Structural Framework of the Soda Lake Geothermal Area, Churchill County, Nevada

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ABSTRACT

The Soda Lake geothermal area is located in the Carson Desert in the western part of the Carson Sink basin in west-central Nevada. The field is centered ~3.5 km NNE of the Soda Lake maar, from which it takes its name. The Soda Lake field was identified serendipitously during the drilling of an irrigation survey well in the early 20th century, and was explored for electricity production potential by Chevron and Phillips in the 1970s. It has been producing power for more than 2 decades and is currently operating at 16 MW.

Dense drilling at the Soda Lake field permits good correlation of stratigraphy in the subsurface below the feature-poor Carson Desert. Unconsolidated sediments extend more than 1000 m below surface in this part of the basin. The upper few hundred meters are composed of non-marine fluvial and lacustrine sediments derived from the surrounding highlands. The basin fill becomes increasingly uniform and volcanic-sourced with depth. In many wells this deeper volcaniclastic fill may grade into a lapilli lithic tuff of similar composition. At variable distances below the tuff, the unconsolidated fill is intruded by a plug-like trachytic basalt body. The basalt overlies fine-grained, organic-rich lacustrine sediments and a thick package of altered basalts.

The Soda Lake geothermal field falls within a NNE--SSW surface trend defined by the Soda Lake maar, the Upsal Hogback cinder cones, and hot ground and silicified sands that overlie the field itself. Drilling and seismic data have confirmed that the field lies within a narrow, NNE-trending graben. The faults that define this structure likely control both upwelling hot fluids and these small eruptive centers – both the surface-breaching volcanic centers and the previously unrecognized buried basaltic plug at the geothermal field. A more complete stratigraphic column, based on analysis of cuttings, is in progress for the immediate Soda Lake area. A stratigraphy based on correlation between lithologic logging and borehole geophysics will allow us to 1) determine local throw on the primary NNE-striking Soda Lake faults, 2) aid in locating the subsidiary faults and/or step-overs, and thereby 3) allow correlation of the prevailing structures with regional-scale trends observed at the boundaries of the Carson Sink basin.

Introduction

The Soda Lake geothermal area is located in the Carson Desert in the western part of the Carson Sink basin about 15 km

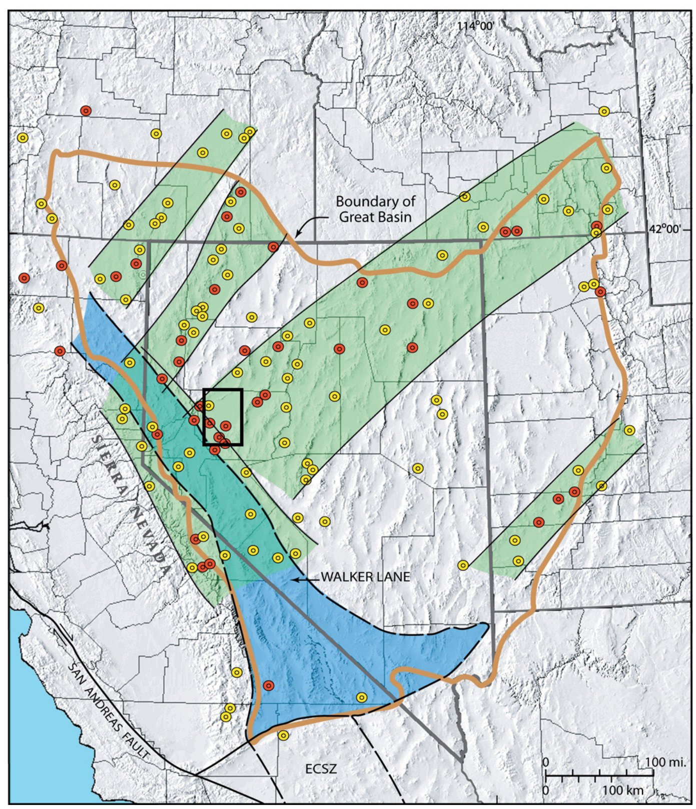

Figure 1. Regional setting of the Soda Lake Geothermal Field. Walker Lane is shaded blue, major geothermal belts and/or structural trends are shaded green. Red rectangle depicts outline of Figure 2.

northwest of the town of Fallon in west-central Nevada (Figure 1). It lies entirely within the Carson Sink basin, one of the largest structural basins in the Basin and Range province within Nevada. The field is centered ~3.5 km north-northeast of the Soda Lake maar, from which it takes its name. The Soda Lake field was first identified serendipitously during the drilling of an irrigation survey well in 1903. First explored for electricity production potential by Chevron and Phillips in the 1970s, it has been producing power for ~2 decades and is currently operating at 16 MW, with a capacity of 23 MW, and 41 MW of indicated resources. (http://www.magmaenergycorp.com/Theme/Magma/files/assets/_pdf/USA%20Assets/Soda%20Lake%20Power%20Plant%20-%20Nevada.pdf, Sibbett 1979).

Regional Stratigraphy

The mountain ranges surrounding the Carson Sink contain thick (2-3 km) sequences of late Oligocene ash-flow tuffs that fill paleovalleys cut into Mesozoic basement, early to middle Miocene generally intermediate composition volcanic rocks, and middle to late Miocene volcanic units (dominated by mafic flows) intercalated with fluvial and lacustrine sedimentary rocks (Faulds and Garside, 2003; Faulds et al., 2010; Faulds and Ramelli, 2009). The Tertiary units overlie a heterogeneous Mesozoic basement composed of Triassic-Jurassic metamorphic and intrusive rocks and are onlapped by Miocene to recent basin-fill deposits, including widespread lacustrine sediments derived from Lake Lahontan.

The stratigraphy in the Carson Sink is probably very similar to that in the surrounding ranges, although basin-fill sediments are much thicker and are locally punctuated by Quaternary volcanic centers.

Well data from the Soda Lake area demonstrates that the greater Carson Sink area is characterized by a thick sequence of unconsolidated basin fill, which overlies thick basalts that must correlate with Miocene basalts exposed in the surrounding ranges. The distinctive basaltic pile is underlain by dacitic through rhyolitic rocks of probable Miocene age in many wells. In others, the basalts lie directly on lithologically variable Mesozoic metamorphic rocks and granite. Quaternary basalts in the Soda Lake area both predate (Upsal Hogback, 0.6Ma) and postdate (Soda Lake maar, 0.01 Ma) the late Pleistocene Lake Lahontan.

Structural Framework

Current understanding of the structural framework of the greater Carson Desert area is modest. The Carson Sink basin is bounded by highlands that express and are controlled by 3 structural trends that prevailed in the region during later Tertiary and Quaternary time: 1) the Humboldt structural zone, 2) the Basin and Range, and 3) the Walker Lane. These major structural trends are exposed in outcrop only at the margins of the Carson Sink basin, more than ~15-20 km away from the Soda Lake geothermal field. However, they are the dominant trends in the nearest exposed bedrock.

The northern boundary of the basin is formed by the southernmost West Humboldt Range, which trends northeast and helps define the Humboldt structural zone (Wetlaufer and Rowan, 1981; Figure 2). This trend extends across much of northern Nevada, and may have influenced structural trends in the northern Carson Sink basin. The Hot Springs Mountains lie to the west of Soda Lake, and form the northwest edge of the basin. They are dissected by numerous north-northeast-striking Basin and Range normal faults. This suite of high-angle, commonly east-dipping normal faults cuts the Hot Springs Mountains near the Desert Queen geothermal prospect, north-northeast of, and on-trend with the Soda Lake geothermal field (Faulds and Garside, 2003; Faulds et al., 2010; Faulds and Green, unpublished mapping). This fault system terminates southward and horsetails through the Parran Mesa area, ~19 km north of Soda Lake, but unexposed faults with similar strikes may take up strain farther south, beneath Quaternary fill in the basin.

The eastern margin of the basin is bounded by the Stillwater Range, a prominent, north-northeast trending mountain range. The northern Carson Sink basin lies between these 3 ranges and forms a broad, north-northeast trending half-graben. It is dropped down to the east along the large north-northeast-striking, bounding faults on the west flank of the Stillwater Range. A seismic line across the northern Carson Sink basin (Hastings, 1979; Figure 4) shows that strata in the northern Carson Sink dip east toward the Stillwater Range front. Drilling in conjunction with this seismic study indicates that sedimentary and volcanic basin fill is > 3750 m thick in the northern Carson Sink (Hastings, 1979; Trexler, 1981; Figure 2).

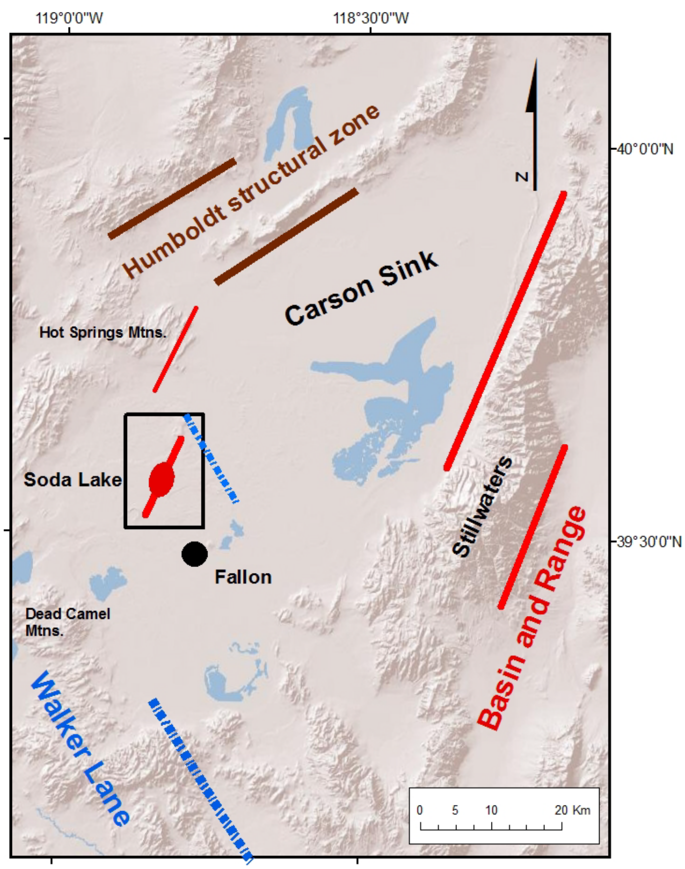

Figure 2. Shaded relief map of the Carson Sink basin. Red line are Basin and Range fault trends, dashed blue lines are Walker Lane fault trends, and dashed brown lines are Humboldt structural zone fault trend. Black box encompasses Soda Lake geothermal field, as shown in Figure 5.

The southwest edge of the Carson Sink basin is bounded by ranges that lie within the Walker Lane, a zone where dextral shear is largely accommodated by northwest-striking, dextral strike-slip faults. There are large north-northwest-striking normal faults bounding the southwesternmost edge of the basin (Faulds and Perkins, 2007; Bell and Faulds, 2010, unpublished mapping). However, the entire west edge of the Carson Sink basin abuts an oroclinal flexure (Faulds and Perkins, 2007; Faulds and Henry, 2008). This deformed zone comprises the eastern extent of the Carson Domain, where Walker Lane dextral shear is not accommodated by northwest-striking dextral faults, but by clockwise block rotation and east-northeast-striking, sinistral faults (Stewart 1988; Cashman and Fontaine, 2000; Faulds and Henry, 2008).

The Soda Lake geothermal field lies ~25 km east of the Walker Lane. Unpublished minerals exploration mapping in this area indicates that the flexure likely extends at least to the western edge of the basin (Dilles, P. 1983, map of the Dead Camel Mountains). The structural trends in this area are complex and may give way to north-northeast-trending structures west of the geothermal field (Faulds and Perkins, 2007; Faulds and Henry, 2008). However, it is possible that Walker Lane-related structures impact parts of the Carson Sink, including the Soda Lake area.

The southwest third of the Carson Sink basin appears to be structurally distinct from the northern basin. A northwest-trending buried gravity high separates the southwestern third of the basin from the east-tilted half-graben in the north (Echols et al., 2011, this volume). Seismic data indicate basin sediments in the southern Carson Sink basin may dip south, rather than east toward the Stillwater Range. (Echols et al., 2011, Figure 6, this volume). Deep drill intercepts at the Soda Lake field and farther south in this sub-basin indicate that Mesozoic basement may be shallower than in the north – as little as ~2500 m below the surface (Horton, 1978; Magma Energy, unpublished lithologic logs). Structural data are sparse in this area, but the south Carson Sink basin is not a simple, northeasterly-trending half-graben, suggesting that it is structurally influenced by something other than the NNE Basin and Range trend that appears to prevail in the northern part of the basin.

Soda Lake Geothermal Field

Stratigraphic Setting

Drilling at the Soda Lake geothermal field began in the mid-1970s and has continued sporadically to the present day. There are now more than 28 deep (> ~500 m) production, injection, observation and temperature gradient wells at and near the production site, along with ~70 other, shallow water wells and survey drillholes. The extensive well coverage means the upper ~1000 m of the local stratigraphy is reasonably well understood.

Upper ~1200 m

Unconsolidated sediments extend more than 1000 m below surface at the Soda Lake geothermal field. This deep basin fill spans all of the Quaternary and likely much of the later Tertiary (late Miocene-Pliocene). The upper few hundred meters are composed of diverse non-marine fluvial and lacustrine sediments, characterized by an arkosic/feldspathic clast population and likely derived from the surrounding highlands. The basin fill becomes increasingly uniform and volcanic-sourced with depth. In many wells this (dominantly) mafic volcaniclastic fill may grade into lapilli lithic tuff of similar composition. At variable distances below this sediment + tuff package, the unconsolidated fill is broken by one distinctive volcanic unit – a nearly aphyric trachytic basalt of restricted lateral extent and highly variable thickness. Sibbett (1979) interpreted this unit as a dike, but we surmise that the basalt is at least partly a plug-like body.

The basalt appears to be bounded by a northwest trending paleo-high in the west half of Section 33 (Figure 3). It is 90 – 150 m thick in wells north and west of the production area (Sections 29 and 28), where it breaks up into 3-4 (flow?) units interlayered with sediments. It is either < 25 m thick or missing in wells on the west and southwest half of Section 33 (Figure 3) and it is absent or < 3 m thick in wells farther south of the geothermal field. However, it ranges from 260 – 580 m thick in the north-central part of Section 33 (Benoit, per. comm.).

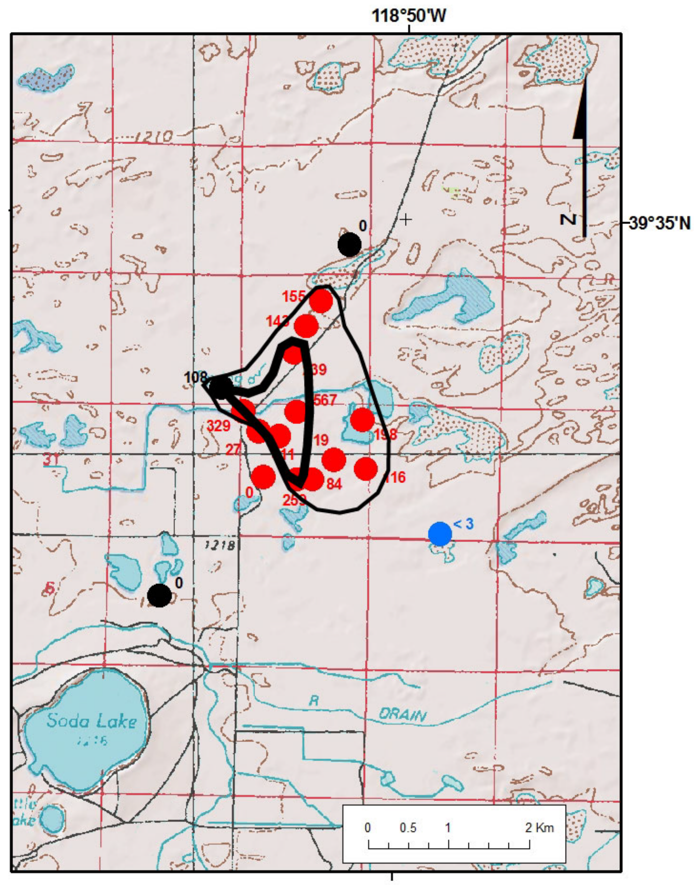

Figure 3. Isopach map of the thickness of the trachytic basalt unit, in meters. Thicknesses at red collars are from this re-logging study; blue are from gamma ray logs; black are from prior lithologic logs. The thick black contour line is the >200 m isopach; thin black contour line, the >75 m isopach.

No deep well data are available to constrain this feature to the northwest. However, it thins to the north, and thickness isopachs suggest that it may form the core of a small volcanic center similar in scale to tuff cones and maar(s) that lie respectively north-northeast and south-southwest of the geothermal field.

Below 1200 m depth

There are ~7 deep boreholes in the Carson Sink basin (Figure 4) that pierced middle to late Tertiary volcanic rocks, 3 of which bottomed in Mesozoic basement. They are 1) the N.U.R.E. test well (2892 m), 2) three deep wells at the Soda Lake property, 84-33 (2893 m), 81-33 (2505 m) and 41B-33 (3065 m), 3) two wells in the Stillwater geothermal field, and 4) an oil well in the north Carson Sink basin (Standard Oil-Amoco S.P. #1, 3749 m, Hastings, 1979).

The oil well (Figure 4) intersected a typical northwest Nevada stratigraphic column: unconsolidated sediments from the surface to 2103 m, basalt from 2103 to 2286 m, more volcanic-derived, fine-grained sediments from 2286 to 2822 m, and from 2822 m to 3352 m (TD) a series of tuffs and volcaniclastic rocks that may correlate with Oligocene ash-flow tuffs mapped in nearby ranges (Faulds et al., 2005; Henry and Faulds, 2010). A 3052 m well at the Stillwater geothermal prospect (Figure 4) bottomed in > 600 m of felsic tuffs, below a thick basalt package (Sibbett and Blackett, 1982).

Five deep boreholes in the southern Carson Sink basin have somewhat different profiles. The southernmost one, the N.U.R.E. well, intersected basin fill sediments from surface to ~1450 m, a mafic dominated volcanic section from 1450 to 2624 m, and a thin layer of dacites from 2624 to 2800 m before bottoming in Mesozoic basement (Horton, 1978). Well 84-33 at the Soda Lake geothermal field intersected a broadly similar stratigraphic column: 1) unconsolidated sediments from surface to 1125 m, 2) a basalt-poor, dacitic to andesitic volcanic pile from 1125 – 2420 m, and 3) granite from 2420 to 2893 m (Benoit 1981, unpublished logs). The granite was presumed to be Mesozoic, but middle Tertiary felsic intrusions crop out in the southern Stillwater Range (John, 1995). Well 81-33 at Soda Lake encountered unconsolidated sediments from 0 – 1082 m (with the trachytic basalt plug at 530 – 683 m), and a thick basalt package below 1082 m that was interbedded with thin intervals (tens of meters) of fine grained sediments. This basalt/diabase package lies directly on graphitic, boudinaged Mesozoic phyllite and quartzose sandstone at 2219 m.

The lithologic logs of Soda Lake wells 84-33 and 81-33, and the N.U.R.E. well suggest that thick Oligocene ash-flow tuffs are largely absent in the southwest part of the Carson Sink basin. A thinner suite of andesitic to dacitic rocks may exist where thick silicic tuffs would be found farther north and east. Mesozoic meta-andesite at the bottom of the N.U.R.E. well and graphitic phyllite identified near the bottom of Soda Lake well 81-33 suggest that Mesozoic basement lies at or slightly below ~2500 m depth in the Soda Lake geothermal field. However, the 2-3 intercepts of Mesozoic basement rocks at or near the Soda Lake field are too limited to draw solid conclusions about basement lithology.

Structural Controls

The Soda Lake geothermal field lies within a broad northwest trending gravity high (McNitt, 1990; Hill, 1979, Echols et al., 2011). However, the Soda Lake geothermal field falls within a ~16 km long north-northeast surface trend defined by the Soda Lake maar, the Upsal Hogback tuff cones, and the argillized and silicified sands that overlie the field itself (Figure 5).

North-northeast striking normal faults appear to dominate the local structural setting at Soda Lake. Drilling and seismic data show that the Soda Lake field lies within a narrow, north-northeast-trending graben (Hill, 1979; Echols et al., 2011). The structures that define this feature are similar in strike to those that are interpreted or predicted to control fluid flow at the Desert Peak geothermal field and the Desert Queen geothermal prospect in the Hot Springs Mountains , ~15 km north of Soda Lake (Faulds et al., 2010). The bounding faults that define the graben may be the primary structural control on upwelling geothermal fluids at the Soda Lake field. Related faults likely also controlled the distribution of the nearby Quaternary eruptive centers.

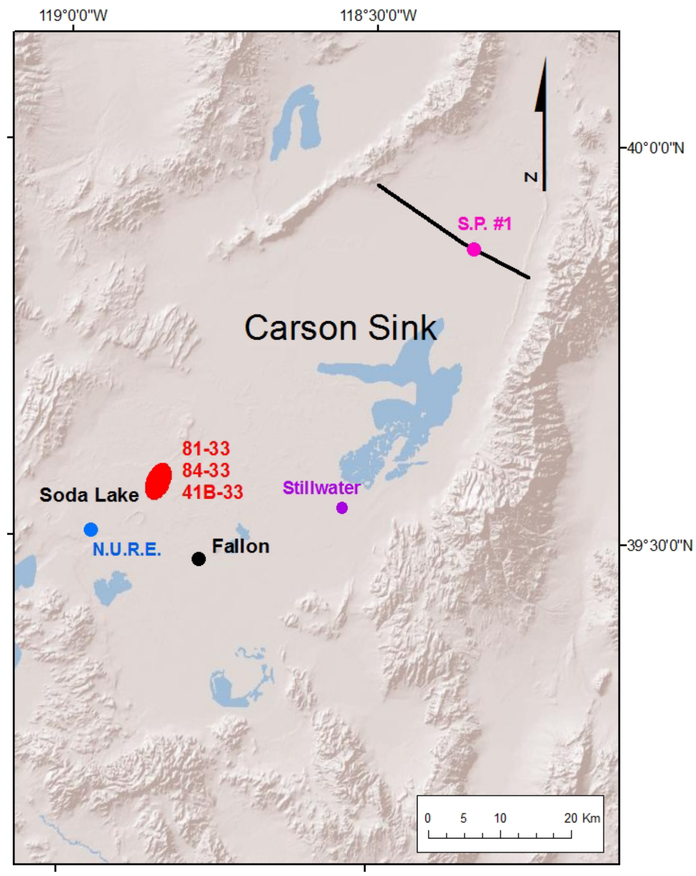

Figure 4. Shaded relief map of the Carson Sink basin, showing selected deep wells. Soda Lake Geothermal field area in red. The northwest-trending line through Standard Oil-Amoco well S.P. #1 is a seismic line that was run in conjunction with this drill program. Modified from Hastings (1979).

The dominant north-northeast-striking faults were not the only structures interpreted from early geophysical surveys at Soda Lake. A northwest fault trend with limited inferred offset had previously been interpreted from gravity (McNitt, 1990) and early seismic data (Stark, 1980). These northwest-striking faults have little to no surface expression. More recent geophysical data confirm the existence of a northwest-trending gravity high, but do not support this interpreted secondary fault trend. En echelon north-northeast-striking faults form the only significant, near-surface structural trend currently recognized at the geothermal field. These faults have local jogs or step-overs that strike ~ 5-10° north of the main traces, but these are not large discontinuities.

Some limited surface data support a northwest trend in the field area. The Sagouse scarp is the surface expression of a young

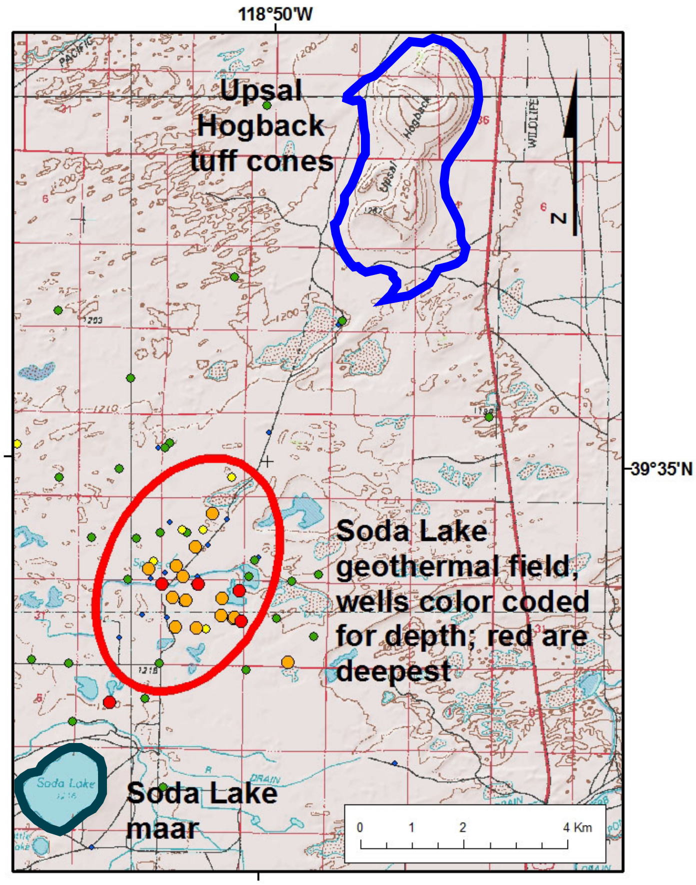

Figure 5. Soda Lake Geothermal field area. Drill data courtesy of Magma Energy Corp. The area of this figure is shown on Figure 2 as a black inset rectangle.

northwest-striking fault (Morrison 1964; Figure 2, fine dashed blue line) mapped at the surface to the east-northeast of the Soda Lake geothermal field. The Sagouse fault extends over ~10 km and would intersect (cut off?) Upsal Hogback on the north, if it extends northwest beyond where it is currently mapped. Significant aeolian deposits cover the greater Soda Lake area, and low relief fault scarps in young surface sediments are easily buried or obscured by windblown sands. The existence of other northwest-striking faults and the full extent of the Sagouse fault might well be obscured by recent aeolian deposits.

A stratigraphic column based on analysis of cuttings is in progress for the Soda Lake geothermal field. Together with cross-correlation of geophysical logs from wells, it should allow for 1) determination of local throw on the primary north-northeast-striking Soda Lake faults, 2) locating any subsidiary northwest-striking faults and/or step-overs, and thereby 3) assessments of how the prevailing structures at the site correlate with the mapped and identified regional scale trends observed at the boundaries of the Carson Sink basin.

Conclusions

Well logs indicate that the stratigraphy below the basin fill regionally correlates with that in surrounding ranges. Thick unconsolidated basin fill grades downward into volcaniclastic rocks directly above one distinctive basalt marker layer. At roughly 1200 m depth, Quaternary (?) sediments transition to a thick package of volcanic flows, breccias, and interbedded fine grained lacustrine sediments. Mesozoic basement rocks in the greater Soda Lake geothermal field area are reached at depths of 2500 to ~2900 m, which is shallower than in the north Carson Sink basin. However, the Mesozoic basement at the Soda Lake geothermal field is quite deep, and the thick, unconsolidated sedimentary cover likely obscures numerous faults and significant topography developed on bedrock units within the basin.

The general structural framework of the Soda Lake geothermal field is dominated by north-northeast-striking normal faults, which trend perpendicular to the contemporary extension direction. Local (100's of meters) scale fault trends are more diverse and include N-S-striking strands. The finer-scale structural complexities at the Soda Lake geothermal field may reflect inherited fabrics or may be due to its location in the western Carson Sink basin near the juncture of the Walker Lane, Humboldt structural zone and the regional NNE-trending Basin and Range structural fabric.

These north-northeast striking faults are the likely deep structural controls on fluid upflow at the Soda Lake geothermal field. As interpreted, they accommodated nearly dip-slip normal offset in accord with borehole data (Hickman and Davatzes, 2010) and abundant fault-kinematics data from the surrounding region (Faulds et al., 2010; Hinz et al., 2010; Rhodes et al., 2010). Very modest, northerly jogs in these faults may serve to concentrate fluids due to an abundance of minor faults connecting major fault strands in these step-over (i.e., relay ramp) areas.

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