Soda Lake Geothermal Field Case History 1972 to 2016

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Sustainable Solutions

Keywords

Nevada, Basin and Range, Soda Lake, case history, exploration, development, production history

ABSTRACT

The Soda Lake geothermal field has one of the longer exploration, development, and production histories in Nevada with initial exploration activities beginning in 1972 and the most recent production well being placed in service in 2016. Six different owner/developers have explored, drilled, and operated the project in its 43 year history with highly variable degrees of success in developing and producing the field. Two of the first three wells drilled prior to 1982 were commercially successful but 21 wells and six redrills since 1990, concentrated in a one square mile area have had a far lower success rate. The project has continuously produced power since 1987 but the capacity factors have been relatively low, primarily due to a shortfall of produced fluid and reduced production temperatures. Over most of the project's history there were remarkably few technical papers published on the resource and its performance. Since 2009 the project output has stabilized and even slightly increased with a renewed emphasis on developing an improved understanding of the overall geothermal resource.

Introduction

The Soda Lake geothermal field has now been in continuous production for over 28 years. It was one of the earliest fields in the Basin and Range province to utilize binary conversion technology and the original generation equipment is still in service. It has produced the hottest fluid of any binary project in the Basin and Range province. Twenty-three wells and six redrills were completed between 1974 and 2012 within an area of about 3½ mi^2. Within this 3½ mi^2 area nine deep temperature-gradient holes have also been drilled between depths of 1300′ and 3664′. All of these nine deep temperature-gradient holes are deeper than the two shallowest active production wells. This makes the Soda Lake field one of the most densely drilled geothermal projects within the Basin and Range province. For all of this drilling, the project is currently selling a year-round average of nine megawatts. This paper reviews the overall history of the project with a focus on detailing the various reasons as to how and why so much drilling effort has resulted in so few megawatts.

Location and Geologic Setting

The Soda Lake geothermal field is located in the west-central part of the Carson Desert about 60 miles east of Reno, Nevada and about 9 miles northwest of the smaller town of Fallon (Figure 1). The Carson Desert is the largest intermontane basin in Nevada and the Soda Lake geothermal field is located at least 10 miles from any surface outcrops of Tertiary or older rocks which define the margins of the overall basin. The topography surrounding the geothermal field consists primarily of sparsely vegetated sand dunes, sandy plains, and clay flats with local relief of as much as 50 ft (Olmsted et al., 1984). The field is also distal end of the delta of the Carson River which enters the basin from the southwest.

The Soda Lake field is located several miles north of the generally accepted northeastern margin of the Walker Lane, which has no surface expression in the vicinity of the geothermal field (McLachlan, et al., 2011, Figure 1). No Quaternary age fault scarps have been recognized within or close to the geothermal field but the surficial geology is not amenable to preserving scarps for any significant length of time. The regional controlling structural feature is interpreted to be a 10 mile long NNE trending deep seated structural zone extending from the very young Soda Lake maars through the Soda Lake field to the late-Pleistocene Upsal Hogback cinder cones (Olmsted et al, 1984, McLachlan et al., 2011). Within this regional zone there is considerable local complexity controlling the permeability on a prospect sized scale (Echols et al., 2011).

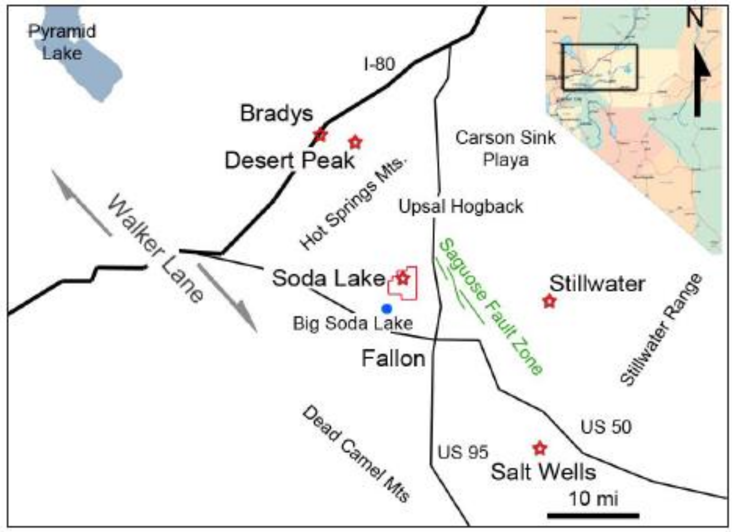

Figure 1. Soda Lake location map showing nearby geothermal fields and selected structural features from Echols et al., 2011. The northeastern margin of the Walker Lane is shown by the grey arrows.

Early Exploration 1972 - 1986

The only surface manifestations of hydrothermal activity at the Soda Lake geothermal field consisted of a small tract of hydrothermally altered sand and clay, and a few intermittently active very weak fumarolic vents surrounding an old shallow well that encountered steam and boiling water at a depth of 60 feet (Garside and Schilling, 1979, Olmsted et al., 1984). There are small areas of silica cemented sand in the dunes surrounding the hydrothermally altered area. These limited local features, along with the regional setting between the Soda Lake maars and the Upsal Hogback cinder cones were enough encouragement for the U. S. Geological Survey to include Soda Lake as one of the original 12 Known Geothermal Resource Areas in Nevada (Goodwin et al., 1971).

In anticipation of a competitive lease sale of the public (BLM administered) lands within the Known Geothermal Resource Area, Chevron and Phillips Petroleum Company began exploration efforts in 1972 and 1973. In 1972 the U. S. Geological Survey also began a program of evaluating selected geothermal systems in Northern Nevada, including Soda Lake (Olmsted et al., 1975).

The land ownership and management at Soda Lake is a mixture of Federal land managed by the Bureau of Land Management consisting of most of the even numbered sections and private lands generally within the odd numbered sections. Phillips and Chevron competitively leased private lands in the area prior to 1974 and in June 1975 they were the high bidders for six tracts of Federal lands at a lease sale. The basic land ownership has shown little or no change in the past 40 years, with the exception of the geothermal project owner changes.

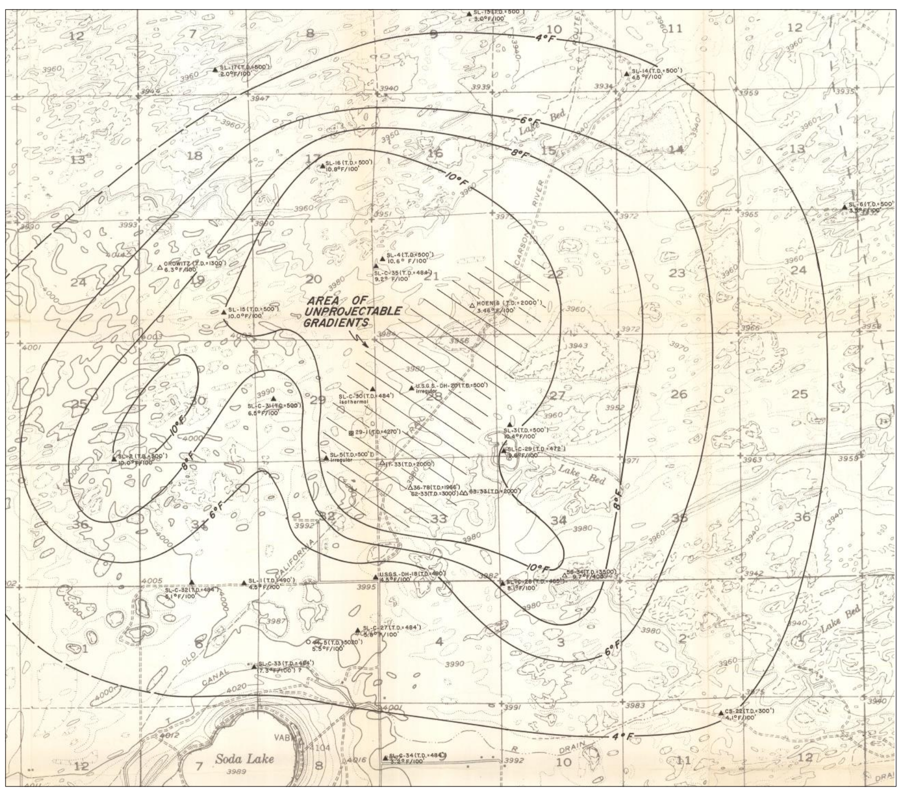

Figure 2. 1979 vintage shallow temperature-gradient map of the Soda Lake thermal anomaly. The outermost contour represents 4 °F/100′ which is slightly above the regional background gradient. The active part of the field lies in the south half of Section 28 and the north half of Section 33, within the lower half of the hachured area in the center of the anomaly. Each square represents one Section or square mile. The small square in the southeastern quarter of Section 29 represents the location of the 1-29 well.

The shallowest thermal information from the Soda Lake thermal anomaly is a January 1974 snow melt pattern defining three small anomalies at and near the hydrothermally altered area (Olmsted, 1977). The shallowest holes at Soda Lake are a series of about 100 one meter deep holes, all completed above the water table, that define the most intense part of the shallow thermal anomaly (Olmsted, 1977). The U. S. Geological Survey (Olmsted, 1977) also drilled nine deeper holes, up to 500 feet deep within the central core of the thermal anomaly. Phillips and Chevron drilled 30 temperature-gradient holes up to 500 feet deep in 1973. (At that time holes deeper than 500′ required blow out prevention equipment.) These holes were far more widely spaced than the U. S. Geological Survey holes and outlined a nearly circular 20 -25 mi^2 thermal anomaly with temperature gradients above 4 °F/100′ (Figure 2). Comparison of the overall size and intensity of the shallow thermal anomaly with The Geysers in California, the only operating geothermal project in the United States at the time, led to optimistic hope that the Soda Lake resource might potentially be capable of hundreds of megawatts. The highest temperature measured in these 500 foot-deep Soda Lake temperature-gradient holes was about 290 °F. Interestingly, the Big Soda Lake maar is located outside of the thermal anomaly (Figure 2).

In addition to the temperature-gradient drilling, other mid-1970s geophysical surveys such as roving dipole, ground noise, magnetotellurics, and a short seismic reflection line were run but from the perspective of 2016 these surveys can be described as primitive or unreliable at best, and more realistically as meaningless. The MT stations were run along two lines, rather than covering an area. The most useful result of a short Phillips seismic line using surface charges in hand dug holes and a single seismometer was the premature detonation during a lunch break of one charge at a depth of 1 meter due to high near-surface heat. Only, the 1970s temperature data have survived the test of four decades.

In late 1974 Chevron and Phillips sited the 1-29 (more recently renamed as 77-29) exploration well a short distance northwest of the hydrothermally altered area, close to the site of the hottest temperature-gradient hole, and on private land (Figure 2) so permitting efforts were minimized. No credible written prognosis of this well was prepared and one could not have been prepared at that time anywhere close to modern standards. It was not targeted to intersect any particular hypothesized fault or stratigraphic unit. The vertical 1-29 well reached a total depth of 4306′. There was nothing preplanned about this depth but it was fortuitously deep enough to assess the area.

There was a partial loss of returns in the 1-29 well at a depth of 954′ which was easily cased off with 13⅜″ casing. A second lost circulation zone was penetrated at a depth of 1100′ but it was also easily cured. There was no completion testing or attempts to unload the well. It was initially completed as an apparently dry hole as Phillips and Chevron did not know how to stimulate or flow test a geothermal well at that time. A meaningless drill stem test was performed in 1975 and immediately thereafter the 13⅜″ casing was perforated between 791′ and 980′ where a shallow thermal aquifer with a maximum temperature of 332 °F was present on the static temperature logs (Figure 3). Temperatures declined slightly below the shallow thermal aquifer. The 1-29 well was abandoned below a depth of 991′ and remained idle in this condition for the next several years. The 1-29 well turned out to be only the first of several wells at Soda Lake that have required post-drilling workovers and/or stimulation to demonstrate commercial permeability.

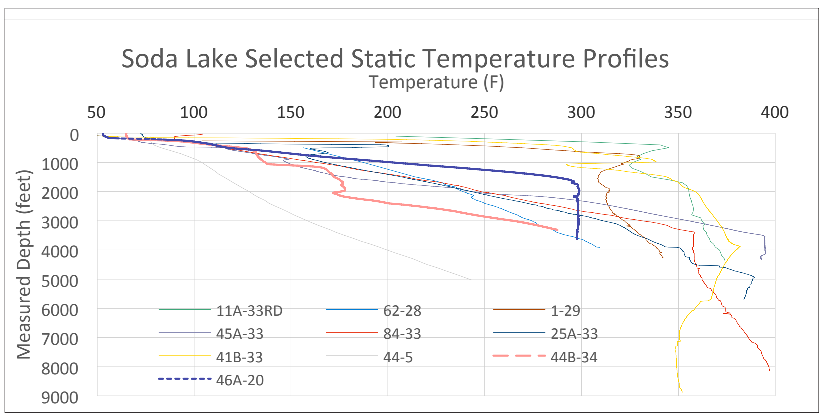

Figure 3. Selected static temperature profiles from the Soda Lake geothermal field showing its wide range of thermal characteristics.

In 1976 the Soda Lake production unit was formed by Chevron and Phillips (Hill et al., 1979) and Phillips drilled the first intermediate deep temperature gradient hole, the 2000 foot-deep Hoenig strat test in the northern part of the thermal anomaly (Figure 4). The Hoenig strat test had a temperature of only 210 °F at 1980′ making it among the coolest holes drilled at Soda Lake. It remains the most northeasterly deeper hole in the thermal anomaly.

In 1977 Chevron obtained 12 line miles of 1200% seismic reflection coverage and drilled the 44-5 well, the southern most well in the field area, about 2/3 mile northeast of Soda Lake (Figure 4). The 44-5 well was actually drilled much more like a deep temperature-gradient hole with minimal casing and a small diameter than a intended production well to a measured depth of 5070′ to "test the shallow interpretation and a companion geologic model of a breccia pipe under Soda Lake" (Hill et al., 1979). The 44-5 well encountered temperatures only modestly above the regional background with a maximum temperature of only 244 °F and an overall linear temperature gradient of 3.8 °F/100′ with no indications of any nearby convecting thermal fluid (Figure 3). It is the coolest well ever drilled at Soda Lake. This should not have been surprising as the 44-5 well is located near the southern margin of the shallow thermal anomaly (Figure 2). Phillips drilled the 1300′ deep Orowitz deep temperature gradient hole in Section 19 (Figure 4) in the northwestern part of the thermal anomaly in 1977, again to evaluate their private land lease and encountered only a modestly elevated temperature gradient with a temperature of 142 °F at a depth of 1286′.

In 1978 and 1979 Chevron drilled five deep temperature-gradient holes within the central part of the thermal anomaly at Soda Lake to depths as great as 3500′ as part of the Department of Energy Industry Coupled Geothermal Development Program (Hill et al., 1979). None of these appeared at the time to have encountered a permeable part of the reservoir and the maximum temperature encountered was 380 °F in the 3300 foot-deep 36-78 hole (This number according to Chevron's numbering system was the 36th hole drilled in 1978, not a Kettleman location). Cuttings from the 1-29, 44-5, 11-33, and 63-33 wells were logged by Sibbett (1979) and correlated to show a horizontal stratigraphy not disrupted by any major fault offsets. This is in agreement with the flat surface topography. Sibbett's 1979 work was the first published paper to present an interpretation of the deeper geology at Soda Lake.

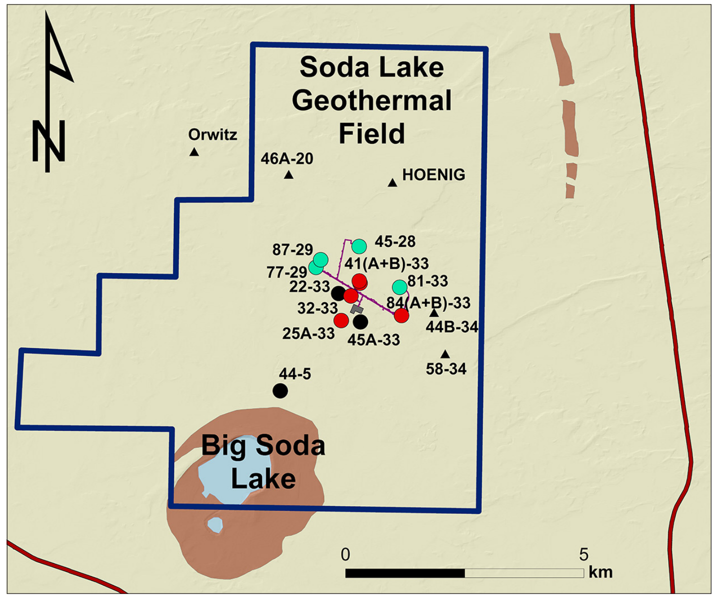

Figure 4. Map showing the locations of selected wells and holes at the Soda Lake geothermal field. Presently active production wells are shown as red circles, active injection wells as green circles, inactive wells mentioned in the text as black circles, and black triangles are selected deeper temperature gradient holes. Not all holes or wells are shown on this map. The 84-33, 84A-33 and 84B-33 wells are shown as one circle as are the 41-33, 41A-33, and 41B-33 wells.

In 1981 the most significant event in the development of Soda Lake occurred with the drilling of the vertical 8489 foot deep 84-33 well in the eastern part of the Soda Lake thermal anomaly. By this time it was recognized that the overall shallow Soda Lake thermal anomaly consisted of at least two separated deeper thermal anomalies (Benoit, 1980) and the 84-33 well was located between two encouraging deep temperature- gradient holes within the southeastern of the deeper thermal anomalies. The 84-33 well encountered a complete loss of circulation at a depth of 3378′ which was easily cured with two gell and lost circulation material pills. The zone was then cased off with 9⅝″ casing and the well drilled to its total depth with some 600 bbl/day circulation losses below a depth of 7911′. Temperature logs run after the well was completed showed abnormally rapid warming near a depth of 3400′. The 9⅝″ casing was later perforated between depths of 3252′ and 3498′ and the well was air lifted in Dec. 1981 and flowed unassisted at the rate of 255,000 lbs/hour with a fluid-entry temperature of 372 °F, marking the first produced fluid from the Soda Lake resource (Benoit and Butler, 1983). This first fluid production was eight to nine years after exploration first commenced. The bottom hole temperature of the 84-33 well was 397 °F (Figure 3) but no fluid was produced from below a depth of 3500′.

The successful flow test of well 84-33 immediately led to a (rather belated) air lifted stimulation of the 1-29 well which flowed at an unassisted rate of 231,500 lbs/hour. Unfortunately, in 1981 the flowing temperatures in wells 1-29 and 84-33 of 330 and 372 °F were viewed as being too cool for a flash-type power plant and binary power plant technology was not yet commercially available. A 31 day free flowing test of well 84-33 in mid-1983 showed that the well was subject to calcium carbonate scaling. After a scale cleanout the 84-33 well was again tested for a month in

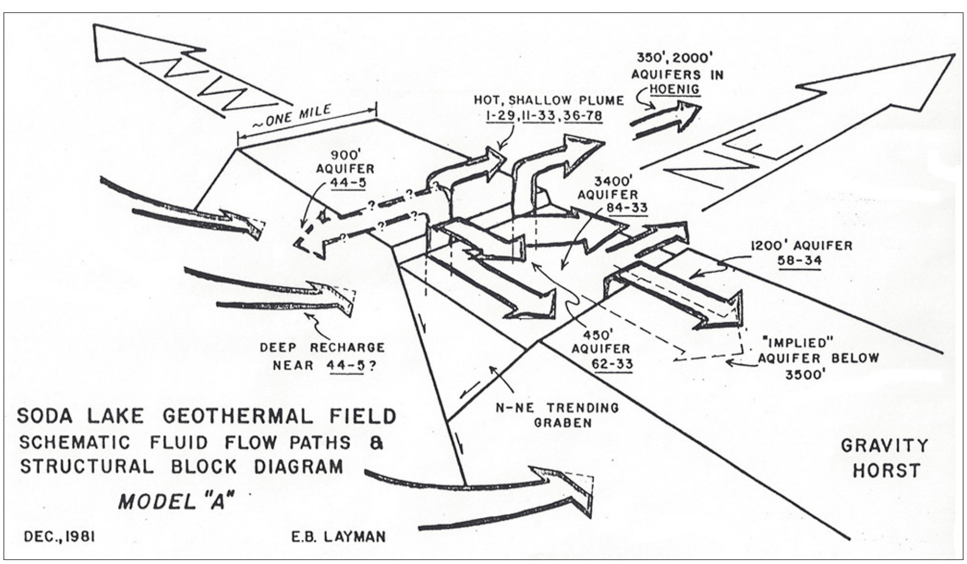

Figure 5. One conceptual Soda Lake fluid flow model from Layman (1982). A second slightly different model was also generated but is not presented here.

late 1984 utilizing Dequest as a downhole scale inhibitor. The 1-29 well produced a sodium chloride fluid with a pre-flash chloride content of 2450 ppm and the 84-33 well produced a fluid with a pre-flash chloride content of 3500 ppm, supporting the concept of multiple deeper thermal anomalies.

The successful flow testing of the 84-33 and 1-29 wells from laterally flowing aquifers at shallow to moderate depths led to the development of the first detailed conceptual flow models of Soda Lake showing a rather complex system of lateral flows at multiple different depths (Layman, 1982) (Figure 5). Although Figure 5 was constructed in 1981 it is quite similar to more recent unpublished conceptual flow paths developed by Magma Energy (US) Corp. on the basis of far more data. Dingwall (2013) also identified three discrete lateral flowing aquifers at depths between 350′ and 4500′ with a much larger data set of wells. What is amazing about all of the dense drilling at Soda Lake is the fact that none of the wells except for the remote 46A-20 show an isothermal temperature profile (Figure 3). There must be an upwelling zone with a temperature near 400 °F but it has yet to be located. If it is near-vertical it must have a very limited horizontal extent.

Following the 1984 flow test, Phillips Petroleum scaled back its geothermal efforts due to reduced oil prices and two attempted corporate takeovers by Boone Pickens and Carl Icahn. To fend off the takeovers Phillips had to raise cash which led to the sale of its Nevada geothermal assets at fire sale prices under the name of Western States to Chevron in early 1986.

Ormat and Chevron Soda Lake I Power Plant 1987 - 1989

After Phillips Petroleum departed the geothermal industry, Chevron and Ormat jointly developed the Soda Lake I power plant which started construction in early 1987 and commenced operations in late December 1987 (Ram and Kreiger, 1989). This project utilized the 84-33 well as a pumped 400,000 lb/hr producer to supply three Ormat Energy Converters making 3.6 MW (gross) and 2.75 MW (net) of power sold to Sierra Pacific Power Company (now NV Energy). Injection was into the 1-29 well located about 1.35 miles distant from well 84-33. Thus, the first two large diameter wells drilled at Soda Lake were proven commercial. The Soda Lake I power plant has a wet cooling tower using shallow groundwater for evaporation. The unevaporated water is eventually disposed of on the surface.

The Soda Lake I plant operated at annual net capacity factors of 76 to 77% in 1988 and 1989 (Figure 6). There were no resource problems such as cooling or injection limitations in 1988 and 1989. The Soda Lake I plant output was limited by the 9⅝″ production casing in the 84-33 production well which limited the size and setting depth of the downhole pump that could be installed. It did not take long after the Soda Lake I plant was determined to be a success for Ormat to begin planning a larger Soda Lake II project expansion.

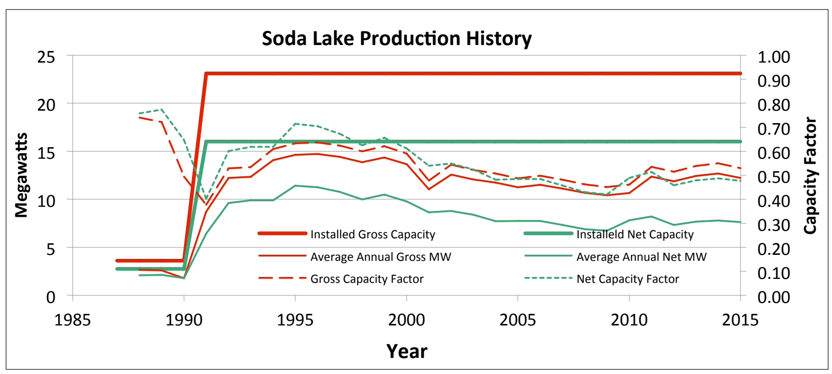

Figure 6. Combined production history of the Soda Lake I and II power plants. The Soda Lake II plant commenced operations in 1991.

The Soda Lake I power plant was expanded from 3.6 MW gross to 5.1 MW gross in 1990 with the addition of one more Ormat Energy Converter and one new cooling tower cell.

In 1990 an alternative interpretation of the geology of the Soda Lake field was published interpreting the various laterally flowing aquifers to be a single tilted layer of pumice tuff charged from deep within the Carson Basin (McNitt, 1990). This 1990 interpretation is incompatible with the earlier work of Sibbitt (1979) and Layman (1982) and with more recent work (Echols, et al., 2011, McLauchlan et al., 2011).

OESI Soda Lake II Power Plant 1990 - 2008

Ormat Energy Systems Inc. (OESI) commenced construction on the Soda Lake II project in late 1989 and transferred a second power purchase agreement to Soda Lake from Stillwater. This second power purchase agreement was blended with the Soda Lake I power purchase agreement into a single agreement. There appears to be no reservoir engineering documentation describing the rational for the size of the Soda Lake II project.

Between March 1990 and December 1991 the most intensive (and unsuccessful) drilling program ever undertaken at Soda Lake with two drilling rigs resulted in 15 new wells with depths between 885′ and 7350′. Six redrills were also undertaken during this time when the original holes did not encounter obvious adequate permeability. All of these OESI wells were drilled within a 1.5 mi^2 area, basically between the 1-29 and the 84-33 wells. Only seven of these OESI wells have seen long-term service as injectors or producers and two of these, 84A-33 and 84B-33, were drilled to within a few feet of the original 84-33 producing location to replace it with larger diameters wells capable of hosting larger and deeper set pumps. This was a far lower success rate than achieved by Chevron and Phillips, who did not precisely target the 1-29 and 84-33 wells as they were initially searching for a widespread resource hopefully capable of producing hundreds of megawatts. However, Chevron and Phillips had the advantage of plenty of time to understand and stimulate apparently unproductive wells while OESI had placed themselves in a position requiring immediate production and at times had two rigs operating simultaneously. The 81-33 OESI well required post completion stimulations (Ohren et al., 2011) to improve the permeability.

After Chevron and Phillips exited the project, the resource exploration and development personnel changed. There was no apparent attempt at any transfer of detailed local knowledge or experience and there were no technical papers published on the resource by OESI's staff or on site consultants. A few unpublished reports on the drilling and results of individual wells were prepared but no comprehensive resource-wide reports were prepared at that time.

In late 1990 the Soda Lake II plant was tested and commissioned into commercial operation in early 1991, almost a year before the OESI drilling program was completed in December 1991. The Soda Lake II plant consists of six Ormat Energy Converters with a gross generation capacity of 18 MW gross. The Soda Lake II plant is air cooled so it has a much greater annual variation in output than Soda Lake I.

The OESI drilling discovered the most prolific and shallowest resource at Soda Lake when a natural artesian flow of 370 °F water was found at a depth of 815′ in the 41-33 well. The 41-33 well was quickly twinned with the 1100 foot-deep 41A-33 well, which is currently the largest volume production well at Soda Lake. The 41-33 well was intermittently utilized as a pumped producer until 2000 when the submersible pump in the well failed. Well 41-33 was idle until Dec. 2009 when a temperature log showed the well to no longer have a liquid level and was full of steam. The pump was pulled from the well and a 2010 flow test demonstrated the 41-33 well to be capable of commercial steam production, which was not readily usable by the existing power plants.

Unfortunately, the OESI drilling program did not develop an adequate number of production wells to allow both power plants to operate at or close to full output, not did it leave behind a written and improved conceptual understanding of the results of the drilling and the overall resource. In 1992 and 1993 the average annual combined plant output peaked out at about 12.25 MW gross with a total plant capacity of 23.1 gross MW and 16 net MW (Figure 5). To increase the plant output OESI drilled one last well at Soda Lake, the 32-33 well, in late 1993. After a stimulation workover a production pump was installed in the well and in early 1994 the 32-33 well was placed in service. The 32-33 well was the hottest pumped geothermal well at Soda Lake and in the world between 1994 and 2005 at 380 °F and it brought the project output up to its all-time high annual average net output of 11.43 MW in 1995. This represented a net capacity factor of 71% (Figure 6).

From 1995 until 2009 the net plant output at Soda Lake declined more or less continuously to a low of 6.73 MW. This output decline was dominated by declining production well temperatures. Hanson et al. (2014) show the weighted average Soda lake production temperature declining from 370 °F to 332 °F between 1995 and 2009 with little or no change in the total flow rate (Figure 7). The amount of temperature decline amongst the individual Soda Lake producers was highly variable ranging from a low of 10 °F in the deeper 32-33 well to a high of 70 °F in the shallow 41A-33 well. To the extent possible, changes were made to the injection program to divert fluid from the 45-28 injection well, which was clearly causing the greatest cooling, to the other three injectors, 77-29 (formerly known as 1-29), 87-29 and 81-33, and this ultimately had a positive impact in both slowing and stopping the temperature declines after 2009. Now the 45-28 injector is seldom in service.

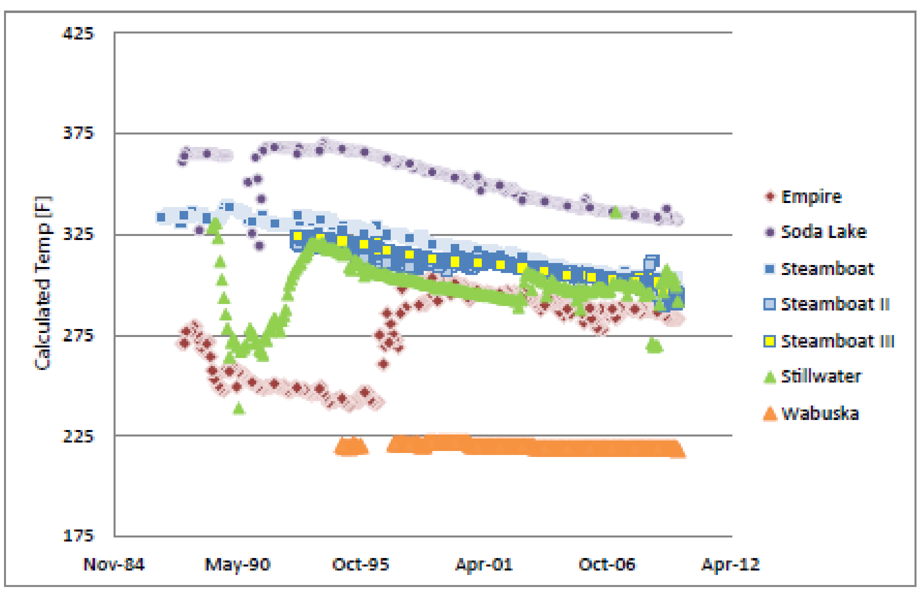

Figure 7. From Hansen et al., (2014) calculated weighted average plant inlet temperatures of selected Basin and Range binary geothermal projects. This figure shows that Soda Lake has had comparable cooling rates to other Nevada binary projects.

Due to the relatively low output and capacity factors the Soda Lake project did not meet the contractual obligations of the power purchase agreement and Sierra Pacific derated the power purchase agreement from 14.2 to 9.2 MW. This removed much of the financial incentive to drill additional wells to try to increase the plant output.

Constellation (1998 – 2008)

In 1997 OESI sold the project to Constellation and Harbert. Constellation had no geothermal resource staff so there was no transfer of detailed resource knowledge or experience. Under Constellation the 22-33 well was drilled as an intended production well in 2002 to try to stem the ongoing megawatt output decline (Figure 6). However, the 22-33 well was ultimately unsuccessful due to the collapse of the wellbore during testing. Attempts to repair and redrill the well were unsuccessful. At 66 days well 22-33 was the longest single well drilling effort at Soda Lake. The 22-33 well was abandoned so that the upper part could be reentered at a later date but there has been no appetite for this to date. Few other wells at Soda Lake took more than a month drill.

Magma Energy (US) Corp (ALTERRA) 2009 - 2014

Constellation and Harbert sold the Soda Lake project to Magma Energy (US) Corp. in mid-2008 at the beginning of the Obama administration when the geothermal industry started the beginning of a short boom, in part due to greatly increased U. S. Dept. of Energy funding of its geothermal program. Magma Energy paid $ 17 million for the project and enthusiastically tried to increase the plant output by refurbishing the above ground equipment, drilling new production wells, and improving the understanding of the resource. Again, there was no transfer of resource experience from Constellation to Magma and the initial Magma staff had no detailed prior Soda Lake resource experience.

Magma quickly drilled two expensive deep new wells in mid-2009 on a turnkey basis before any improvement was made to understanding the resource. The 41B-33 well (Figure 4) was drilled in a highly directional manner with major lost circulation difficulties through the shallow resource supplying the 41-33 and 41A-33 wells to a depth of 8995′. This makes it the longest, but not the deepest, well in the field. The 41B-33 well was targeted to cross a fault hypothesized from the 1977 vintage Chevron seismic survey. Whether it crossed any faults is uncertain, but it did not encounter any significant permeability below a depth of 2204′. The tactic of directionally drilling across faults has not generally been very successful in Nevada as the wellbore penetrates a minimal distance across the fault and permeability can be very patchy along faults. A better tactic is to try to keep the well within the fault for as long as possible but this requires a precise knowledge of the fault location and geometry. The bottomhole temperature in well 41B-33 was 350 °F which is 47 °F cooler than the temperatures in the 84-33 well at a similar depth (Figure 3) and probably not much above the regional background temperature at that depth. The unsuccessful 8995 foot deep 41B-33 well is completed almost directly beneath the 1-29 well (Figure 4). An extensive series of remediation efforts (Ohren et al., 2011) ultimately led to the well becoming capable of producing 336 °F fluid from between depths of 910′ and 1008′ and the well was placed in service as a shallow producer.

Magma also drilled the 4668′ deep 45A-33 well in mid-2009 and this well produced the highest temperature fluid yet documented at Soda Lake, 390 °F (Figure 3). The 45A-33 well encountered one large aperture fracture with complete loss of circulation at 4168′ (Ohren et al., 2011). Air lift testing of the 45A-33 well indicated it might be possible to install a pump and use it for production purposes. Heroic efforts were made to pump the well but it produced too little water at too high a temperature with repeated pump failures. The well was temporarily placed in service as an injector but tracer testing showed unacceptably fast returns to the 32-33 well, (Reimus et al., 2012, Rose et al., 2012) which is currently the hottest production well in the field, so the 45A-33 well was taken out of service. Only after the initial drilling of these two unsuccessful wells did Magma bring prior Soda Lake resource experience into its in house staff.

Magma Energy performed a comprehensive tracer testing program involving every active injector at Soda Lake starting in 2009. These unpublished tracer tests showed first return times of tracers ranging from 1-2 days to 29 days and peak return times varying from less than 5 days to over 200 days. These return times are similar to those seen in other Basin and Range geothermal fields. The tracer testing showed the field to be quite compartmentalized between eastern and western wells and that vertical separation between producers and injectors is more important in generating longer return times than horizontal separation. In June 2011 a tracer was injected into the 45A-33 well at a rate of 600 to 700 gpm but it returned to the 32-33 production well in less than 2 days. This rapid return was reconfirmed three months later when a research sorbing tracer test utilizing Safranin-T and a conservative tracer was performed between wells with a known short return time to develop a method for calculating the fracture surface area between the wells (Rose et al., 2012, Reimus et al., 2012).

In 2009 and 2010 Magma reprocessed existing gravity data and acquired a considerable amount of new precision gravity data within and outside of the operating field. Gravity data were recognized as being spatially associated with the silicified sand deposits on the surface, giving it a direct tie to the geothermal system (Echols et al., 2011). A more aerially extensive precision gravity survey then located two other shallow positive gravity anomalies suspected to be associated with shallow thermal anomalies located a mile to the east and a mile to the northwest of the gravity anomaly overlying the producing area (Figure 8).

These gravity anomalies led to the drilling of 6 temperature-gradient holes to a maximum depth of 1000′ in 2010 in undrilled areas to the east and northwest of the producing field. These areas had not previously been drilled due to, a lack of existing roads in sandy areas and the fact they were in BLM managed sections, requiring a greater permitting effort. A series of fortunately timed late summer thunderstorms temporarily stabilized the sand and allowed drilling without road improvements. These six new temperature-gradient holes confirmed that the two new gravity anomalies were reflecting the presence of geothermal fluids at relatively shallow depths and confirmed two new target areas for possible future development (Echols et al., 2011). These holes were drilled with either a drag bit or a long tooth mill bit over a period of two days each and cost about $20,000 per hole. They were completed with 2″ black iron pipe so that gamma ray logs could be run at a later date.

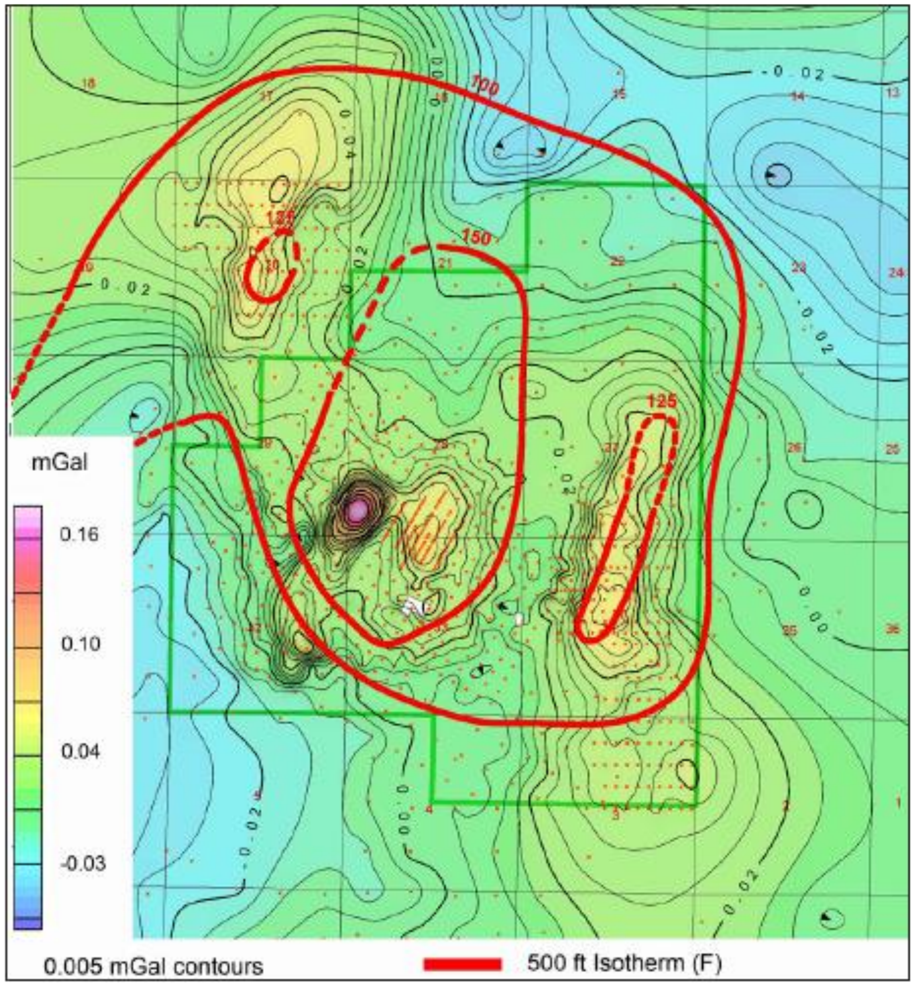

Figure 8. From Echols et al., 2011. Complete Bouguer gravity anomaly, 100 m – 50 m single-pole bandpass filter. The combination of tight spatial density and precision allows separation of fine, shallow details.

Based on these new temperature gradient holes Dingwall (2013) calculated heat loss values of 1.6 to 2.6 MW thermal for the eastern anomaly (Figure 8) and 1.7 to 2.6 MW thermal for the northwestern anomaly depending upon the assumed thermal conductivity. These heat-loss values are significantly smaller than the 7.3 to 10.0 MW thermal values for the producing central anomaly. In part, this is due to the fact that thermal fluids in the eastern and northwestern anomalies do not closely approach the surface (Figure 3) to create very high shallow temperature gradients as is the case in the central thermal anomaly.

After 16 months of permitting effort, Magma was able to run a 13 mi^2 3D reflection seismic survey in mid-2010 (Echols et al., 2011). This survey was partially funded by a grant from the U. S. Dept. of Energy under the American Recovery and Investment Act of 2009 which also included partial funding for the drilling of 4 new wells at Soda Lake. The 3D seismic survey forced Magma to completely reassess the geological understanding and interpretation of the area to constrain the seismic results. The seismic survey was designed to best image the 3000 to 4000 foot depth range and the top of a basaltic unit near a depth of 2000′ was expected to be the strongest reflector. However, the strongest and most continuous reflector(s) turned out to be near a depth of 800′ in poorly consolidated uppermost Tertiary lacustrine sediments. The top of basalt contact was discernable outside of the producing field, but not within it. Within the producing geothermal field little was imaged but outside of the field it was possible to correlate the shallow reflectors with units defined and correlated on gamma ray logs and present a reasonably coherent subsurface picture of the geology (Echols et al., 2011). The survey did image several probable faults with small offsets passing through the known production area and the outlying thermal and gravity anomalies (Echols et al., 2011). If the seismic data were able to discriminate between permeable and impermeable sections of the fault, it was not recognized in the interpretation. Without having abundant drilling information to constrain the seismic survey interpretation the results would likely have been considerably different than those presented by Echols et al. (2011). Dingwall (2013) reevaluated the seismic data utilizing a similarity attribute method and came up with a more or less the same interpretation as Echols et al. (2011).

In mid-2010 Magma drilled its third and last large diameter deep well at Soda Lake, the 6000 foot-deep 25A-33 well. When completed, the 25A-33 well would only accept 150 gpm of water at an injection wellhead pressure of 400 psi (Ohren et al., 2011). This led to a series of deflagrations and periods of gradually increased injection. After many months of utilizing the 25A-33 well as an injector, the injectivity increased to the point that a production pump was installed in the well in January 2016 and the well is now producing 1000 gpm of 329 °F fluid to the power plant with only a tiny impact on its nearest neighboring producer, well 32-33.

In 2011 Alterra put the 41-33 well back into production in an innovative and unique fashion. As the well was now producing saturated steam it could not be utilized in the existing plants. Instead a side stream of the injection fluid has been routed to a series of heat exchangers by the 41-33 wellhead and the steam from well 41-33 reheats the injectate and it is pumped back into the main production line upstream of the power plant for a second pass through the heat exchangers.

Following the interpretation of the seismic survey Magma changed its name to Alterra due to a merger with Plutonic Resources and drilled two slim holes or deep temperature-gradient holes to further evaluate the outlying thermal and gravity anomalies (Alterra, 2012). The 44B-34 slim hole was drilled a half mile east of the 84-33 well (Figure 4) to a depth of 3342′ over 24 days in September 2011 at a cost of $589,000. This relatively high cost included building a pad and sump large enough for a 13⅜″ diameter well to be drilled, fighting lost circulation and setting three cement plugs in a major permeable zone below a depth of 895′ with a temperature near 175 °F (Figure 3). Below a depth of 2000′ the temperature gradient is linear and temperatures near 350 °F could be present at a depth of 4100′. The 44B-34 hole could be deepened and the shallow permeable interval may have potential as a future injection zone but no testing has been performed to further evaluate this possibility. A fluid sample collected from the shallow 44-34 temperature-gradient hole near a depth of 750′ had a chemistry more or less identical to fluids produced from the Section 33 wells (Alterra, 2012). The 44B-34 static temperature profile was a challenge to model (Dingwall, 2013) due in large part to the convective character of over half of the profile (Figure 3) and required a flowing period of about 15,000 years in the nearby fault.

The 46A-20 slim hole was drilled by Alterra to a depth of 3664′ over a period of 13 days with no significant problems at a cost of $394,000. Below a depth of 1600′ the 46A-20 hole had isothermal temperatures of 298 °F (Figure 3), which happens to be the current production temperature of the 41A-33 well, the largest volume production well at Soda Lake. Dingwall (2013) interpreted the 46A-20 temperature profile as being roughly 500′ east of a fault transmitting thermal fluid upward for the past 4000 years. It is quite remote, being over a mile northwest from any of the other wells (Figure 4) and could potentially be a separate resource. No fluid samples have yet been recovered from this area.

Dingwall (2013) concluded that the Soda Lake field has a relatively complex flow system, which is in agreement with the earliest conceptual model of Chevron (Layman, 1982) (Figure 4).

Following the drilling of the 44B-34 and 46A-20 slim holes, Alterra decided to exit the United States geothermal business and did not continue its participation in the Dept. of Energy grant program. None of the four intended large diameter wells were ever drilled.

CYRQ 2015 - 2016

In January 2015 Alterra sold the Soda Lake project to CYRQ Energy for $8.5 million, half the price it paid for the project in 2008, so Alterra could focus on other alternative energy technologies. During 2013 and 2014 Alterra made no significant expenditures on the project as it was in the process of being sold.

In 2015 CYRQ reevaluated the injectivity of the 25A-33 well and determined that the permeability had improved to the point that the risk was acceptably low in funding the installation of a production pump to determine if the well would now be capable of a commercial volume of sustainable production. In January 2016 CYRQ installed a production pump in the 25A-33 well and the well has since remained on line as a 1000 gpm producer with a gradually increasing temperature of 328 °F (as of the time of preparation of this document) (strongly impacted by previous long-term injection into the well). The injection depth of fluid in well 25A-33 was just below 5000′ and the production zone depth(s) are below 4160′, giving 25A-33 the deepest fluid-entry depth of all the actively producing wells. Only the now idle 45A-33 well produced from comparable depths.

Discussion

Over the 44 years from 1972 to 2016 that saw the exploration, development and long-term production of the Soda Lake field the geothermal industry has undergone huge changes and improvements that have allowed the field to be developed and understood. Some obvious lessons stand out in this long case history of Soda Lake, some interesting or good and some painful learning experiences.

During the 1970s the geothermal industry, the U. S. Geological Survey, and academia had no real understanding of geothermal resources in the Basin and Range province. The Basin and Range geothermal systems were an exploration laboratory for all sorts of geological, geochemical, and geophysical exploration techniques and strategies. Soda Lake was a part of this learning process, despite being the subject of very few publications. A number of primitive geophysical surveys were run at Soda Lake in the 1970s but only the temperature information has provided lasting long-term insight into the overall resource. Geophysical techniques, such as ground noise and roving dipole, that have long since been discredited, were tested at Soda Lake. Fortunately, Chevron and Phillips relied far more on the temperature information and that led to two of the first three wells being utilized for production and injection. The one unsuccessful early well, 44-5, in hindsight appears to have been drilled to test a questionable geophysical and geological interpretation rather than to penetrate a geothermal resource.

It is unlikely that the Soda Lake field could have been successfully developed as a flash-type project in the 1970s so the slow pace of early development between 1974 and 1987 was justified while the binary geothermal power plant technology was being developed.

The Soda Lake I power plant with one producer and one injector 1.35 miles apart and with good vertical separation between them was very successful, not overly taxing on the resource, and would likely have been sustainable for many decades. But at 2.75 net MW it was simply too small to be commercially viable. OESI deserves credit for moving ahead with the rapid expansion of Soda Lake II. However, the strategy of focusing efforts on starting construction of the plant first and then starting to drill out the field led to numerous dry holes with the overall project never operating at a net annual capacity factor above 71% and barely exceeding 50% in only one of the last 15 years. An alternative interpretation to this argument could be that without OESI's determination to simply forge ahead any sized expansion would never have occurred. There has to be a more optimal and cost effective middle ground in timely resource assessment than was shown during the development of Soda Lake II. It is uncertain as to how many of the unsuccessful OESI wells believed to be impermeable might have been usable given time to perform additional stimulations or workovers. Some of these wells have already been abandoned.

Following the commissioning of Soda Lake II there was minimal involvement in the project by resource specialists from 1992 until late 2009. Between 1984 and 2011 only one paper was published on the Soda Lake resource (McNitt, 1990) and the basic geology conclusions of that paper have not withstood the test of time. Between 1995 and 2009 resource cooling reduced the average annual net megawatt capacity factor from 71% to 42%. The only well drilled during this time, the unsuccessful 22-33, was drilled by Constellation and was intended to be a producer, when the field clearly had an injection problem. This is a prime example of outcomes when resource specialists are not regularly involved in the field management and preparing written documentation of the field resource performance. The cooling was ultimately reduced to a minimal level by 2009, but at the loss of up to 42% of the projects annual net MW sales.

In 2009 Magma Energy (US) Corp. repeated some of the previous missteps by drilling two wells within the field without first performing any kind of overall review or assessment of the resource. One well was drilled over 7000′ beneath the reservoir at great cost, in part due to the well being drilled on a turnkey contract, wherein the drilling contractor is responsible for the drilling operation. A geothermal resource development company must be capable of both in house drilling management and resource assessment to be successful, or must have an exceptionally large and easy to develop resource.

Most Basin and Range geothermal systems have quite restricted areas where the hottest fluid is rising from depth along faults or fractures and it is in these locations where the hottest and most permeable wells are generally easily located. Great costs have been expended to locate such an upwelling zone at Soda Lake. The deepest production prior to the 25A-33 well being put on line in early 2016 came from a depth of 3910′ in the 32-33 well where production temperatures were initially 380 °F. A total of 15 wells and redrills have been drilled to 4000′ or deeper in a search for hotter and/or more productive wells with only the 45A-33 well temporarily producing 390 °F fluid in 2010 and the 25A-33 well to show for the overall effort. Obviously, this has been a source of frustration for all of the Soda Lake operators but it still offers the possibility of stronger future wells, if the upwelling zone can be located.

Magma Energy (US) Corp. placed a big bet on 3D seismic in improving the understanding of the Soda Lake resource. However, at the end of the day, the existing subsurface geological information ended up being utilized to constrain and support the seismic interpretation, rather than the seismic results leading to new or updated geological interpretations. And this is in one of the few areas in the Basin and Range province where 3D seismic reflection surveys can be reasonably expected to provide credible images. Many 1000′ deep temperature gradient holes or four slim holes could have been drilled within a fraction of the two years and the $1,314,000 budget required to design, permit, process, and interpret the 3D seismic results.

The first unpublished numerical modeling effort at Soda Lake occurred in 2010 and was performed by an outside consultancy with the intent of public fund raising. To date this model has played no role in siting wells or in actively managing the resource. Had a numerical model been developed earlier in its history, the Soda Lake field development history might have been different as the modeling process should have exposed data gaps and weaknesses in the initial interpretations, perhaps leading to the development of improved data collection and conceptual understandings of the resource. However, if the modeling is quickly done by an outside consultant with limited existing data to satisfy financial issues it would probably not have changed the development history.

Perhaps the most significant criticism of past development at Soda Lake comes down to a case of target fixation. Within a 1 ½ mi^2 area a total of 22 wells with six redrills and 4 deep temperature gradient holes have been drilled. One well was drilled near the southern edge of the thermal anomaly and only three deep temperature-gradient holes have been drilled within the $\pm$20 mi^2 of thermal anomaly outside of the 1 ½ mi^2 core area. It was particularly egregious that to the east of the 1981 84-33 discovery well not a single hole to any depth had been drilled as of 2010. Fifteen years after production began declining in 1995, a review of possible targets outside of the core area was begun by Magma. Since the late 1970s temperature information has been available to show that the Soda Lake prospect consisted of a central core with potential surrounding targets (Figure 2). There are multiple reasons and excuses why these more remote targets were ignored for almost three decades by a variety of project operators but at the present time one has to wonder if the areas targeted and partially tested by the 46A-20 and 44B-34 slim holes really represent potential undeveloped resource and what the current field layout might look like had a small fraction of the money spent on unproductive wells in the core area been redirected to evaluating a larger fraction of the overall thermal anomaly.

Lastly, the Soda Lake geothermal field has been unique in the Basin and Range province with most of the production and injection wells requiring post-drilling completion analysis and remediation to develop commercial permeability. In a rushed development scenario one has to ask the question as to how many of the past unsuccessful wells drilled might have been commercially viable given time to perform additional post-completion work? The current field layout at Soda Lake is rather unique in Nevada in that there are no real clusters of concentrations of injectors and/or producers. Production is from and injection is into a good variety of differing depths and formations. The production is not from or dependent upon a single narrow structure. At the present time the temperature declines are minimal to nonexistent so after 28 years of production this field still has a future. If production and/or injection can be extended to the east and northwest there is a definite possibility of significantly expanding the output.

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