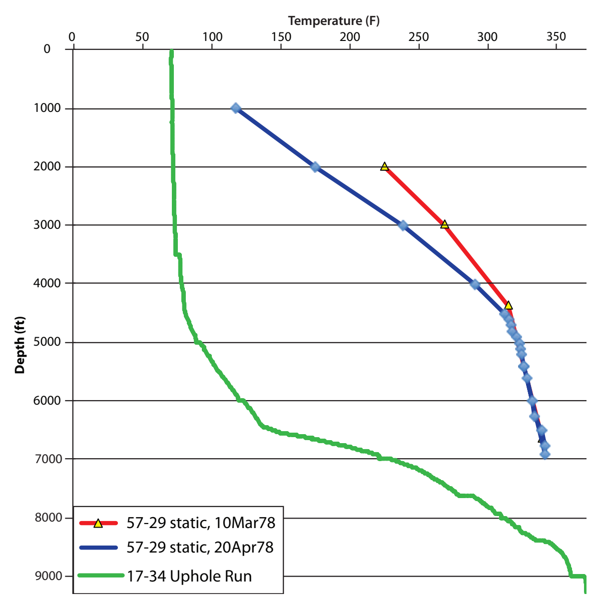


Figure 5. Stratigraphy and temperature profiles of wells 57-29 and 17-34.

5. Thermo Hot Springs Geothermal System

Quaternary fault scarps of Thermo Hot Springs strike in one of two directions: (1) in the alluvial fill of the valley floor the faults that control the hot spring deposits strike north – south; (2)

and although poorly expressed in the alluvial deposits, the faults that cut the Quaternary basalts exposed in the Black Mountains strike east – west (Figure 2). Gravity and magnetic data show the north-south and east-west faulting with substantial (>300 ft) bedrock displacement. Figure 6 illustrates how these faults offset the low-angle detachment, allowing the thermal fluids to ascend along these high-angle fault conduits.

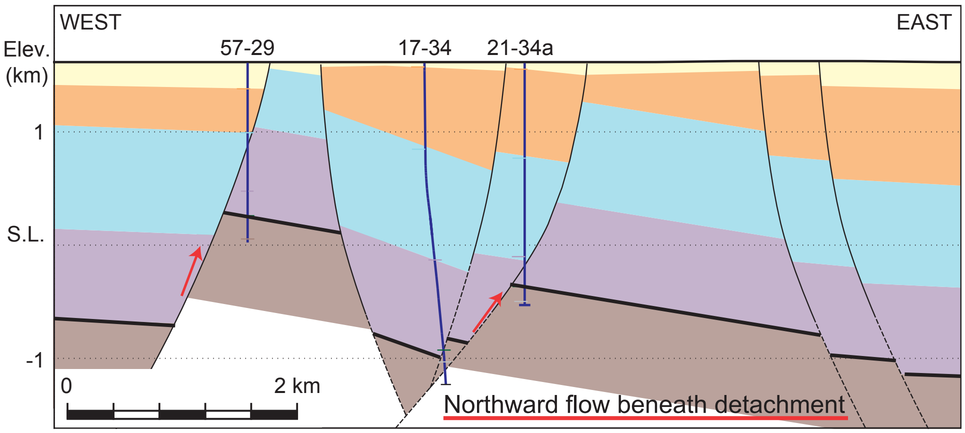


Figure 6. Structural cross section of the Thermo Hot Springs. Constructed using subsurface well data and Quaternary fault scarps, unit thicknesses and fault offset are estimated. From top to bottom: Oligocene to Quaternary sediment and volcanics (Yellow and Orange) Mesozoic rocks (Cyan), Paleozoic rocks (Purple), and Crystalline basement (Brown). Arrows indicate the fluid pathways.

6. Implications for Geothermal Resources

The close correspondence between the geology of the southern Mineral Mountains and that encountered in the Thermo Hot Springs reservoir serves to reinforce the hypothesis that large volumes of hot fluids may lie beneath low-angle faults in southwestern Utah. Comminution of rocks during shearing along low-angle fault systems creates cataclasite that is susceptible to rapid sealing by hydrothermal alteration unless breached by continued movement on the fault zone (Brown and Bruhn, 1996), or if high-angle faulting cuts and displaces the low-angle fault zone, breaching the relatively impermeable mineralized cataclasite.

There are several large detachment faults in southwestern Utah and adjacent parts of Nevada that are of interest to geothermal exploration. These include the Cave Canyon detachment fault that we discuss in this report, the Sevier Desert detachment fault that dips westward beneath the northern part of the Sevier geothermal anomaly, and the Snake Range detachment that may extend beneath western Utah to intersect the Sevier Desert detachment at depth. Anders and others (2001) suggest that the Sevier Desert detachment may be a subsurface unconformity rather than a low-angle fault, but seismic reflection profiles would suggest that at least part of the feature is a fault that extends to mid-crustal depth. Lastly, Coleman and others (1997) cite evidence for a detachment fault with a break-away or head located on the eastern side of Beaver Valley. This latter fault is of great interest when evaluating the structural geology of Thermo Hot Springs because it purportedly extends beneath the Mineral Mountains and contains the Cave Canyon detachment fault in its upper plate. We note that if this fault does exist, then it contains the entire Thermo Hot Springs KGRA in its upper plate, including the granite and east-dipping detachment fault that we tentatively correlate with the Cave Canyon detachment. The existence of this cryptic Beaver Valley detachment is based primarily on evidence for uplift and back-rotation towards the east of the Mineral Mountains. Notably, the southern edge of one or both of the Beaver Valley and Cave Canyon detachment faults lies along the east-trending geomorphic escarpment that extends from the southern end of Beaver Valley almost continuously westward past the southern margin of Thermo Hot Springs (Figure 1).

Thrust faults may of course also be extensive barriers to upward migration of fluids because hydrothermal sealing of comminuted rock or cataclasite is likely. We note however, that thrust faulting within the Sevier orogenic belt of Utah was not accompanied by extensive volcanism or elevated heat flow. Conversely, development of detachment faults was accompanied by extensive plutonic and volcanic activity that elevated heat flow and generated hot fluids to enhance hydrothermal alteration and mineral sealing of the laterally extensive fault zones. While we would not exclude remnant thrust fault flats as important features for channeling lateral movement of subsurface fluids, we are particularly interested in the presence and permeability structure of the younger detachment faults that were associated with middle to late Tertiary volcanic activity.

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