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"A 3D-3C Reflection Seismic Survey and Data Integration to Identify the Seismic Response of Fractures and Permeable Zones over a Known Geothermal Resource: Soda Lake, Churchill County, Nevada."

1. Introduction

Magma Energy (U.S.) Corp. (Magma) received an award through the American Recovery and Reinvestment Act of 2009: Geothermal Technologies Program, Topic Area 1: Validation of Innovative Exploration Technologies. In the eighteen months since pre-award spending authorization, the tasks in the Statement of Project Objectives are substantially complete. Two step-out targets one-half to one mile outside the known production and injection areas are identified and proposed for Phase II drilling.

Magma undertook a 3D-3C seismic survey to better understand the geology and structures in the field and their control over the geothermal resource. Seismic data can, as it has in the oil industry for many years, show structure and offsets in stratigraphic layers and aid in well targeting. The technique has not been in wide use in the geothermal industry because most geothermal reservoirs are in a non-layered volcanic stratigraphy with a paucity of clean reflective surfaces that are critical to interpreting seismic data. A 1500 ft to 2000 ft thick near-surface sequence of sedimentary rocks at Soda Lakes offers one of the few places in Nevada where a seismic survey should be capable of providing quality data on sub-surface structures associated with an extensively drilled geothermal system. Four 1970s-vintage 2D seismic lines showed that coherent reflectors are present in the Soda Lake area, making this a viable candidate field for a 3D-3C survey.

Location

The Soda Lake geothermal field is located in the south central part of the Carson Sink, about six miles northwest of the town of Fallon (Figure 1). It is literally surrounded by other operating geothermal fields such as Desert Peak, Bradys, Stillwater, and Salt Wells. Press releases indicate a new power plant is being planned at the Patua (Hazen) site 10 to 15 miles west of Soda Lake.

Soda Lake Geothermal Project History

The presence of an extinct fumarole or an area of steaming ground, small and scattered amounts of silica cemented Quaternary alluvium, and the young Soda Lake and Upsal Hogback volcanic features led the U. S. Geological Survey (USGS) to classify the Soda Lake area as one of the original Known Geothermal Resource Areas in 1971. The USGS did a hydrogeologic appraisal of the area in the early 1970s (Olmsted et al., 1975) which included 23 small diameter test holes, most less than 100 ft in depth.

In 1972 Phillips Petroleum Company and Chevron, occasionally as partners and sometimes as competitors, began geothermal exploration efforts at Soda Lake, primarily focusing on the drilling of shallow temperature-gradient (TG) holes up to 500 ft deep. Eventually, 36 TG holes were drilled to depths of 450 ft to 500 ft deep over an area of 35-40 mi^2 (Figure 2). The Phillips and Chevron holes were located on the odd numbered private land sections. The few deeper USGS holes are on the even-number Federal Sections.

The TG holes outlined a roughly circular thermal anomaly covering an area of about 20-25 mi^2 whose heart is aligned NNE-SSW along a hypothesized structure connecting Soda Lake and Upsal Hogback (Olmsted et al., 1975). The first well, Soda Lake 1-29, now known as 77-29, was jointly drilled by Phillips and Chevron to 4306 ft in December 1974 in a convenient location on private land near the highest shallow temperatures. This well encountered only modest lost circulation between 954 ft and 1025 ft and had a maximum temperature of 342°F that was not then usable for flash-type production. Well 77-29 was not properly flow tested until 1981.

Following the apparent lack of success of the 77-29 well, Chevron and Phillips performed further geophysical exploration, including a four-line seismic survey by Chevron (Hill et al., 1979). Between 1976 and 1980 seven small diameter holes with depths from 1300 ft to 3500 ft were drilled to better define the deeper thermal structure of the area (Figure 2).

Chevron drilled the small diameter 44-5 well to a depth of 5000 ft in 1977. Well 44-5 was drilled south of the known shallow thermal anomaly to test a seismic feature. It encountered a bottom hole temperature of 244°F making it by far the coldest deep well drilled at Soda Lake.

In May 1981 Chevron and Phillips completed the 8489 ft deep 84-33 well. This well is 1.35 miles SE of well 77-29 in an area of more modest shallow temperature gradients that were anticipated to continue to depths of at least a few thousand feet. Well 84-33 encountered modest lost circulation between 3300 ft and 3400 ft which was easily put behind cemented casing. It did not encounter any deeper permeability, but had a maximum temperature of 397°F at 8100 ft, the hottest yet measured at Soda Lake. After the cemented casing covering the 360°F permeable zone was perforated, the 84-33 and 77-29 wells were successfully flow tested in Dec. 1981. These two wells were utilized by Ormat and Chevron as the sole production and injection wells for the 3.6 MW (gross) Soda Lake 1 binary power plant which commenced operations in Dec. 1987 (McNitt, 1990).

The Soda Lake 1 power plant and wellfield operated successfully so Ormat quickly started developing the 18 MW (gross) Soda Lake 2 project and an additional 1.5 MW (gross) at Soda Lake 1. Ormat drilled 15 consecutive wells and two redrills at Soda Lake between March 1990 and June 1991. Unfortunately, these Ormat wells were all basically located between the earlier 84-33 and 77-29 wells and only seven of them were attached to the gathering system for long-term utilization. OESI Power did not develop adequate fluid to operate both power plants at full output and drilled its last, and successful, well, 32-33, in October 1993 before selling the project to Constellation Energy. Constellation drilled one new unsuccessful well, 22-33 and its redrill, in 2002. Magma Energy (U.S.) Corp. purchased the Soda Lake project from Constellation in 2008 and drilled three deep wells in 2009 and 2010 within the existing field. One side effect of the very rapid early expansion at Soda Lake is that the natural pressure state of the field was never adequately characterized and its overall pressure history is poorly documented and poorly understood.

The fact the power plant has never reached its nameplate output simply confirms the geothermal resource has proven difficult to understand and develop. Twenty-three large diameter wells and six redrills have been completed to date but only five wells are being utilized for production and five for injection. Several other wells were briefly tested or utilized for injection or production purposes but for multiple reasons including limited permeability, inadequate depth, improper completion, etc. did not provide long term service. The overall drilling success rate of 34% (including the redrills) is abnormally low for a Basin and Range project. The 33%, redrill success rate (2 out of 6) is also equally low. The low success rate is in large part due to the absence of a detailed understanding of the resource. In hindsight, it is amazing that two of the first three widely spaced wells drilled were successful given the simplistic understanding of the resource at that time. They were simply drilled near the central part of the shallow thermal anomaly.

2. Geology

Regional Geology & Tectonic Environment

The Soda Lake geothermal field lies directly between the ±10,000 year-old Big Soda Lake volcanic explosion crater, and the mafic Quaternary Upsal Hogback volcanic complex (Figure 1). These 3 features define a narrow NNE trending 11 mile-long feature that presumably is the surface expression of a buried deep-seated feature. The surface of the Carson Sink is covered by Quaternary alluvium, sand dunes, silt, and a large playa surface. There are only four small and widely scattered outcrops of Tertiary or Quaternary mafic volcanic rocks within the Carson Sink, which is the widest valley in Western Nevada. Geophysical techniques best define the regional structural setting of the Soda Lake area.

The southern part of the Carson Sink is bounded to the northwest by the low relief and irregularly shaped Hot Spring Mountains and unnamed hills southwest of Patua (Figure 1). To the south of the Carson Sink, the Dead Camel Mtns., White Throne Mtns., Blowsand Mtns., and Bunejug Hills define an irregular and generally low relief margin. Only the Stillwater Mountains to the east of the Carson Sink have high relief and a classical northerly to northeasterly trending linear and steep range-front. The Carson Sink defines a major change in topography from the classical Basin and Range mountains and valleys to the east to the lower relief and irregular topography typical of far western Nevada. These surrounding lower relief ranges are composed primarily of Miocene and Pliocene mafic lava flows, tuffs and lacustrine sedimentary rocks which vary considerably from range to range. Exposed thickness of these rocks in the surrounding ranges is at least a few thousand feet. Various formation names from the surrounding ranges such as Bunejug and Chloropagus basalts, Truckee Formation, and Desert Peak Formation that have been utilized in individual ranges. McNitt (1990) extrapolated these names to units in the Soda Lake area but, there is little chance that this past and informal nomenclature is meaningful or correct.

Beneath the Miocene mafic rocks in the surrounding ranges there is a variable sequence of Miocene and Oligocene rhyolitic ash flow tuffs which can be the oldest rocks exposed in the individual ranges. Rarely are there small outcrops of pre-Tertiary rocks, such as shale or greenstone and a few small outcrops of intrusive rocks which define the deepest basement of the region. These basement rocks have been penetrated in the 81-33 and 84-33 wells at depths of 7500 and 7800 ft, beneath 3000 to 4000 ft of Tertiary volcanic and sedimentary material.

The Soda Lake geothermal field is located on top of a gravity high defining a semi-circular ridge or ring about six miles across (Figure 3). Hill et al., (1979) with a much smaller gravity data set described the field as being on the east rim of a two mile-wide circular low. Gravity anomaly shapes near Soda Lake are more representative of the irregular topography currently surrounding the southwestern part of the Carson Sink than of classical NNE trending basin and range topography. Deeper drill holes in the Soda Lake area, with the exceptions of well 81-33, which reached pre-Tertiary sedimentary rocks, and well 84-33, which terminated in granite, were completed in Tertiary volcanic rocks. This suggests the gravity high represents a relatively shallow buried Tertiary volcanic basement surface covered by Quaternary sediments of the Carson River delta, NE of Lahontan Reservoir, and the Pleistocene-age Lake Lahontan. On a more detailed level the Soda Lake resource lies within the northwest trending portion of this gravity high. The Soda Lake field is the only geothermal system associated with this buried gravity high.

The Walker Lane, a region defined by northwest-striking, right lateral strike-slip faults, is recognized as being the easternmost expression of lateral motion between the North American and Pacific plates and accommodates $\pm$20% of the dextral motion between the two plates. The northern edge of the Walker Lane has historically been viewed as being located seven or eight miles southwest of the Soda Lake geothermal field (Hill et al., 1979). There are no mapped surficial indications of the Walker Lane's presence south of Soda Lake (Figure 1). The poorly defined and little-studied Sagouse fault zone (Adams and Sawyer, 1999) is located sub parallel to the Walker Lane and passes through the Upsal Hogback area several miles north of the Soda Lake geothermal field (Figure 1). This opens the possibility that the Soda Lake field could be within an outer fringe of shear along the Walker Lane.

Faulds, et al. (2006) propose that most of the operating geothermal fields in Nevada result from transfer of NW-trending dextral shear in the Walker Lane to WNW extension in the northern Great Basin. Enhanced extension favors dilation and pull-apart basins which are prospective environments for geothermal resources. Possible comparable structural analogues for Soda Lake may be found at the Needles Rocks at the NW end of Pyramid Lake and Salt Wells in the southeastern corner of the Carson Sink (Faulds et al., 2006). Obviously, much additional analysis is needed to develop a comprehensive regional structural model(s) of the local Soda Lake area.

Local Geology

The sub-surface geology of the Soda Lake geothermal field has not been updated in the public literature since 1990. The surficial geology of unconsolidated sand dunes and lacustrine deposits at Soda Lake has been mapped and described (Morrison, 1964) but provides little insight on the sub-surface geology pertinent to the geothermal resource. The public sub-surface record contains only four reasonably detailed lithologic logs developed by one person who correlated a lacustrine package across four of the Soda Lake holes between depths of 670 ft and 1010 ft (Sibbett, 1979). Sibbett was unable to make any shallower lithologic correlations but made two deeper correlations; a lithic arkose unit between depths of 1210 ft and 1370 ft in the producing part of the field, and the top of a basaltic unit near a depth of 1900 ft between two holes in the central part of the field. Sibbett's 1979 correlations indicate a nearly horizontal stratigraphy to a depth of 2000 ft. There is no indication that Sibbett utilized downhole geophysical logs in preparing or refining his lithologic logs.

McNitt (1990), with a larger selection of then existing wells noted that "the wells were logged by a number of different geologists, using different logging criteria and methods" so he used only downhole gamma, sonic, resistivity, and density logs to correlate sub-surface units between four holes in the field. These interpreted log correlations show offsets of thousands of feet between the nearby 77-29 and 11-33 wells that Sibbett (1979) horizontally correlated, providing much different structural interpretations.

During the past two years Magma has made a concerted effort to improve the basic understanding of the geology by performing additional geophysical surveys and analyzing and integrating a significant volume of geophysical log information from the files. This review confirmed the lack of confidence in the quality of the original lithologic logs from the wells (McNitt, 1990). Consequently, Magma is funding a geology graduate student at the University of Nevada Reno to review the cuttings, most of which have been preserved at the Nevada Bureau of Mines and Geology. However, this work will not be completed for at least another year and explains why this report is notably short on geological nomenclature and formation descriptions.

Lithologic Correlations

Since the early work of Sibbett (1979) and McNitt (1990) gamma and resistivity logs have been obtained from numerous additional wells at Soda Lake to depths between 500 ft and 9000 ft. Magma digitized the pre 2009 geophysical logs, created paper strip charts so that any pair or combination of logs or wells could be conveniently compared at the same scale, and then correlated a variety of features on the 25 gamma and resistivity logs with some assistance from lithologic and self-potential logs. Occasionally a sonic or density log was available to provide some additional support but the bulk of the field-wide correlations are based on the gamma ray logs. These logs show the detailed Soda Lake stratigraphy is composed of many dozen to perhaps hundreds of units, most with thicknesses ranging from a few feet to tens of feet. Many different units are recognizable and correlatable on these logs but only 15 of these correlations or surfaces are presented in this report.

Pairs of logs available from closely spaced wells such as 84A-33 and 84B-33 or from original wells and redrills such as 64-33 and 64-33 RD, and 11A-33 and 11A-33 RD show both very detailed correlations and a surprising amount of variability. In the eastern part of Section 33 and in Section 28 there are obvious correlations and repeatability in the gamma and resistivity responses between nearby wells or redrills at similar depths over the entire length of the holes. Figures 4a and 4b show detailed examples of 15 correlations or surfaces across the central part of Section 33. Often individual gamma spikes and even the shapes of spikes can be correlated.

In the northwestern part of Section 33 and in Sections 29 and 20 correlations, even at depths of hundreds of feet, are more tenuous. In traversing across the field the character of individual correlations often show gradational changes in character. The strongest correlations involve using both the gamma and resistivity logs (not presented in this report) but only rarely do these differing physical responses show changes or inflections at identical depths. The correlations are most convincing when a sequence is repeated over depths of a few hundred feet. Fortunately, there are multiple packages of correlatable features spread out over most of the drilled depths to provide confident correlations. There are convincing correlations from depths as shallow as 50 ft to as deep as 4000 ft across the southern, eastern, and northern parts of the drilled area. Correlations are fewer in number and have greater vertical offsets in the western part of the area that contains wells 41B-33, 32-33, 22-33, 11A-33, 77-29, and 87-29. Multiple solid correlations have been made to depths below 6000 ft only between the 84-33 and 81-33 wells, in part due to a paucity of wells deeper than 5000 ft. As a general observation, wells in the northwestern part of Section 33 and in Section 29 correlated more cleanly with the Section 28 wells than with wells in the eastern part of Section 33.

From the surface to depths of 1550 ft to 1800 ft the geology consists of layered unconsolidated Quaternary and perhaps Pleistocene sediments deposited as part of the Carson River delta and Lake Lahontan mud (Morrison, 1964, Sibbett, 1979). These soft deposits are most rapidly drilled with a drag bit. Convincing correlations extend to the most outlying wells such as 62-28, 58-34, and 44-5 and to four recently drilled shallow TG holes (Figure 2). This stratigraphy is as laterally continuous as geology is ever likely to be in a Nevada basin. Elevations of five sharp and widely recognizable gamma ray surfaces between depths of ±200 ft and ±1650 ft show a maximum relief of about 200 ft, indicating no more than 200 ft of vertical offset of these layers since they were deposited in the last several hundred thousand years (Figures 5 & 6). Closely spaced pairs of wells such as 84A-33 and 84B-33; 41A-33 and 41B-33; 77-29 and 87-29; 25-33 and 25A-33; and 45-33 and 45A-33 have offsets of tens of feet to perhaps 200 ft of some surfaces so these small offsets appear common. This is also reflected in the often irregular or inconsistent plan view contouring of the surfaces (not presented in this report). One of the most striking correlations as defined between surfaces 5 and 6 on Figure 4a is informally referred to as the four peaks unit after its gamma ray logs in the eastern part of Section 33.

Between depths of 1470 ft and 2190 ft the top of a very prominent basaltic unit is present as surface #7 (Figure 4a). The top of this basalt unit in some wells can be surprisingly ambiguous to pick from just the gamma ray log. The top of the basalt surface shows a maximum relief of 713 ft, about 3x greater than any of the six shallower surfaces (Figures 5 & 6). The bottom of this basaltic unit is the most obviously recognizable feature on most of the gamma and resistivity logs and that surface has a relief of 2045 ft between depths of 1680 ft and 3725 ft and is shown as Surface #8. This basalt has the general shape of a downward pointed cone about one mile-wide at its upper surface. The sedimentary and volcaniclastic units immediately above the basalt thin and thicken rapidly reflecting the progressive burial of a hilly basaltic topography.

In the upper part of the basaltic unit there is a sharply defined high gamma ray interbed from 20 ft to 70 ft thick whose upper surface shows an elevation difference of only 150 ft across the field area at depths near 2000 ft (Figure 4b). This is the deepest nearly horizontal correlation. This high gamma ray interbed separates deeper more homogenous basalt from shallower more variable basalt. It is the more variable shallower basalt which forms the buried topography representing constructional features such as cones, domes, or flows. The basalt has by far the greatest thickness variation of any unit present at Soda Lake. The thickest basalt is highly concentrated within a one square mile area in the north half of Section 33 and the south half of Section 28. The basalt is absent in outlying wells such as 44-5 (Sibbett, 1979) or the 2000 foot deep Hoenig Strat Test and appears to be only 10 ft thick in the 58-34 well. The vent area(s) for the basaltic unit have not been identified.

Beneath the basalt the stratigraphy was more difficult to initially correlate between wells but there are multiple convincing correlations that can be made across the field with depth offsets up to 2000 ft that generally parallel the bottom of the basalt (Figures 4b, 5 & 6). The thicknesses of formations between some selected surfaces below the basalt show modest variations across the field but isopach contours of the different layers (not presented in this report) do not show a consistent pattern. There is one obvious consistent pattern with the 62-33 and 64-33 wells showing sub-surface elevations ±200 ft higher than wells to the east and west at all depths below the basalt, suggesting a small north-south trending horst like feature is present. These log correlations show that very similar stratigraphic sections are present in the area beneath the thickest known basalt as well as in areas of thin basalt. The increased thickness of basalt does not come at the price of local elimination of a significant part of the deeper stratigraphy. This indicates that the basalt is filling in some type of down-dropped block that is close to equidimensional in shape.

The best deep correlations at Soda Lake that have yet been made are between wells 81-33 and 84-33 where a package of rocks between about 5400 ft and 6400 ft has several convincing correlations offset less than 10 ft. Deep correlations between 81-33 and 84-33, and the other deeper wells (i. e. 41B-33 below 5700 and 25A-33 below 3500 ft) have not yet been made. It is possible some deep correlations can or will be made but such correlations are not likely to be useful in drilling wells to shallower targets. The Magma correlations are much different from those provided by McNitt (1990).

The most questionable correlations at Soda Lake involve the 22-33 well below a depth of about 1650 ft. Only a gamma ray log is available from well 22-33. There appears to be an exceptionally thin basalt unit in this well relative to its closest neighbors. Unfortunately, the lithologic log does not even mention basalt in the depth interval where the gamma log indicates its presence. As no drilling is proposed in the vicinity of the 22-33 well this complication or inconsistency is not further addressed in this report.

Outside of the immediate Soda Lake field area the deep drilling record consists of only the 5069 ft deep 44-5 well located 1.4 miles SW of the Soda Lake 2 plant and the 8502 ft deep Carson Sink #1 located five miles SW of 44-5 (Figure 1). Both of these wells have much thicker Quaternary deposits than are found in the Soda Lake geothermal field (Sibbett, 1979).

Generalized Geologic History

Based on the gamma ray interpretation a generalized geologic history of the Soda Lake geothermal field involves the development of a pre-Tertiary surface that was not necessarily flat (Figure 7). Volcanic and sedimentary rocks were deposited on top of this surface in a locally layered sub horizontal sequence. At some point in the Pleistocene (?) there was a rapid down-dropping by up to 2000 ft of a small block on the order of a square mile or less. This down-dropped basin was then at least partially filled in with a homogenous basaltic flow or sequence and a short-lived lakebed was deposited across most of the field area. Basaltic volcanism then resumed with the development of constructional features and a local topographic relief that exceeded 700 ft, perhaps much like the current Upsal Hogback field. Following this basaltic volcanism the Carson Sink continued to subside and fill with lacustrine material from pluvial lakes and deltaic sediments from the Carson River.

Currently there is between 1600 ft and 2200 ft of flat-lying sedimentary and volcaniclastic material above the basaltic unit. Since the basaltic volcanism there has been some localized normal faulting in the area but the vertical offsets associated with the post-basaltic faulting cannot exceed about 200 ft. There has not been any faulting recent enough to develop any recognized fault scarps in the immediate vicinity of the geothermal field. The most recent volcanism occurred $\pm$10,000 years ago with the phreatomagmatic eruptions at Soda Lake and the slightly older phreatomagmatic volcanism at Upsal Hogback. Within the geothermal field area the most recent activity has been a small amount of localized and spotty silicification of some sand dunes to the west and north of the Soda Lake 2 power plant (Figure 20). Gravity data indicate that there has also been localized sub-surface deposition of silica or other precipitates.

There are no credible existing sub-surface radioactive dates at Soda Lake. Chevron acquired some K-Ar dates from the well 77-29 cuttings but these dates were progressively younger with greater depth indicating thermal reset of the dates due to the high near-surface temperatures. In the absence of any dates it is presumed that the material lying above the basaltic unit is mostly or entirely Quaternary and Pleistocene in age. Ages below the basalt are speculative but most likely are Pleistocene and Pliocene.

Thermal Structure

The Soda Lake shallow thermal anomaly was generally outlined in the 1970s to a depth of 500 ft, defining a crudely circular 30 to 35 square mile area (Figure 8). Temperatures from 69 to 338°F were measured at a depth of 500 ft. Temperature gradients above a depth of 500 ft range from a background of about 3°F/100 ft to extreme values in the heart of the anomaly which cannot be extrapolated to greater depths. These shallow temperature profiles are quite linear and lack large overturns or reversals that define shallow thermal water flows away from most Basin and Range geothermal fields.

The high shallow temperatures and temperature gradients were so seductive that the deeper exploration and development focus for the past 35 years was largely confined to the heart of the shallow thermal anomaly in the south half of Section 28, the north half of Section 33, and the southeast corner of Section 29. The east, north, and west boundaries of the shallow thermal anomaly are gradational and defined by holes spaced from one to two miles apart which in places did not adequately define the margins of the geothermal system. The southern boundary is much sharper implying some shallow flow of cold water toward the north into the thermal anomaly. No shallow thermal anomaly is associated with the Quaternary Soda Lake craters. The closest known thermal anomaly outside the Soda lake geothermal field is centered just east of Upsal Hogback (Olmsted et al., 1984). The Upsal Hogback thermal anomaly is much smaller and much less intense than the Soda Lake thermal anomaly.

A recent reexamination of the 1970s vintage shallow temperature maps indicated that the western portion of the shallow thermal anomaly was not well defined and probably contains a NNE trending subsidiary anomaly. This reexamination also confirmed that there had been no drilling immediately east of the operating field in Section 34. Three quarters of the area around the discovery well, 84-33, was never further explored! These observations led to the drilling of six new TG holes up to 1000 ft deep during the fall of 2010 to the east and northwest of the operating field.

Measured temperatures at a depth of 1000 ft and temperatures extrapolated to 1000 ft from the 450 ft or deeper holes (Figure 9) show a similar contour pattern as the 500 ft map but the subsidiary thermal anomalies in Sections 20 and 34 now stand out more definitively with maximum measured temperatures of 210°F and 213°F respectively.

A deeper map at 2000 ft (Figure 10) shows that temperatures in the subsidiary thermal anomalies may potentially be equal to the measured temperatures at equivalent depths in the central core anomaly.

The linear extrapolation of shallow temperature gradients to 2000 ft represents an optimistic scenario as temperature gradients will experience some decrease as the thermal conductivity of the deeper rocks increases. Comparison of the Section 34 TG holes with nearby deeper holes in Section 33 shows that shallow gradients in this area can continue to depths below 3000 ft with only modest declines in the gradients (Figure 11). There is no way to predict at what depth or temperature the gradients in the TG holes on Figure 11 will suffer their inevitable and major decline.

In the northwestern part of Soda Lake the existing deeper wells 77-29 and 33-28 show more complex temperature profiles with laterally moving thermal fluid (Figure 12) creating classical temperature reversals. The TG 46-20 well is already deeper than the temperature reversals in the 77-29, 87-29, and 33-28 wells so there is a reasonable expectation that its high temperature gradient can continue and by a depth of 1600 ft it could possibly have the highest temperatures measured in the northwestern part of the field. However, it is always possible that the TG46-20 hole likes above an as yet undiscovered laterally out-flowing plume of thermal water.

At depths near 100 ft there is a regional groundwater flow toward the northeast as detailed by Olmsted et al. (1984) which elongates the shallow thermal anomaly in that direction. At a depth of 500 ft and deeper the central core of the thermal anomaly is only modestly elongated in a N-S direction and due to a minimal amount of data it is uncertain how much the subsidiary thermal anomalies are elongated (Figure 8). This is solid evidence that the Soda Lake geothermal system is not highly elongated along a single N-S to NE-SW trending fault. Thermal water could still be rising along restricted lengths of such faults or perhaps along intersections of some structural trends. These restricted lengths provide multiple possible production or injection targets at the expense of smaller individual size and additional geological complexity.

Changes in the temperature gradient and a few shallow reversals in temperature profiles from the TG holes and wells define three rather diffuse thermal aquifers flowing laterally for distances of one-half to one mile away from the central upwelling. The shallowest thermal aquifer or complex of aquifers is found at depths of 400 ft to 1000 ft and appears to flow in all directions from near the 41B-33 pad (Figures 13 & 14). It cools from a maximum temperature of 370°F down to 150°F in the northernmost Hoenig hole and to 244°F in the southern 25-33 well, which has the sharpest (and therefore youngest) temperature reversal yet documented at Soda Lake. This aquifer is flowing through unconsolidated Quaternary alluvium above the mudstone layer which may be acting as a lower bounding aquitard. This shallow thermal aquifer is utilized by the 41-33 pad production wells and the 77-29 and 87-29 injectors.

A weakly-flowing and relatively poorly-defined intermediate-depth thermal aquifer is found near a depth of 2000 ft. It flows northwesterly from the vicinity of well 41B-33 cooling from a temperature of about 360°F in well 41B-33 to 266°F in well 33-28 (Figure 15) The temperature inflections defining this aquifer are quite subtle changes in temperature gradient (Figure 16). This aquifer is generally associated with the basaltic unit but is not significantly utilized for production or injection purposes.

The deepest and hottest of the sub-horizontal aquifers flows east and northeast from the vicinity of wells 25A-33 and 45A-33 toward the 84-33 and 81-33 wells at a depth of 4000 ft to 3300 ft (Figure 17). It is currently utilized by wells 84A and 84B-33 and 32-33 for production and by well 81-33 for injection. This aquifer cools from about 390°F in the central upwelling to about 360°F in wells 84-33 and 81-33. It is defined by a sharp loss of temperature gradient (Figure 18) and a progressive easterly loss of temperature at the top of the aquifer. It is not known much farther east of 81-33 and 84-33 it extends. The gamma ray logs show that this aquifer is hosted by a variety of Tertiary age formations which implies sub-horizontal fracturing cutting across differing lithologic units.

At depths of 4100 ft to 4950 ft the highest temperatures of ±390°F are found in the 25A-33 and 45A-33 wells so the deep near-vertical feed into the producing parts of the geothermal system must be located near these two wells at these depths. It is frustrating that the hottest wells at Soda Lake have only modest permeability. Normally the hottest wells in a geothermal field are hottest because high local permeability allows rapid movement of the hottest water. The deep vertical feed at Soda Lake is located close to the sharp southern margin of the thermal anomaly. Chemical geothermometry indicates maximum temperatures a little above 400°F, slightly above the 397°F maximum temperature measured near the bottom of the deep 84-33 well.

Vertical permeability which allows temperatures as high as 372°F at 850 ft must be connecting these three aquifers with a deeper source of the thermal water. This vertical permeability is greatest at shallow depths near the 41-33 pad and with increasing depth dips southerly toward the 25A-33 and 45A-33 wells.

Four tracer tests were conducted in Soda Lake in 2009 and showed generally conventional returns from injection wells to producers. One interesting and as yet not well-understood result was an apparent absence of sub-surface flow between the western part of the field as typified by wells 32-33 and 41A-33 and eastern part of the field with wells 84A and 84B-33. The chemical tracers primarily travelled north-south and not east-west. This indicates some compartmentalization of the wellfield at depths of 800 to 4000 ft with north-south trending barriers to lateral flow. The deeper temperature profiles have not yet been modeled to confirm or deny this possible compartmentalization and there have been no pressure interference studies performed between these wells.

Permeability Distribution

Permeability in the Soda Lake geothermal field at all depths has proven difficult to locate and understand as compared with other Basin and Range operating fields. As a few examples, the circulation losses in the 77-29 well were only partial when the shallow thermal aquifer was penetrated by the drill bit but later there were complete losses while running the 13 3/8" casing. The permeability was cemented behind the 13 3/8" casing and only later did perforations in the 13 3/8" casing restore high productivity and injectivity to the well. The same held true for the 84-33 well where the producing zone was initially put behind cemented casing. Drilling of the 84A-33 and 84B-33 wells to within tens of feet of the original 84-33 production zone required three redrills to access permeability. During drilling of the 81-33 well there were no major lost circulation zones but when the well was changed over from mud to water, total lost circulation developed and the injectivity greatly improved over time as it was used for injection. Sustained permeability in well 25A-33 developed only after the well was deflagrated and injected into for a period of a few weeks (Ohren et al., 2011).

These increases in injectivity over time indicates either poorly developed fractures that can be improved by inadvertent or minimal stimulation or perhaps marginal fractures that are exceptionally easily damaged during the drilling process or perhaps some of both. Only the shallow 41-33 and 41A-33 wells and the deep 32-33 well were drilled into obvious major loss zones and easily placed in service as producers with no additional workovers or stimulation.

McNitt (1990) suggested that the Soda Lake geothermal field primarily consists of thermal fluid movement along stratigraphic horizons. Drilling since 1990 has not resolved the question of whether the permeability is primarily sub-horizontal or near-vertical in nature. Considerable effort has been made at Soda Lake to directionally drill into or across a hypothesized steeply dipping NNE trending fault zone in the central thermal anomaly with little apparent success to date in terms of high flow rates.

Wells that are or have been in service as producers or injectors show a bimodal distribution of usable permeability with depth. Injection wells 77-29 and 87-29 and production wells 41-33, 41A-33, and 41B-33 all access permeability between approximate depths of 750 ft and 1100 ft in unconsolidated Quaternary alluvium. All other active wells encountered major permeability below a depth of 3300 ft. The deepest utilized permeability at Soda Lake is at 4930 ft in well 81-33 and ±4950 ft in well 25A-33.

At depths below 3300 ft the available and inconsistent lithologic logs indicate that the stratigraphy is more volcanic than sedimentary and fracturing is probably a must for any significant permeability development. This is supported by the five available density logs from the Soda Lake wells (Figure 19). The density logs show unconsolidated Quaternary alluvium to have a density of 2.0 or less g/cc near the surface and a generally irregular increase with depth. The basaltic unit has a density of 2.4 to 2.6 g/cc. Immediately below the basaltic unit, densities decrease to about 2.1 g/cc, indicating poor consolidation, and then progressively increase. By a depth of about 3400 ft the densities are mostly close to or above 2.5 g/cc indicating lithified formations below about 3400 ft. The 44-5 well lacks volcanic rocks to a depth of 4600 ft (Sibbett, 1979) and does not reach a density of 2.5 g/cc until a depth of about 4400 ft. These density data show that the basaltic unit does not represent the top of a volcanic sequence. Instead, the basaltic unit is imbedded within a progressively lithifying sedimentary sequence that bottoms as shallow as 3400 ft. The top of the Tertiary volcanic sequence stratigraphically is coincidental with Surface #13 (Figures 4b, 5, & 6) as shown on the gamma logs. The most obvious change on the gamma ray logs related to the transition from dominantly sedimentary to dominantly volcanic is a modest reduction in the amount of spikiness in the more volcanic section (Figure 4).

The gamma ray logs show that permeability is found in different stratigraphic units in each of the deep wells, except in the very closely spaced 84-33, 84A-33, and 84B-33 wells. It is uncertain if the deep and hottest permeability found in wells 32-33, 25A-33, and 45A-33 is primarily steeply dipping and associated with small offset normal faults or if it is primarily gently dipping and associated with a laterally flowing thermal aquifer. The greatest permeability is found in well 41A-33 which has been sustainably pumped at 2000 gpm. All of the other active producers are incapable of producing at much over 1000 gpm in part due to pump setting-depth limitations.

Usable permeability has not yet been encountered between depths of about 1100 ft and 3300 ft. Stratigraphically this apparently impermeable depth interval includes the basaltic unit and poorly consolidated sedimentary rocks several hundred feet above and below it. The minimum distance to known major permeability below the basalt is 625 ft in well 32-33. The second closest permeability below the basalt is 930 ft in well 81-33. The greatest known distance to known permeability capable of creating a large lost circulation zone during drilling below the basalt is 2150 ft in well 45-28.

In summary, permeability in the producing field at Soda Lake has a crude bimodal permeability distribution with depth and to date shows no particular preference for any specific lithologic unit. There has not yet been any significant permeability encountered within the basaltic unit although there is a suspiciously close spatial correlation between the thickest basalt and highest near surface temperatures. The deeper permeability at Soda Lake appears to be more associated with Tertiary volcanic rocks than with sedimentary interbeds.

3. Geophysics

Precision Gravity

During the past two years precision gravity surveys at Soda Lake have significantly improved the understanding of the overall resource and strongly support the temperature information in defining new step out drilling targets. The first gravity survey at Soda Lake (McNitt, 1990) defined a NW- trending six mGal gravity high or ridge passing through the field which led to the poorly supported hypothesis that a buried NW trending fault was controlling the gravity high (Figure 20). There were no indications of NNE faulting trends on the 1990 contour map. The 1990 map shows three separate highs with one mGal of relief standing on top of this ridge.

A much more precise and detailed unpublished gravity survey with 0.05 mGal resolution (Teplow, 2001) confirmed the presence of these local positive anomalies a fraction of a milligal in intensity on top of the NW trending feature (Figure 20). A 2008 detailed gravity survey with 0.03-0.05 mGal resolution largely replicated the 2001 results and fortuitously led to the recognition that the 2001 data points were mislocated. After the 2001 survey was properly relocated the small positive gravity anomalies were recognized as being spatially associated with the small scattered silicified sand deposits found on the surface (Figure 20).

Recognition of a likely relationship between near surface densification and geothermal activity led to the acquisition of additional micro-gravity data with a resolution of 0.003-0.005 mGal extending beyond the existing field boundaries in areas where geothermal activity was suspected to be present (Figures 20 & 21). These micro-gravity data reconfirmed the existence of small residual gravity anomalies sitting on top of the larger previously known gravity ridge.

The complete Bouguer gravity anomaly associated with the producing field has a relief of 0.8 mGal and is outlined by the 96 Mgal contour (Figure 21). Similar size and magnitude Bouguer anomalies are found to the northwest in Section 20 and to the east in Section 34 and lie within the overall shallow thermal anomaly. A filtered residual gravity map using a single pole bandpass, 328 ft-164 ft wavelength emphasizes small-contrast density anomalies within the upper 650 ft of the sub-surface (Figure 22). These shallow features show two distinct slightly elongated anomalies in the producing part of the field which supports the concept of two possible upflow zones or perhaps a separation within one larger zone. There are much longer densified intervals to the northwest in Sections 20 and 17 and to the east in sections 34 and 27. These outlying gravity anomalies correlate closely with elevated temperatures and temperature gradients (Figure 22) supporting the concept of shallow active hydrothermal flow and densification of poorly consolidated Quaternary alluvium in these two areas. In hindsight, it may be unfortunate that the relationship between geothermal activity and the Bouguer gravity highs was not recognized decades ago and tested by drilling. Also, with a poor geological understanding of the sub-surface it was not possible to credibly ascribe the gravity high(s) to any specific geological feature(s).

Electrical Data/MT

A 74-station Tensor Magnetotelluric survey with station spacing of 1600 ft to 3200 ft was completed in late 2009. Attempts to generate a 3D model were unsuccessful due to noise in the data and errors in single inversions so results presented here are based on a 3D gridding of the 1D determinant.

The total variation of resistivities at Soda Lake ranges from 1 ohm-meter near the surface to as much as 120 ohm-meter at depths of two to three miles (Figures 23 & 24). To a depth of ±3000 ft resistivities are less than 15 or 20 ohm-meters and vertically stratified. This agrees with horizontally layered fluid salinity in the Soda Lake area. In the upper several hundred feet the water chemistry is generally dominated by a dilute bicarbonate groundwater, especially to the south of the geothermal field where there has been a century of agricultural irrigation with fresh water from the Carson River. This shallow meteoric or ground water has a resistivity generally between 10 and 50 ohm meters. The meteoric water is absent in the heart of the geothermal field where geothermal brines make their closest approach to the surface. From the southern margin of the geothermal field and northward geothermal sodium chloride water with a TDS of about 6000 ppm and resistivities of 0.5 to 4 ohm-meters is the dominant shallow water. This geothermal fluid has dispersed outward from the core of the geothermal field into poorly consolidated material primarily through the shallowest sub-horizontal thermal aquifers (Figure13) between the surface and a depth of 1000 ft. Temperature contours on the MT cross sections correlate closely with resistivity values showing that at Soda Lake the resistivity reflects active geothermal fluid movement in the producing field area and not some older alteration feature.

An iso-resistivity surface of 3.4 ohm-meters, generated from the MT model as a proxy for the interface between the meteoric and thermal waters shows a very sharp northwesterly trending boundary at the southern edge of the geothermal field (Figure 25). Shallower depths north of these tightly spaced contours correspond with the producing geothermal field and greater depths to the south correspond with a known cooler non-geothermal area. This resistivity feature correlates closely with rapidly declining temperatures at the southern margin of the geothermal field. There is a remarkable coincidence of shallower depths to the 3.4 ohm-meter surface and plan view temperatures at a depth of 500 ft including the subsidiary thermal anomalies northwest and east of the core area (Figure 25). A 150°F water sample recovered from a depth of 750 ft in the TG 44-34 hole (in the center of Section 34 east of the field) had sodium and chloride contents virtually identical to the deep primitive Soda Lake geothermal water. The 3.4 ohm-meter surface is found at greater depths in Section 20 and 34 than in the core thermal area. This presumably reflects the mudstone unit simply being a more effective cap in these outlying areas and confining the geothermal fluids to greater depths.

Ground Magnetics

In October 2009, Magma acquired a ground-based, total magnetic field intensity survey consisting of ±225 line-miles, over the area between Big Soda Lake and Upsal Hogback. Approximately 60% of the total survey area is presented (Figure 26). Magnetic data have a less direct relationship with geothermal activity than temperature or MT data. At Soda Lake the magnetic data show some correlations with the geology, temperature, gravity, and MT results. Within the operating field there is a general overlap of magnetic lows and surficial silicified sediments as shown by anomalies 5 and 6 (Figure 26) which presumably reflects near-surface oxidation of magnetite by the now extinct fumarolic or steaming ground activity located just east of well 77-29. There are no holes drilled into the smaller and less intense anomaly 6 to determine if there is some buried shallow steam alteration in this area.

The largest and most intense low-magnetic anomaly in the area is centered on the 44A-34 TG hole. There was no obvious oxidation or hydrothermal alteration in the cuttings from the TG hole so the origin of the magnetic low remains uncertain but it does closely overlap with northerly trending temperature, gravity and MT anomalies (Figures 8, 21, & 25). The northern extension of this anomaly partially overlaps three playas where the sand dunes are absent, indicating that the sand covering most of the area has a higher magnetite content than the playa silt and clay. The sand dunes may also be relatively thin between the playas. Higher magnetic areas largely surrounding the geothermal field (anomalies labeled "3" on Figure 26) may represent either thicker and/or higher magnetite content sediments.

The second largest magnetic low lies to the west of well 77-29. However, this low does not have a northerly or northeasterly trend to follow the shallow thermal anomaly (Figure 8) and the hot 46-20 TG hole is not within the magnetic low. There are no deeper holes within this magnetic low. Its origin may reflect a relative absence of magnetic sediments as indicated by a possible subtle unconformity and/or thickening of the magnetic unit on Inline 63 (Figure 26).

4. SOPO Tasks

The centerpiece of the Phase I investigation of innovative technologies is the three-dimensional, three-component reflection seismic survey intended to identify fluid-filled fractures and permeability.

Calibration of the surface seismic data is required to achieve this goal. The primary calibration tools are checkshot or time-depth surveys and synthetic seismograms.

Vertical Seismic Profile

In the oil & gas industry, vertical seismic profiles (VSP) have been successful in identifying features proximal to the borehole. The week before shooting the 3D seismic survey, an injection test in well 41B-33 provided an opportunity to conduct a VSP deep in the heart of the producing field by cooling the well below the temperature limits of the downhole equipment. This VSP included a check-shot survey to 7000 ft to obtain a time-depth relationship, a vertical wave test to measure frequency absorption with depth prior to seismic field testing, and a two-leg orthogonal walkaway profiles to identify anisotropy from fluid-filled fractures. Results and discussion of these VSP tests are presented in Appendix 1.

3D-3C Reflection Seismic Survey Data Acquisition

A 3D reflection seismic survey was planned for the Soda Lake geothermal field from Magma's acquisition of the project in Oct, 2008. Magma filed a Notice of Intent to Conduct Geothermal Resource Exploration Operations to acquire the seismic data with the Bureau of Land Management on February 23, 2009. Dawson Geophysical Company arrived on site June 16, 2010. Data acquisition of the 13 mi^2 survey was completed between June 19 and 30. Shot lines were laid out parallel to the anticipated NNE strike of normal faults in the area (Figure 27) with perpendicular receiver lines. Cultural and physiographic features prohibited data acquisition in a few areas. More detailed discussion of the planning and execution of the survey is presented in Appendix 2.

Seismic Data Processing

Geokinetics, Houston, TX, received the field tapes on July 9, 2010. Processing of the p-wave time section was completed in September, 2010. Processing of the converted-wave data as planned was not successful. Further discussion of the processing sequence and issues is in Appendix 3.

Seismic Interpretation

The goals of the seismic interpretation are to map significant horizons and fault planes, correlate known production intervals to the seismic data, and identify exploration targets for Phase II drilling.

Time-Depth

Reflection seismic surveys are recorded in time but geologic and well information is measured in depth. Time and depth are related by a spatially variable velocity function derived from both direct and indirect measurements; the vertical seismic profile, well ties using synthetic seismograms, and interval velocities from seismic stacking velocities. The range of time depth functions generated by synthetic seismograms and the VSP shows increasing divergence below a depth of about 1200 ft (Figure 28). Below a depth of about 2000 ft the separation of the curves increases more rapidly. This 2000 ft depth crudely corresponds with the high velocity basalitic unit and results in a 200 ms time difference by a depth of 5000 ft.

Synthetic seismograms are generated from an impedance series derived from the velocity and density values measured in sonic and density logs (Sengush, 1961). When the impedance series is convolved with a wavelet, a seismic trace is produced that can be matched to the reflection seismic data. By compressing or stretching the synthetic trace, empirical matches are made that define a time-depth relationship (Figure 29). The synthetic well tie is expanded on the right side of Figure 29 to show where major changes in acoustic properties should be associated with changes in reflectivity. Between the well bore and the sonic trace is a narrow strip of a variable density display showing a representative tie between the synthetic trace and the seismic data. When the data are zero-phase and the polarity is known, an acoustic impedance interface is coincident with a denser black peak or a less dense red trough. There is only a mediocre correlation of the synthetic seismogram with the seismic records at Soda Lake. With only the mudstone and the basaltic unit producing distinctive reflectors, time-depth functions based on synthetic well ties are uncertain.

A seismic trace is a composite of reflections from many interfaces. At Soda Lake the lacustrine and deltaic sediments do not appear to produce reflections corresponding to a single pick or surface from gamma ray correlations, but rather from a thin package of sedimentary units. The basalt has a 2x increase in velocity and a >10% density increase compared to the poorly consolidated overlying units, but the top of the basaltic unit is most likely weathered and/or eroded and in much of the area lacks a distinctive reflection. Unfortunately, at Soda Lake the poorest seismic data quality, defined by a lack of coherent reflectors, is in the central part of the producing field and the area of highest well density.

Merging the wireline, geologic, and seismic data in the 3D GIS model requires a depth conversion based on a velocity model. After time-structure maps were converted to depth, discrepancies between formation tops as defined by the gamma ray and resistivity logs and mapped seismic horizons required iterative revisions of both the velocity model and some formation tops to improve consistency between the two independent data sets.

Without a continuous reflector between wells in the central part of the field, a difference in the time pick of a formation top of similar depth between two wells can either be offset by faults or can be an artifact of the time-depth function. With many of the fault picks being ambiguous, we are unable to resolve these discrepancies to a high degree of certainty. In the heart of the field, in addition to variations in stratigraphy, there are likely velocity distortions in the sedimentary section due to the effects of hot water (-10%), densification of sediments through precipitation (+5%) and saturation (-10%). As an example of saturation variation, a localized shallow steam cap around the 41-33 well has developed within the past several years with an unknown lateral extent. In the 1,700 ft – 3,800 ft depth range, the large variation of the basalt thickness introduces a doubling of interval velocity. The equivalent depth of 1.0 second surface varies from 4000 ft in a well such as 25A-33 with a 100 ft thick basaltic unit to 5000 ft in 41B-33 with a 2000 ft thick basaltic unit.

Mudstone Reflector

Above a time of about 0.5 seconds or a depth of about 1500 ft there are a series of strong coherent reflections across most of the surveyed area (Figures 30 & 31). These near-horizontal reflectors are in good agreement with the shallow layer cake geology recognized in the gamma ray and resistivity logs from the wells (Figures 5 & 6) and show a regional dip toward the southeast. The older Chevron data extended to the south in Figure 31 shows a thickening basin to the southwest of the geothermal field.

The strongest and most continuous reflector extends across most of the survey area at time of 0.2 to 0.3 seconds which equate to a depth of ±800 ft, the same depth as the mudstone unit of Sibbett (1979). The gamma ray and electrical resistivity logs (not shown in this report) show several 10 ft to 30 ft thick widely-correlatable inflections near this depth (Figure 4a). It is uncertain as to which one or more of these inflections provide the seismic reflection surface(s). The depth of the mudstone reflector is less certain in Sections 20 and 29, near the 46-20 TG hole, where an alternative interpretation could place it deeper in the hole (Figure 30). Also, the shallower the mudstone becomes the more difficult it is to pick it out as receiver intervals of 220 ft and line spacing of 550 ft make the shallow data single or low fold. In hindsight, the mudstone in the western part of the survey area could have been better imaged with more closely-spaced data.

The initial depth conversion systematically miss-tied the mudstone depths from the gamma ray and resistivity logs in the wells by as much as 120 ft. Only 10 of 20 initial mudstone picks from wells were within a reasonable distribution of ±15 ft. Wells located in the heart of the shallow thermal anomaly were found to have the greatest discrepancies between the seismic picks and the gamma ray picks (Figure 32). P-wave velocities decrease with increasing temperature (Jaya et al., 2010). Over the temperature range from ±100°F at a depth of 800 ft near the fringes of the survey area to 370°F at a depth of 800 ft in the core of the thermal anomaly velocity reductions up to 10% could occur. Interval velocities in existing time-depth functions were then adjusted to empirically match the seismic horizon with the wireline pick.

After revising the velocity model with the temperature corrections, the time horizon was converted to depth using a constant velocity and a static shift to identify residual errors (Figure 32). Differences between these depths and the depth-converted mudstone horizon created elevated and depressed cones around wells where the velocity model needed further refinement. Comparisons to adjacent time-depth functions identified time-depth pairs that needed further modification. In the final analysis, the systematic errors were removed bringing the depth-converted time horizon and the wireline picks to a reasonable distribution of ±15 ft.

This mudstone surface is now the most studied seismic reflector in the survey and offers the best visual depiction of a three mile-wide NNE trending fault zone (Figure 33). Within this zone, Faults 1- 4 are the most significant. All are east-dipping, normal faults and appear to be the west edge of a smaller-scale step-over. The faults also show some manifestation of hydrothermal fluids, either from direct surficial evidence or inferred from the gravity anomalies. The overall Soda Lake fault pattern of curving en echelon faults is similar to those from seismic images of other extensional or rifting environments such as the Viking Graben in the North Sea (Haakon, et al., 2010) and the East Africa Rift Valley (JPL, 2003). The mudstone horizon provides the map of recent tectonics in far more detail than interpretations from well correlations alone (Figures 4a & 4b). The mudstone map suggests a small extensional, pull-apart basin hosts the Soda Lake geothermal resource and that this basin has been active in the past few hundred thousand years.

The thickest and widest packages of reflectors below the mudstone extending from 0.3 to 0.5 ms are located outside of the operating field (Figures 30 & 31) where there is no well control.

Basaltic Unit

The basaltic unit was anticipated to be the dominant reflector in the seismic survey, but over most of the developed field it failed to produce a strong or consistent reflection. In the central part of the field it is not recognizable in the seismic data without well control. In wells 32-33, 11A-33 RD, and 41B-33 the basaltic unit is over 1000 ft thick and exceptionally homogenous on the gamma logs, but is nearly indistinguishable in the seismic cube. Outside of the developed field, where the basalt thickness ranges from 100 ft to 600 ft it is a better reflector (Figures 30 & 31). However, even where a strong reflection is present, the sonic logs do not necessarily show an abrupt change in velocity (Figure 34 upper left). Instead, there can be a gradual velocity transition that would be expected from a weathered, eroded, or brecciated volcanic surface. Therefore, the top of the basalt picked from wireline logs, similar to the mudstone, may not have a consistent seismic signature of a strong trough followed by a strong peak. For structural mapping purposes, the top of the basalt was picked on the trough with the highest amplitude (Figure 30, Inline (IL) 129-154, top row of seismic annotation near wells 64-33 and 84-33).

The bottom of the basalt, which overlies poorly consolidated sedimentary material, is not associated with a recognizable reflector. It is inferred from wireline correlations and the character of a low-frequency "shadow" showing fainter or more blurry responses in the basaltic unit. The shadow could be a reverberation or absorption phenomena due to high acoustic impedance contrast (Figure 30, 650 ms IL 129-154, and Figure 31, 600 ms IL 177-235).

Preparation of a structure map of the top of the basaltic unit (Figure 34) was more interpretative than for the mudstone. It required combining the strong seismic response of the thinner basalt on the flanks of the central gravity high and well control where the basalt reflectivity is absent. Seismic maps associated with the basaltic unit are more ambiguous than the top of mudstone map.

The top of basalt unit structure map (Figure 34) has more complexity than the mudstone map (Figure 33) with approximately three times the relief. This in part results from the paleo-topography of the top of the basaltic unit (Figure 4a). The basaltic unit does not underlie the entire seismic survey area. It covers a smaller area than the more extensive shallower mudstone (Figure 34). The 44-5 and Hoenig holes failed to encounter the basaltic unit. The gamma ray logs have been interpreted to indicate a basaltic unit thickness of 10 ft in well 58-34 but well 58-34 is shown as effectively being outside of the basaltic unit on Figure 34 suggesting that it is not a recognizable reflector at that location or perhaps it is a different formation.

Down to the east normal faulting is still recognizable on the top of the basalt map with the same four faults (1-4) as shown on the mudstone map. It is important to note that the 41B-33 well crosses at least 5 faults (Figure 34) yet failed to encounter major fault-controlled permeability. This is a reminder that many, if not most, interpreted faults in these seismic sections may not contribute significant permeability.

In spite of these difficulties a time-slice map at 600 ms, which is the approximate depth of the thinner and more aerially extensive portion of the basaltic unit, shows features in reasonable agreement with the gamma ray logs (Figure 35). The broad, red and black bands to the north and east of the central gravity high correlate with the basaltic unit. The basaltic unit is thickest beneath the central gravity high but as noted earlier lacks a coherent reflection here. The bulk of the upper part of the basaltic unit lies between east dipping graben fault 2 and west-dipping fault, W-1. There are other thick bands shown of Figure 35 that are not known to be related to the basaltic unit. For instance, north of the central gravity high and in the western corner of the survey southerly dips are inferred. To the east of the eastern gravity high there are reflective thick north-south trending bands of uncertain origin as no wells have yet been drilled in this area. The gravity highs shown on Figure 35 are created by the basaltic unit and by density features located above and below the basaltic unit. It is unfortunate that a formation as geologically and seismically prominent as the basaltic unit at Soda Lake is not known to provide a direct control on geothermal fluid movement.

Tertiary Volcanic Basement

Below the basaltic unit at a depth of about 2000 ft or a time of about 0.6 seconds the seismic results in the field area show little or nothing in the way of coherent reflectors. Outside of the field area in a lower temperature regime probable reflectors are found much deeper to the north of the Hoenig hole and to the south of well 25A-33 (Figure 31). Most likely this reflects thicker sedimentary formations in these areas combined with a paucity of volcanic material. However, given the relative importance of understanding the depth to the Tertiary volcanic rocks which host the deep permeability it is still useful to make the effort to define the top of this surface. This is a highly interpretative process incorporating the geophysical well logs and gravity data as well as the geological concept of a Tertiary paleo-topographic high that has been buried by younger sediments.

Previously described density logs (Figure 19) show that the basaltic unit is imbedded in a poorly consolidated relatively low-density sedimentary sequence with about a 0.25 g/cc density contrast between the basalt and the sediments. Recognition of the relatively limited extent of the basaltic unit requires a different and more laterally extensive geologic feature to explain the much larger semi circular gravity high between Soda Lake and Upsal Hogback (Figure 3). The density logs suggest that the shallowest occurrence of Tertiary volcanic rocks in the Soda Lake area is near a depth of 3400 ft (Figure 19) in wells with a thin basaltic unit. In wells with a thicker basaltic unit, the top of the Tertiary volcanic rock sequence is up to 2000 ft deeper (Figure 7), but this extra 2000 ft is taken up with higher density basaltic rock giving no significant density contrast. The 44-5 well, the only Soda Lake well not located on the high gravity ridge, has sedimentary material to a depth of 4600 ft. There is at least 1200 ft of relief on the top of the Tertiary volcanic surface or Tertiary basement, suggesting that the depth to the volcanic basement is probably the major control on the overall semi-circular Bouguer gravity anomaly.

With only four density logs available from within the field, more data points defining the density increase are needed to constrain the seismic interpretation. Initially sonic log data were converted to density values using Gardner's equation (Gardner, 1974) and successfully compared to the existing density logs. With trial and error the log of resistivity can also approximate density through a scalar plus a constant ($\rho = A*\log_{10}(R)+C$). Compared to the density, the match was excellent for depths below 1000 ft and densities less than 2.7 g/cc. It was later independently recognized that surface number 13 on the gamma ray logs (Figure 4b) also defined the top of the Tertiary volcanic basement.

Outside of the existing truthed field area, the Tertiary volcanic basement has considerable relief as defined in the seismic data by an onlap of sedimentary horizons, event truncations, frequency content, and a lack of coherent reflections (Figures 30 & 31). Arbitrary seismic lines (seismic profiles independent of Inline or Cross-lines) were also employed to extrapolate away from areas of better seismic character or well control. This is highly interpretative and provides one more example of the difficulty of confidently utilizing the seismic reflection method in volcanic terrains with limited well control.

In Figure 30, filtered and unfiltered gravity profiles are plotted above the seismic data to show the correlation between the gravity highs and the seismic data. The depth picks for the Tertiary volcanic basement in the wells come from density and gamma logs, and are in good agreement with picks from the sonic and resistivity logs. There are three gravity highs, each is associated with high elevation of the Tertiary volcanic basement and with elevated shallow temperatures. The central gravity high has the greatest apparent character, being complicated by shallow densification of the Quaternary alluvium and the thick basaltic unit. Without these complications the central gravity anomaly may actually have the smallest amplitude. The western anomaly associated with the 46-20 TG hole is only partially covered by the seismic survey. The eastern anomaly associated with TG hole 44A-34 is quite narrow and appears to be completely covered by the seismic survey. There is a good correlation of increased seismic complexity above a depth of 400 ms with the eastern and western gravity anomalies and with the Steam Bath House portion of the central anomaly. Recognizing the Tertiary basement as a buried, topographically-high ridge is a major accomplishment in data integration.

A highly interpretative Tertiary volcanic basement structure map shows a relief of over 4000 ft within the seismic survey area (Figure 36). As the faults below a depth of about 500 ms are largely invisible on the seismic sections (Figures 30 & 31), the locations of faults shown on Figure 36 were linearly extrapolated from shallower depths. Therefore the Tertiary volcanic basement structure map shows the same basic en echelon pattern as seen in the mudstone and basaltic unit structure maps (Figures 33 & 34).

Fault Planes

All interpreted faults penetrating a 600 ms time-slice at the approximate top of the basalt near a depth of 2000 ft define a strong N-S to NNE-SSW en echelon trend (Figure 37). A second preferred fault orientation is oriented roughly perpendicular to the larger offset faults in a general E-W to NW-SE direction. Faults penetrating this level define the structural fabric of the survey area. A NNE-SSW trend is optimally oriented for faults in western Nevada to pull-apart during movement and create the large scale permeability necessary for a geothermal system. Reverse faults are less common. A likely structural model for this fault pattern is a left-stepping, sinistral strike-slip fault system in rigid basement where synkinematic sedimentation fills localized grabens (Dooley and McClay, 1997) (Figure 37 inset).

Fault offsets near a depth of 800 ft in the mudstone vary from 0-30 ms or up to 150 ft (Figure 30). This is in good agreement with a maximum relief of 135 ft on surface #3 defined by gamma ray logs between depths of 670 ft and 805 ft.

Nineteen of the largest vertical offset normal faults recognized at depths of approximately 300 ft all dip 60°-70° to the east (Figure 38). Strikes of these sub parallel faults range from N-S to NE-SW with strike changes indicating left-lateral movement. In the deeper section, fault offsets are greater. In the southernmost part of the survey, the major extensional faults have offsets of 100 ms (500 ft) or more and have an interpreted listric character and rotated fault blocks (Figure 38). Fault 1 is the western boundary to the pull-apart system. There are only a few short and shallow faults west of Fault 1. Portions of Faults 2 and/or 3 may be providing the vertical permeability to supply the currently producing part of the Soda Lake geothermal resource. Fault 3 may be cut by in the hottest wells in the field, 32-33 (1,400 ft), the 41-33 group (2,450 ft), and 45A-33 (1,230 ft). However, offsets on Fault 3 are small enough that there has not yet been any recognition of faulting crossing these wells. Fault 4 is associated with numerous parallel and antithetic faults and is coincident with a long and narrow gravity anomaly (Figure 22).

Correlation to Production

A seismic response to known permeable zones is a difficult correlation. A fence diagram constructed through the production and injection wells shows the location (LC) of the major permeable zones (Figure 39). Wells with large aperture faults may show offsets in the shallow seismic horizons, but lack coherent events at depth which makes placement of deeper fault cuts highly interpretative.

Two shallow sedimentary sections are the primary zones for production (IL 140, XL 190) and injection (IL 132, XL 138). Well 41A-33 produces the largest volume in the field indicating that Fault 3 is associated with vertical permeability. Wells 41-33, 41A-33, and 41B-33 are all on the same pad and solving a simple 3 point problem based on the top of the lost circulation zone in each well gives a strike of N 25 E and a dip of 57° to the west which agrees well with Fault W2 (Figure 39). Wells 77-29 and 87-29 are the two primary injection wells for the Soda Lake 2 plant. These two wells are on the up-thrown side of Fault 2 and in the vicinity of the Steam Bath House and silicified surface sediments. These surface manifestations indicate Fault 2 has direct connection with the deeper geothermal resource. The cooling of 41A-33 and the differential gravity data indicates injectate has followed a similar path of horizontal flow through permeable sediments and vertical movement along fault segments.

The other major zones of permeability are in the Tertiary basement. The most notable deep loss of circulation in the field is in well 45A-33. The large aperture fault encountered at 4,168 ft in 45A-33 cannot be attributed to a specific fault, but lies near the intersection of both an east-dipping and west-dipping fault and shows no obvious offsets below the level of the basalt (Figure 39). The LC zones in the Tertiary basement in wells 84-33 and 81-33 are not imaged in the seismic data.

One goal of the 3D seismic survey was to identify a "seismic signature" associated with production, either a structural relationship related to the orientation of the faults or through shear-wave anisotropy. Unfortunately, neither of these goals is satisfied. The degraded quality of the data over the producing area introduced uncertainty in determining convincing orientations of faults. Issues with the shear-wave data are discussed in Appendix 4.

Lessons Learned

The 3D reflection seismic survey has provided useful insights in unraveling the structural complexity of the Soda Lake field and the surrounding area. The two Tertiary volcanic basement anomalies in Sections 20 and 34 were identified by the gravity anomalies and temperature gradients concurrent with planning, acquisition and interpretation of the seismic survey. At this writing, there are no "geothermal indicators" identified at Soda Lake, as there are hydrocarbon indicators in oil & gas. However, with additional drilling planned in Sections 20 and 34, there is opportunity to test the predictive capabilities of these seismic data.

The cost of this 13 sq mi 3D reflection seismic survey is equivalent to the cost of one-half of a production well. The application of reflection seismology in geothermal exploration in the Basin and Range Province will be limited because the alluvial fans and exposed or shallowly buried volcanic rocks absorb and scatter seismic energy. There will be few locations where the seismic method can provide useable data and be considered a proven field exploration tool. Existing well control and geologic knowledge is absolutely critical to provide context to the seismic interpretation.

This 3D survey was designed with a zone of interest of 3000 – 4000 ft with maximum source-receiver offsets over 7000 ft. Now that the data have been acquired and interpreted, the most reliable data are above 2000 ft and below 500 ft. With 770 ft source lines, 550 ft receiver lines, and 220 ft receiver groups, the shallow data are low fold and riddled with skips (no-data because of non-uniform source-receiver offsets). Higher surface sampling is necessary to image horizons at depths less than 500-750 ft.

A major drawback in Nevada to reflection seismology is that conventional seismic acquisition technology requires a Class III cultural resource inventory due to the restriction of vehicles greater than 10,000 lbs. In reality, the weight of the vehicle is not the controlling factor, it's the soil compaction associated with the tires. Making rules for soil compaction is hard. Limiting gross vehicle weight is easy.

In many parts of the country, a reflection seismic survey is considered "casual use," activities ordinarily resulting in "no or negligible disturbance of the public lands or resources." In this survey, most sources were acquired using three-60,000 lb vibrators due to the target depth and the surface noise associated with two operating power plants, an active well field, and drilling the 25A-33 well. A 3D survey conducted early in the development cycle of a field could eliminate much of this surface noise.

Understanding recent tectonics is critical to unraveling these geothermal systems. The combination of a low-impact seismic source weighing less than 10,000 lbs with a cable-less recording system could pass the casual use threshold in Nevada. Geokinetcs has a synchronized electrical impulse source, onSeis that compares very favorably to conventional vibroseis.

The time and effort involved in planning, permitting, processing, and interpreting the seismic data is great, especially for what is likely to be a one-time effort for Magma Energy (U.S.). No other United States geothermal companies, including Magma, are properly staffed or equipped to efficiently and routinely conduct and interpret such seismic surveys. All seismic supporting services are centered in Texas, far from the locations of all geothermal companies.

5. Conceptual and Structural Model

Description and integration

The only previously published conceptual model of the Soda Lake geothermal system is that of McNitt (1990) which was based on the first three wells and seven slim holes. This model postulated that the "Soda Lakes reservoir is contained in a stratigraphic, rather than a structural feature" and "the thermal fluid probably originates in the deep part of the Carson basin, east and northeast of Soda Lakes. From there, it migrates updip, westward and southwestward, along a permeable horizon in the lower Truckee Formation; further migration to the southwest is prevented by fault B." Unfortunately McNitt did not show the location of fault B in the 1990 paper and this model does not agree with the temperature data which conclusively prove the thermal upwelling is in the southwestern part of the field near wells 25A-33 and 45A-33 with a lateral outflow in the opposite direction to that proposed in the 1990 model (Figure 17).

Regional gravity data show the Soda Lake field is localized on top of the northwest-trending portion of a semicircular gravity high (Figure 3 & 40). The composite shallow thermal anomaly overlies 5-6 miles of this buried ridgeline which represents only a portion of the overall paleo-topographic high. Deep drilling within a small part of this gravity high, and in the 44-5 and Carson Sink #1 wells to the southwest of the high, shows the top of Tertiary volcanic and volcaniclastic rocks is found at elevations at least 1200 ft higher in the geothermal field and over the ridge. Therefore, the gravity ridge is interpreted to define a paleo-topographic high of Tertiary-age volcanic material denser than poorly consolidated Quaternary alluvium. There has been no deep drilling north or east of the gravity high but the seismic and gravity data show poorly consolidated sedimentary material is much thicker on both sides of the gravity high.

A three mile-wide fault zone, probably connecting Big Soda Lake and Upsal Hogback and consisting of generally NNE trending small offset normal faults, cuts across the Tertiary volcanic basement ridge (Figure 40). The great majority of this fault zone and individual faults within it are not geothermally active. It appears that it is the intersection of this fault zone and the Tertiary volcanic basement ridge that regionally controls the location of the Soda Lake geothermal system. A possible regional model of the fault zone involves left-lateral movement (Figures 40 & 41). However, the amount of left-lateral movement since the Tertiary volcanic basement ridge was created is not large enough to produce a recognizable gravity displacement of this ridge.

Three distinct and closely-spaced residual gravity anomalies on top of this ridge are connected or perhaps slightly overlap to define an approximately four-mile-long northwest trending segment (Figure 21). Each of these residual gravity highs is associated with upwelling thermal water that create distinct shallow thermal anomalies (Figures 8 & 22). The central of the three residual gravity anomalies appears to show two particularly closely spaced thermal upwellings. This could in agreement with tracer testing results showing no east-west sub-surface movement of thermal fluid between wells across the operating field.

Geological, gravity, and seismic results show no indication of large offset buried N-S to NE-SW trending normal faults being a controlling structure for the geothermal system. Instead, it appears that thermal water from depths of two or three miles is presumably diffusely migrating from a horizontally-extensive source area to the buried Tertiary topographic high, which may be generically viewed as an antiform. This bears some similarity to the 1990 model but the depth of horizontal migration is much deeper than intimated in the 1990 model and is therefore not a serious potential drilling target. The Tertiary bedrock high acts as a concentrating mechanism focusing a diffuse thermal flow into a restricted area where it becomes concentrated and can be accessed.

Once the thermal fluid is concentrated in Tertiary volcanic bedrock below the gravity highs, probably near a depth of 10,000 ft and below any depth yet reached by drilling, the fluid movement is near vertical in quite restricted areas beneath the more intense portions of the overall thermal anomaly. At this point the fluid temperature, at least in the central anomaly, is probably slightly above 400°F as suggested by the cation geothermometers. Presumably there are similar deep temperatures in the two subsidiary thermal anomalies. At some depth below 4000 ft, the rising fluid funnels into three or more different near vertical channels or individual faults. The one or two channels in the central anomaly allow 338°F thermal fluid to locally pass up through the shallow mudstone unit and rise to within 500 ft of the surface. All four of these channels have some NNE elongation (Figure 40) suggesting upward movement along relatively short segments of optimally oriented normal faults. The eastern and northwestern channels do not appear to pierce the mudstone so there are more subdued near-surface temperatures in these areas. None of these channels move enough thermal water close to the surface to supply a long lateral sub horizontal outflow plume above a depth of 1000 ft.

Once the central channel(s) transmit water with a maximum temperature of 390°F up to a depth of about 3500 ft some of the thermal water accesses sub-horizontal permeability and spreads laterally toward the eastern edge of Section 33 as the deepest documented laterally-flowing aquifer. Thermal water remaining in the vertical channel continues to rise toward the surface in the immediate vicinity of a locally-thick basaltic unit losing a bit more temperature and charges another horizontal aquifer near a depth of 2000 ft with 370°F fluid. It is not known exactly where the thermal fluid rises. No significant production has yet been obtained from the basaltic unit so it does not appear to be providing the primary near-vertical channel. Above a depth of 2000 ft the thermal fluid remaining in the main upflow then continues up to a depth of 1000 ft to 400 ft and diffuses into Quaternary alluvium in all directions, with its ultimate shallow flow downhill toward the NE. In the natural state of the geothermal system a tiny amount of thermal fluid actually reached the surface as steam.

Less detail is known about the eastern and northwestern vertical channels. The thermal fluid does not rise as closely to the surface but temperatures of about 350°F could be present at depths as shallow as 2000 ft. A shortage of deeper holes in these areas makes it uncertain how much thermal water may be laterally leaking out from these vertical channels below a depth of 1000 ft and in what directions it is flowing. No shallow (< 1000 ft) laterally-flowing thermal plumes have been recognized in these two areas but there has not yet been enough drilling to conclusively rule out the presence of any lateral outflows. Given the possible range of temperatures in the eastern and northwestern areas there is no way to predict which geological units might preferentially host permeability. The greatest difference in stratigraphy between the central thermal anomaly and the subsidiary anomalies is expected to be a greatly reduced to nonexistent basaltic unit beneath the subsidiary anomalies. Most of the other recognized units from the gamma ray logs are expected to be present and hopefully be recognizable.

6. Next Steps

Justification for step-out exploration

There are multiple possible next steps that could be taken at Soda Lake to improve the understanding of the resource and increase the megawatt output. In order of increasing costs; 1) additional geophysics or geological analysis can always be performed in the near-term but this will not quickly produce more megawatts, 2) shallow or deep TG holes can be drilled around the margins of the field to more precisely target future step out large diameter wells, or 3) large diameter infill or step-out wells can be drilled. Additional geophysics is not preferred as a reasonably detailed understanding of the area now exists. Only minor improvements in understanding the resource can be expected with additional geological or geophysical analysis. Large diameter infill drilling is also not preferred at this time due to fact that 2009 and 2010 infill drilling at Soda Lake produced the three hottest wells in the field with mediocre flow rates. Step out drilling without some deep TG drilling in Nevada is a tactic that was decades ago demonstrated to have high risk.

Option 2 is preferred by the following logic. Soda Lake is a mature resource, having been in production for over two decades. All production and injection to date have occurred within an area approximately 0.75 mi^2 in size and all of the large-diameter wells are in an area less than 1.5 mi^2 in size. This small field footprint, combined with a 20-year production history, has resulted in 10 to 70°F of cooling of all four of the long-term production wells currently being utilized. The operating field area in Soda Lake is one of the most-densely explored and drilled geothermal areas in the Basin and Range province with 23 large diameter wells and six redrills ranging in depth from 885 ft to 8995 ft. Having never operated at full-output there is no question that Soda Lake needs additional production. However, with the historic cooling, Soda Lake also needs new and different injection capacity to maximize the life of the existing production wells. At this time additional production or injection capacity are both welcome with production capacity being preferred due to its rapid contribution to increased megawatt output and there is currently an excess of capacity in existing injectors.

There are multiple potential drilling targets within the limits of the existing Soda Lake well field. By example, the most conservative drilling scenario could be twinning an existing well such as 32-33 to provide more capacity. While this could have a near-term increase in flow rate and megawatt output it would do little to extend the overall life of the field or increase the overall resource understanding. It may even have the opposite effect with increased injection into existing wells accelerating the cooling. Step-out drilling targets of perhaps one-quarter mile from existing wells within or adjacent to the known field are possible but these are likely to result in only temporary megawatt output improvements. There are no possibilities for step-outs on the order of one-half mile or more within the existing explored field.

Deep drilling, i.e. significantly below 4000 ft at Soda Lake has met with limited technical and financial success to date. The 8489 ft deep 84-33 well successfully produced from between 3300 ft and 3900 ft. The 8995 ft deep 41B-33 well is producing an uncertain but small amount of water from below 3900 ft. The 7350 ft deep 81-33 well is accepting most of its injectate between depths of 3340 ft and 3700 ft with a small fraction exiting as deep as 4990 ft. The 6000 ft deep 25A-33 well has its primary permeable interval at a depth near 4950 ft and is currently being evaluated for its production and injection possibilities. The 4835 ft deep 64-33 RD well encountered most of its permeability above 3500 ft. The 5070 ft deep 11A-33 redrill failed to encounter permeability. The 4950 ft deep 22-33 redrill was lost during drilling. Any future deep drilling within the known wellfield at Soda Lake should be delayed until there is an improved conceptual or geologic model of the area and a financial incentive that justifies the higher costs and risks associated with deeper drilling.

Shallow (up to 1000 ft deep) TG drilling has identified two significant and undrilled subsidiary thermal anomalies within the overall thermal anomaly. These are one-half to one mile outside of the extensively explored core area and have not yet been tested by deeper drilling. Should one or both of these areas contain significant permeability at depths of a few thousand feet, it would at a minimum add a substantial amount of new heat resource to the Soda Lake geothermal field. Whether this heat is directly produced to the power plant via production wells or is more slowly obtained through injection depends upon a variety of financial and engineering factors.

The shallow gravity anomaly to the east of the producing field defines a two mile-long, north-south trending feature crossing the central part of Section 34. This trend continues north into the central part of Section 27 and south into Section 3. The geophysics indicates an overall length of about two miles but there are no temperature gradient holes yet available to define the ends of this anomaly. A water sample collected from the 44-34 temperature gradient hole from a depth of 750 ft at 150°F shows high chloride water similar to the Soda Lake geothermal fluid to be present in this anomaly.

To the northwest of the producing field more widely-spaced temperature gradient holes indicate a NNE –trending anomaly about three miles long. No geochemistry is available from this anomaly.

The fact that the geophysical and temperature signatures of these two anomalies are miles-long is very encouraging as this indicative of previously unrecognized faults or structures which should be optimally oriented to create open space during normal faulting movement. There can be very large amounts of open space along a few mile-long normal faults, as opposed to a fault intersection or a short change in direction along a fault.

Within Option 2 there are possibilities for drilling additional shallow TG holes, deeper TG holes, or perhaps some combination of both. At this time deeper drilling is the preferred next step as the shallow TG holes have already identified locations where temperatures above 300°F can reasonably be expected to be present below depths of about 1500 ft. It is currently more important to demonstrate that these predicted temperatures, and perhaps permeability, actually exist in these target areas than it is to drill additional shallow holes to more narrowly define the shallow thermal anomaly. If the observation holes encounter high temperatures, say greater than 350°F they will prove the presence of a hot and active geothermal system(s) at shallow depths and it will reduce risks for any large diameter well drilled nearby. If the slim holes fail to demonstrate temperatures above 300°F then there is likelihood that these targets may not be hot enough to be considered for possible future production. In that case additional shallow TG holes may be needed to determine if another part of these structures, such as their ends, is more prospective. Possible temperature gradient changes or even temperature reversals below 1000 ft may exist to complicate things, but knowing such complications exist and utilizing them as deeper targeting tools is a well known geothermal exploration strategy. For these reasons, it is concluded that there exist adequate data and knowledge to advance to the deep TG hole or observation hole stage of exploration. This does not rule out the possibility of a few more, shallower TG holes at a later date to further refine a large diameter exploration well target(s).

Targets

Targeting Criteria and Justification

Proposed Section 34 Observation Hole (44B-34)

In 2010 Magma Energy, after going through a rather lengthy permitting process, completed an Environmental Assessment containing two well sites in Section 34. These sites were largely based on the results of a microgravity survey that outlined a two mile-long north to north-northeast-trending high-gravity anomaly passing through the central part of Section 34 (Figure 22). This anomaly was interpreted to result from shallow densification of Quaternary sedimentary formations, most likely from silica deposition related to the geothermal system. The 44-34 site sits near the center of this gravity anomaly and the 75-34 site was located just east of the anomaly.

The first TG hole drilled by Magma in 2010 was the TG44-34 hole which managed to reach a depth of 750 ft but could only be completed and temperature logged to a depth of 170 ft due to formation instability and the lack of a suitably sized mud pump on the reverse circulation rig. A second hole, 44A-34, also suffered instability problems but was completed at a depth of 584 ft with a maximum temperature of 142°F and a gradient of 16°F/100 ft. Both of these values are substantially greater than were found in the 84-33 well located about 0.4 mile to the west (Figures 11 & 24). The TG44A-34 confirmed the discovery of a new thermal upwelling zone previously indicated only by the microgravity survey. At a depth of 584 ft the 44A-34 hole is the hottest of the six Magma TG holes. Nevada regulators require that the next hole drilled on this location be named 44B-34.

Normally extrapolating a 16°F/100 ft temperature gradient to greater depths is a speculative endeavor as it is certain that the gradient will suffer a large decline or even a reversal. However, in this case the nearby 84-33, 81-33, and 58-34 wells indicate that this gradient can and probably will continue until temperatures > 300°F are present (Figure 11). There is no reason to expect that the temperature gradient will increase above 16°F/100 ft. The most optimistic temperature extrapolation, a linear extrapolation of the measured 16.3°F/100 ft gradient, gives a temperature of 360°F near a depth of

1900 ft. Temperatures above 360°F are possible but it would be highly optimistic to plan on that at this time (Figure 24).

The 58-34 hole, drilled prior to any recognition of the gravity data, is also located over the microgravity high and this similarity with TG44A-34 therefore is also a likely predictor of temperatures at greater depth beneath the 44-34 pad. The 58-34 temperature profile shows a pronounced drop in gradient below a depth of about 1200 ft which makes it significantly cooler than the 81-33 and 84-33 holes (Figure 11). The 58-34 profile offers a general guide as to a reasonable less optimistic extrapolation. How the 44A-34 profile could drop down to the 58-34 profile is uncertain. An actual reversal of gradient seems unlikely. A modest decline in gradient at some point is inevitable simply due to the rocks having higher thermal conductivity at greater depths. It seems reasonable to expect that a deeper well at the 44-34 pad will encounter a temperature of 306°Fat a depth between 1500 ft and 3500 ft. How much above 306°F the 44B-34 observation hole may be is uncertain.

The seismic reflection survey supports the temperature and gravity data by indicating the presence of one larger-offset east-dipping fault located a few hundred feet east of the proposed 44B-34 location (Figure 42). There are other possible small offset faults crossing the proposed 44B-34 trajectory and there is really no way to predict which, if any, of these faults is likely to provide good permeability. In the absence of lost circulation it will be very difficult or impossible from cuttings and a gamma ray log to recognize if or where the 44B-34 crosses any or all of these faults until multiple holes have been drilled in this area.

The geology at the 44B-34 site is expected to be generally similar to that found in the 58-34 well one-half mile to the south. The 4000 ft planned maximum depth of the observation hole should be deep enough to penetrate several hundred feet into the Tertiary volcanic basement where the deep fractures have historically been found. Volcanic basement is present at a depth of 3400 ft in well 84-33, one-half mile to the west. Drilling an observation hole to a depth of 5000 ft would require that a larger drilling rig be utilized, greatly increasing the mobilization and hourly charges.

Proposed Section 20 Observation Hole (46A-20)

Based on micro-gravity data, the 46-20 TG hole was located near the expected heart of the northwestern thermal anomaly and showed a bottomhole temperature of 196°F at a depth of 912 ft and a bottomhole temperature gradient of about 17°F/100 ft (Figure 12). It did not encounter any shallow thermal aquifers. A simple linear extrapolation of this gradient permits a temperature of 350°F as shallow as 1750 ft.

As the TG46-20 hole did not encounter any shallow thermal aquifers a second hole, TG64-29, was later drilled between TG46-20 and 77-29 with the dual objectives of trying to better constrain the extent of the shallow thermal aquifer utilized by wells 77-29 and 87-29 and further demonstrate that the northwest thermal anomaly truly overlies a distinct anomaly and not a outflow plume from the operating field. The TG 64-29 hole is cooler than the TG46-20 hole reinforcing the concept of a cooler septum between the central and the northwestern thermal anomalies (Figure 24). 64-29 TG did not encounter a shallow thermal aquifer which further limits the western extent of the shallowest aquifer a short distance (perhaps only hundreds of feet) west of wells 77-29 and 87-29 (Figure 13).

There is no reliable method available to predict the depth at which there will be either a reversal in the TG46-20 profile or a very large decrease in its temperature gradient which define its effective maximum temperature. The only way to know the temperature at depth is to drill deeper and in this case a hole should be planned for a depth of at least 3000 ft with the possibility of going to as much as 4000 ft to again be reasonably certain the hole can extend into the Tertiary volcanic basement rocks. The uncertainty is in the temperature and the quantity of the fluid. On the most pessimistic side of things the maximum temperature beneath the 46-20 pad could be less than 200°F to a depth of a few thousand feet. While this is unlikely given the known temperatures of the nearby producing area, it is also the reason why lower-cost small diameter observation holes are drilled.

The northwestern thermal anomaly is strongly elongated in a NNE-SSW direction which is the perfect direction in Nevada for faults to pull-apart to create the open space needed for a geothermal reservoir (Figures 8, 9 & 10). This suggests that the thermal anomaly is associated with a normal fault and permeability associated with this thermal anomaly may occur in a narrow NNE-SSW trending band. The length of this anomaly as currently defined appears to be between three and four miles, which makes it an exceptionally long feature for Soda Lake. The northwest anomaly lacks the very shallow intensity of the currently producing thermal anomaly but this may simply be a function of a more effective "caprock" overlying the northwest anomaly. The reduced shallow temperature gradients should not be interpreted to imply that the northwest anomaly is of a lesser quality.

The seismic survey indicates a plethora of small offset down to the east normal faults in the vicinity of the 46A-20 site (Figure 43). One potentially larger offset fault has been interpreted. It will be very difficult to impossible to recognize these faults in one hole without a large loss of drilling fluid.

The geology of the 46A-20 area to a depth of 912 ft is more or less identical to that known from the producing area. Below 912 ft it is expected that the geology will also be similar. Perhaps the greatest difference will be in the thickness of the basalt, which may not even be present in the 46-20 area. The basalt has not historically been a productive unit so there is no reason to view it as a permeability target. It is not possible to predict which, if any, of the stratigraphic units recognized in the producing field, will be preferred fracture hosts.

There are currently only two sites approved for drilling on the federally-managed Section 20, 46-20 and 51-20. No hole has yet been drilled on the 51-20 site. The 51-20 site is one-half mile farther from any existing plant facilities and requires an additional one-half mile of road upgrade so it is not now the preferred of the two approved locations in the northwestern thermal anomaly.

7. Drilling

Drilling Prognosis

The purpose of drilling the vertical 44B-34 and 46A-20 observations wells is primarily to demonstrate that temperatures above 320°F exist at depths above 4000 ft to supply geothermal fluid to one or both of the existing Soda Lake power plants. The term observation hole is utilized here as there will be no attempts made to flow or flow test either of these holes. Use of the term slim hole implies at least an attempt to flow test the well. If major permeability is also encountered in terms of lost circulation it will define a complete success. Even if lower temperatures (280 – 300°F) and permeability are encountered the results may still be considered successful for future injection purposes. A hole that is both cool and impermeable will obviously not be considered successful, but the existing body of knowledge indicates that low temperatures are a low probability event. There is much less certainty in predicting the amount of permeability.

The technical drilling prognosis for the two observation holes is reasonably certain given the number of existing holes and wells between them. None of these existing holes encountered any geological problems that resulted in slow drilling or significant costs. The only artesian flows ever found in the Soda lake area is in the vicinity of the 41-33 pad.

There are six other deep TG holes in Soda Lake which have applicability in predicting how long it should take to drill the observation holes to about 4000 ft. These deep TG holes all reached a depth of ±2000 ft in 5 to 7 days following spud with one casing string cemented to depths of 200 ft to 400 ft so an annular

BOP could be used. It is assumed it will take six days from spud to reach a depth of 2000 ft in the proposed observation holes. Drilling below 2000 ft is a bit more uncertain as only two slim holes have been drilled below 2000 ft to date. The 62-33 hole suffered through two fishing jobs, dropped drill pipe, and mud pump repairs. The 58-34 rig was plagued by rig repairs deep in the hole but did reach a depth of 3120 ft in 11 days. With this experience in hand it is likely that a hole can be drilled to 2000 ft in six days and then further deepened to about 4000 ft in an additional eight or nine drilling days.

Drilling will be performed 24 hours a day below the 7" casing. Prior to setting the casing the drilling can be either during daylight hours or around the clock.

The shallow formations consisted of unconsolidated sand, fine gravel, and mudstone which can be easily penetrated with a drag bit perhaps to depths approaching 2000 ft. Once a drag bit suffers a reduced penetration rate it will be replaced by a tri-cone bit. The seismic data permit the Tertiary volcanic basement to be present below depths of 2200 ft to 2700 ft.

The temperatures are relatively well known in the Section 33 and 34 area. The 44A-34 temperature gradient hole is the hottest of any hole in the local area at its total depth. For planning purposes it seems most likely that the 44B-34 hole will most closely track the 81-33 well profile at greater depths. This is why the 44B-34 hole is conservatively programmed for a total depth of 4000 ft to be relatively certain of reaching the maximum temperatures present in the area. Should the 44B-34 hole be significantly hotter than the 81-33 profile then it can or will simply be terminated at a depth shallower than 4000 ft, especially if lost circulation is encountered. There is no intent to seriously fight any lost circulation that might be encountered deep in 44B-34 that may represent reservoir permeability. The temperatures at depth in the 46A-20 hole are less certain.

The holes will be drilled with a simple pH controlled bentonite mud system utilizing a shaker table to remove solids. Only in the event of drilling difficulties will a mud engineering service be requested. The least-cost mud will most likely be obtained from the closest supply depot to minimize trucking charges and delivery time. An onsite water storage tank will be filled by a water truck.

The high formation temperatures will result in high mud-out temperatures but are not anticipated to be a serious problem for drilling as some of the other previously drilled slim holes encountered higher sub-surface temperatures than anticipated here. Mud coolers have not been utilized on any previous Soda Lake slim holes. An oversized split sump or a second sump where hot mud can be dumped have been utilized to control mud temperatures in the past and could be used here if needed.

At the completion depth the hole will be full of mud if there is no lost circulation. This mud is necessary to assure that the wellbore stays open so that completion tubing can be installed to the bottom of the well. Changing out the mud to water runs the risk of allowing the soft formations to cave in which would prevent the completion tubing from reaching the bottom of the well. If the well encounters lost circulation at relatively shallow depths, efforts will be made to seal it up with lost circulation material or cement plugs so that drilling can safely continue. If severe lost circulation is encountered deep in the well, the drilling will be terminated.

The well will be completed by hanging a mule shoed string of 2 7/8" EUE from a tubing hanger flange bolted to the top of the casing head. A valve will be placed on a nipple on top of the flange used to secure the tubing. The EUE tubing will be rabbited as it is run into the well and filled with clean water so that high temperature memory logging tools are certain to reach the bottom of the tubing. It is anticipated that from 1 to 3 weeks after completion, a temperature/gamma ray log will be run in the well with a 1 ¾" O. D. high temperature memory logging tool. The gamma log will allow geological correlations with the existing wells. A second memory tool temperature log may be run at a later date after the well has unquestionably had time to thermally equilibrate. After the fully equilibrated temperature log is obtained then the 2 7/8" tubing may be perforated in or near its bottom joint for use as a possible pressure monitoring well. If the tubing is perforated then it is likely attempts will be made to inject some clean water to have the best possible connection with the lost circulation zone.

Cuttings will be collected every 10 feet from the well and placed in cloth bags, two sets of paper envelopes, and plastic chip trays. They will be logged by a graduate student currently involved in studying the basic geology and evaluating the cuttings from the other Soda Lake wells. Two sets of paper envelopes will need to be delivered to the Nevada Bureau of Mines and Geology in Reno.

The holes have been permitted as an observation well as per the Nevada Division of Minerals regulations. Bureau of Land Management drilling permits are also required and have been submitted. The environmental work for permitting the 44B-34 access road improvements and pad has been completed under an Environmental Analysis. The environmental work for 46A-20 has been submitted to the BLM

The 3/8 mile-long unimproved road to the 44B-34 site will need to be slightly straightened and covered with a 2–3" layer of crushed rock to ensure heavy vehicle access in the flat sandy terrain, especially during the dry summer months when drilling is anticipated. This will eliminate the need for watering the road. About 1.2 miles of existing road will need to be improved with gravel or crushed rock to enable trucks to reach the 46A-20 site.

The pads will need to be approximately 200 ft by 200 ft with a sump approximately 75 ft long, 25 ft across, and up to 8 ft deep. The sump will not be lined. A two to three foot-deep cellar utilizing culvert material for its walls will be installed when the pad is prepared and a 10" conductor pipe will be set to a depth of 40 ft with a bucket rig prior to the drilling rig moving on location. During drilling there will be a port-a-potty on location and a dumpster for trash. There will not be a "company man" continuously on site so there will be no need for a living trailer, although 24-hr communication channels must be established and the rig crew clear on protocols in the case of difficulties or lost circulation.

If the observation holes do not encounter significant deep permeability it may be abandoned within a few months. If the hole encounters significant permeability then the holes may be utilized over the long term by perforating the 2 7/8" tubing near its bottom and monitoring the liquid level.

At this time it is unclear if a specialized casing running crew will be utilized to run the 7" casing. In part, it will depend upon the capabilities of the selected rig to effectively handle the 7" casing. A local redi-mix concrete company will deliver wet neat cement to the site that will then be pumped with the rig pumps or another pumping unit. Due to the short length of casing there is no need to bring out a specialized cement pumping unit typically utilized on larger or deeper wells.

A core rig is simply not the proper equipment for least cost drilling at Soda Lake. The advantages of core rigs, other than having the core, are rapid near surface penetration in hard formations and minimal water requirements in severe lost circulation drilling. Neither condition is present at Soda Lake. Reverse circulation equipment can be utilized at Soda Lake provided that the rig is equipped with an adequately sized mud system. Recent experience at Soda Lake has shown that reverse circulation drilling without a mud system results in unstable boreholes that make recovering the drillpipe and running completion tubing questionable. Reverse circulation drilling has the potential drawback of using much more expensive double wall drillpipe should any of it be lost in the well. Of course, core or the higher quality cuttings from reverse circulation drilling are nice for the geologic interpretation, but experience has shown that gamma ray correlations at Soda Lake are also very effective in defining the stratigraphy and making correlations between wells.

Drilling Programs for 46A-20 and 44B-34

1. Place 2-3" of gravel on 1.2 miles of existing sandy access road to 46A-20 and on 0.4 mile of existing sandy access road to 44B-34. Use proposed pad and existing intersections as turnaround sites. Have turnouts every 1/8 mile on road to 46A-20 where there are no nearby road intersections suitable for turnouts.
2. Construct pad 200 ft x 200 ft and gravel with 2-3" of gravel. Construct sump 80 ft x 20 ft x 6 ft deep using onsite material.
3. Construct 2-5 ft deep cellar
4. Use bucket rig to drill hole for 9 5/8" or 10" conductor pipe and install and cement conductor pipe
5. Move in and rig up drilling equipment
6. Mix up 8.6 to 9.0 lb/gal bentonite mud with funnel viscosity of 60 - 80
7. Drill 8 ½" hole to 500 ft with drag bit and mud, collect cuttings samples every 10 ft.
8. Run 500 ft of 7" 23 lb/ft casing
9. Cement in 7" casing with Redi mix truck,
10. Wait on Cement
11. Cut off casing and weld on casing head
12. Nipple Up 2000 psi Annular BOP
13. Pressure test BOP and Casing
14. Drill out cement inside casing with a 6 1/8" tricone bit
15. Pull out of hole and change to a 6 1/8" drag bit
16. Drill 6 1/8" hole with mud and a drag bit until penetration rate becomes unacceptably low, collect cuttings samples every 10 ft.
17. Change to 6 1/8" tricone bit and drill with mud to either lost circulation or a maximum depth of 4000 ft. If significant drilling difficulties are encountered the hole will likely be completed at the existing depth. Collect cuttings samples every 10 ft. Monitor mud-out temperatures.
18. Circulate hole clean with mud and run mule shoed 2 7/8" EUE tubing and hang from tubing hanger on top of casing head.
19. Fill 2 7/8" tubing with clean water
20. Clean mud tanks, rig down, secure well with a valve on top of the tubing, and demobilize
21. Run repeated temperature logs and one gamma ray log inside tubing after the well has had some time to thermally stabilize.

Note: Unconsolidated lacustrine and alluvial material is expected to a depth of 1500 ft-2000 ft where a basaltic layer may be present. Sticky clays above a depth of 1000 ft have resulted in slow tricone drilling in some previous holes. Below the basalt soft to moderately hard formations are expected. Other than the basaltic unit there are no recognized or named formations at Soda Lake. Instead, the geology consists of dozens of thin units.

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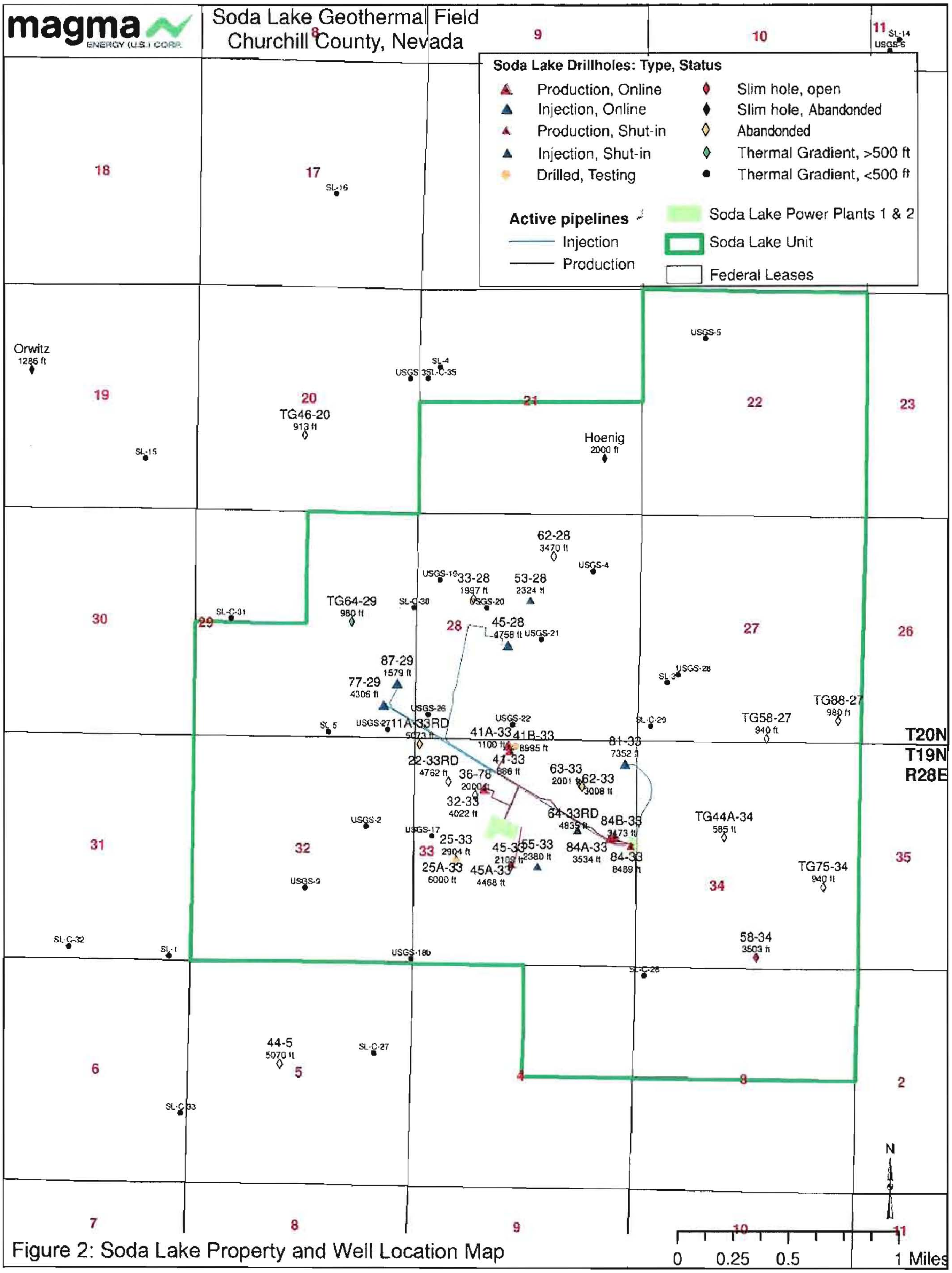


Figure 2: Soda Lake Property and Well Location Map

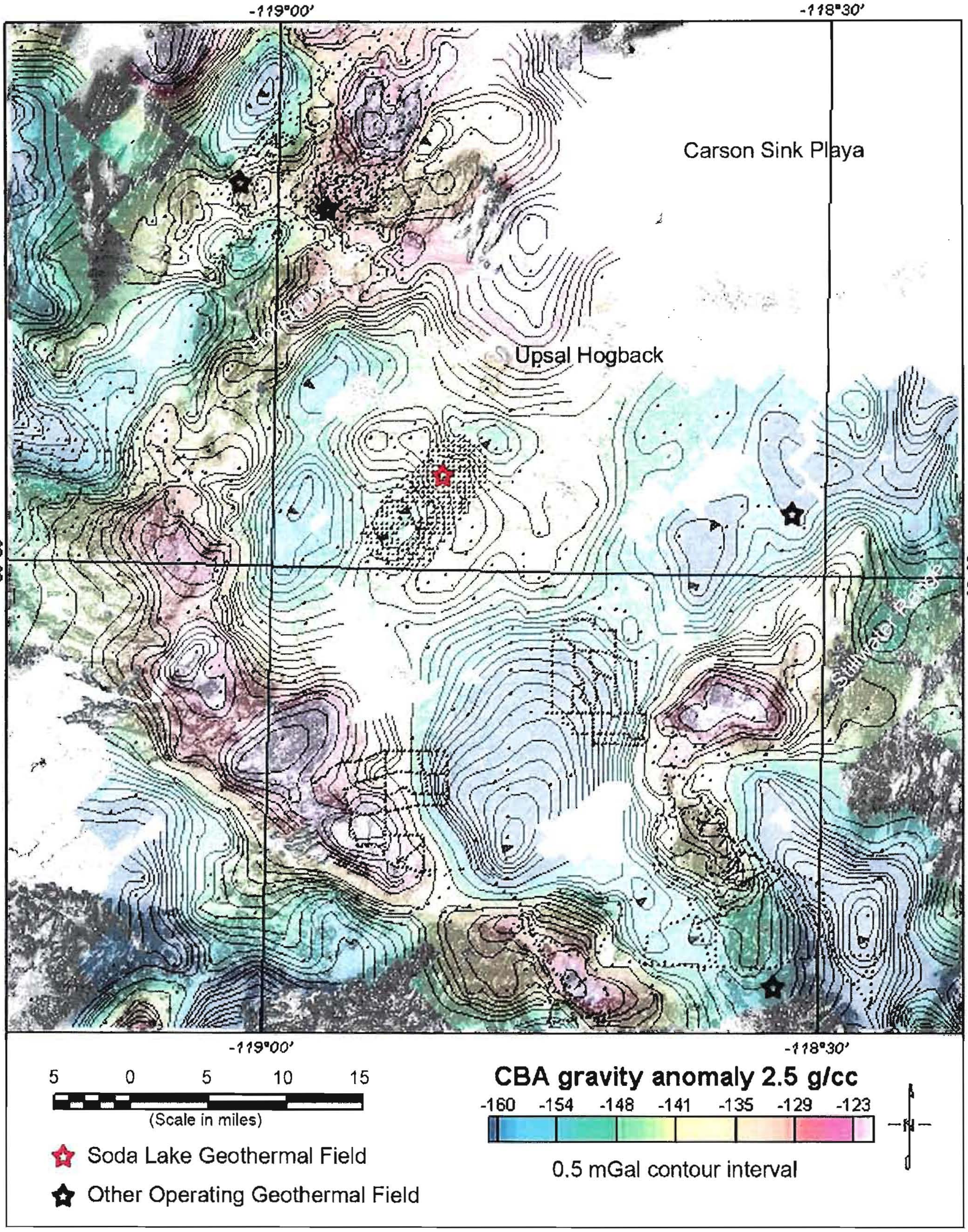


Figure 3: Carson Sink Regional Gravity Map. Complete Bouguer anomaly (CBA) gravity data from a variety of publicly available data and new Magma surveys.Gravity station shown as black dot.

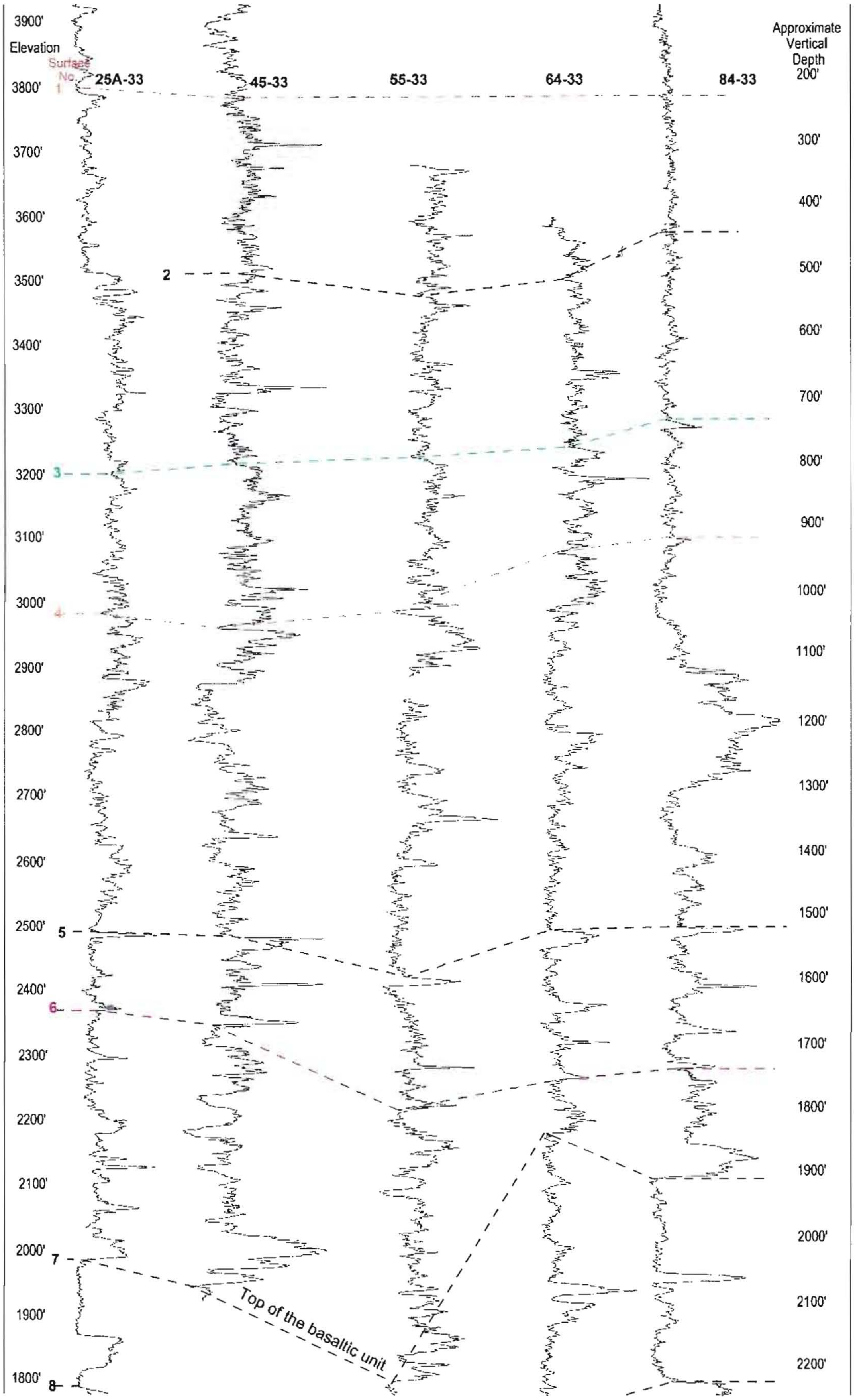


Figure 4a: Examples of Shallow Gamma Log Correlations in Section 33. The 8 labeled correlations are based on sharp individual inflections or spikes and define surfaces that can be recognized in most of the wells in the field. Many other correlations are possible, especially between more closely spaced wells. Surface 7 is the top of the basaltic unit. The 4 peaks unit lies between surfaces 5 and 6.

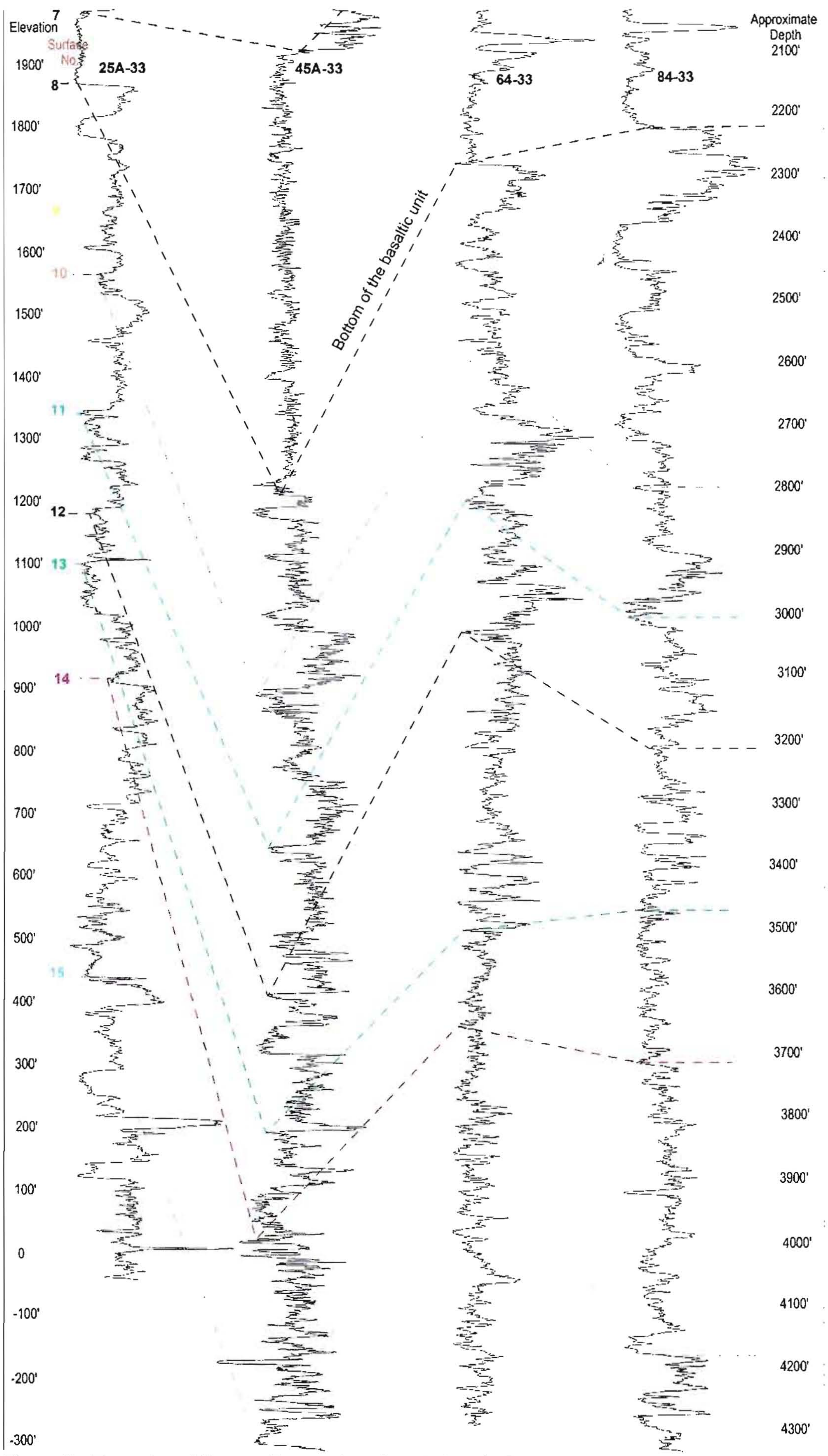


Figure 4b: Examples of Deeper Gamma Log Correlations in Section 33

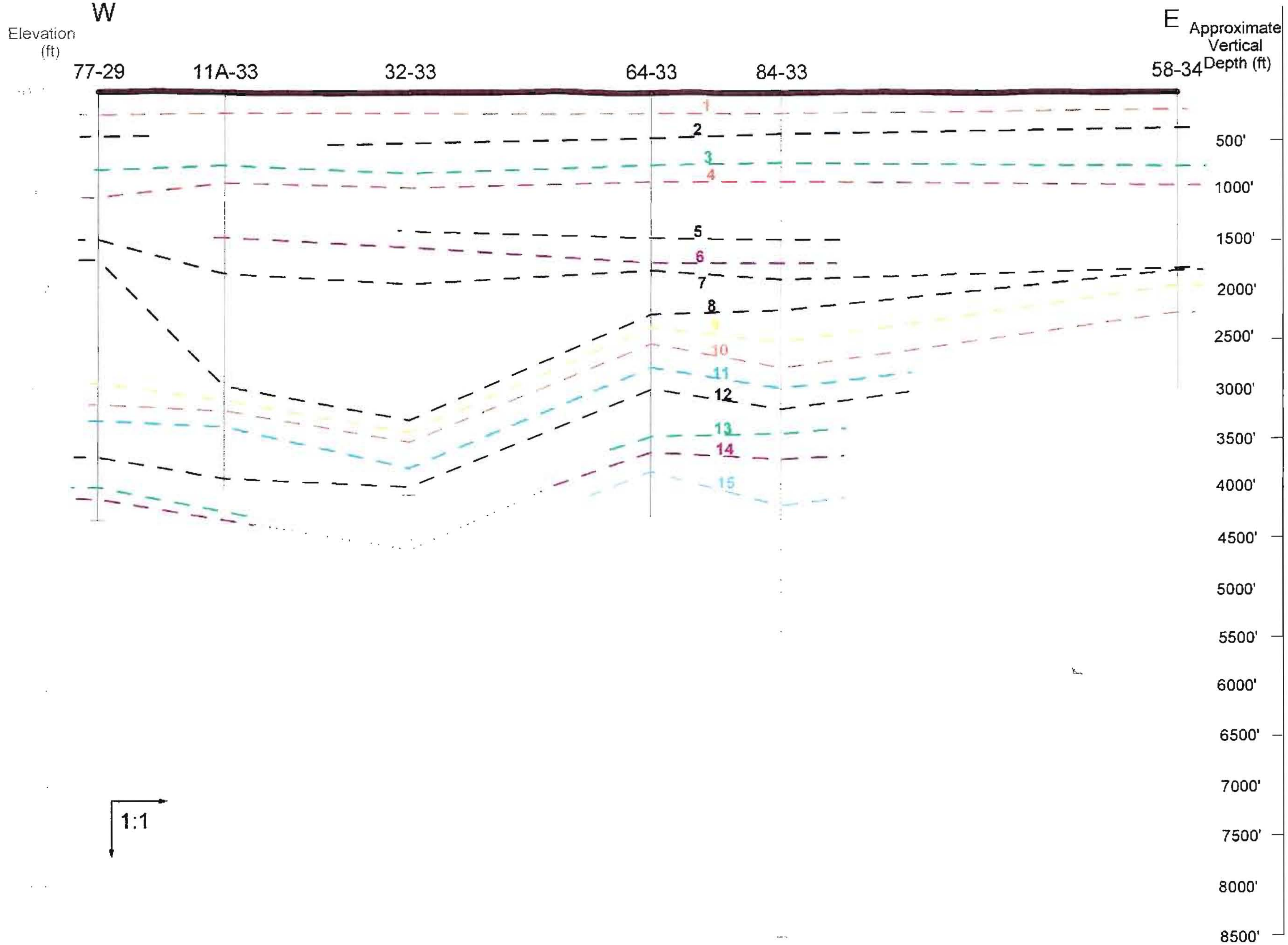


Figure 5: Gamma ray correlations across Soda Lake geothermal field, east-west

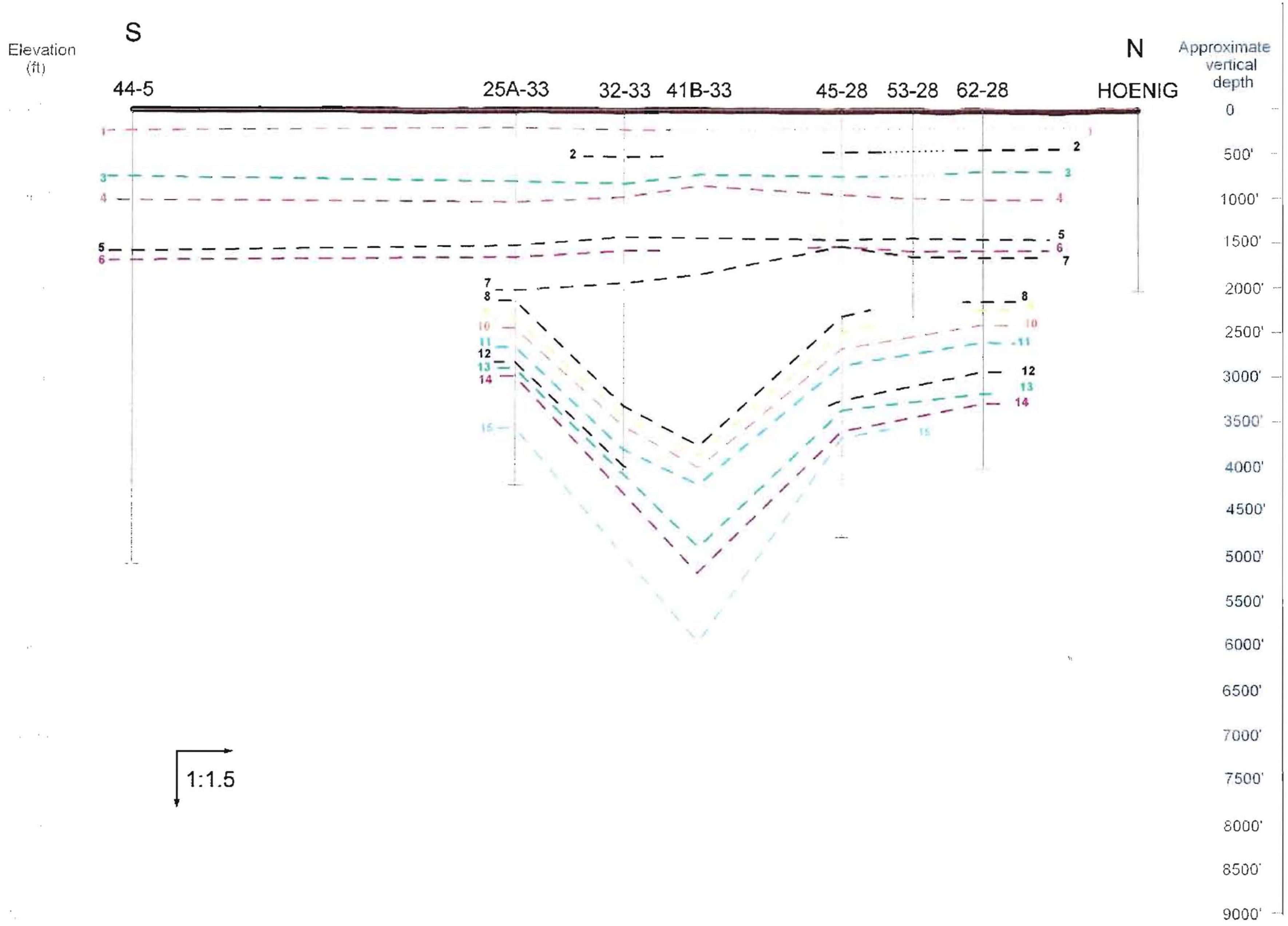


Figure 6: Gamma ray correlations across Soda Lake field, north-south

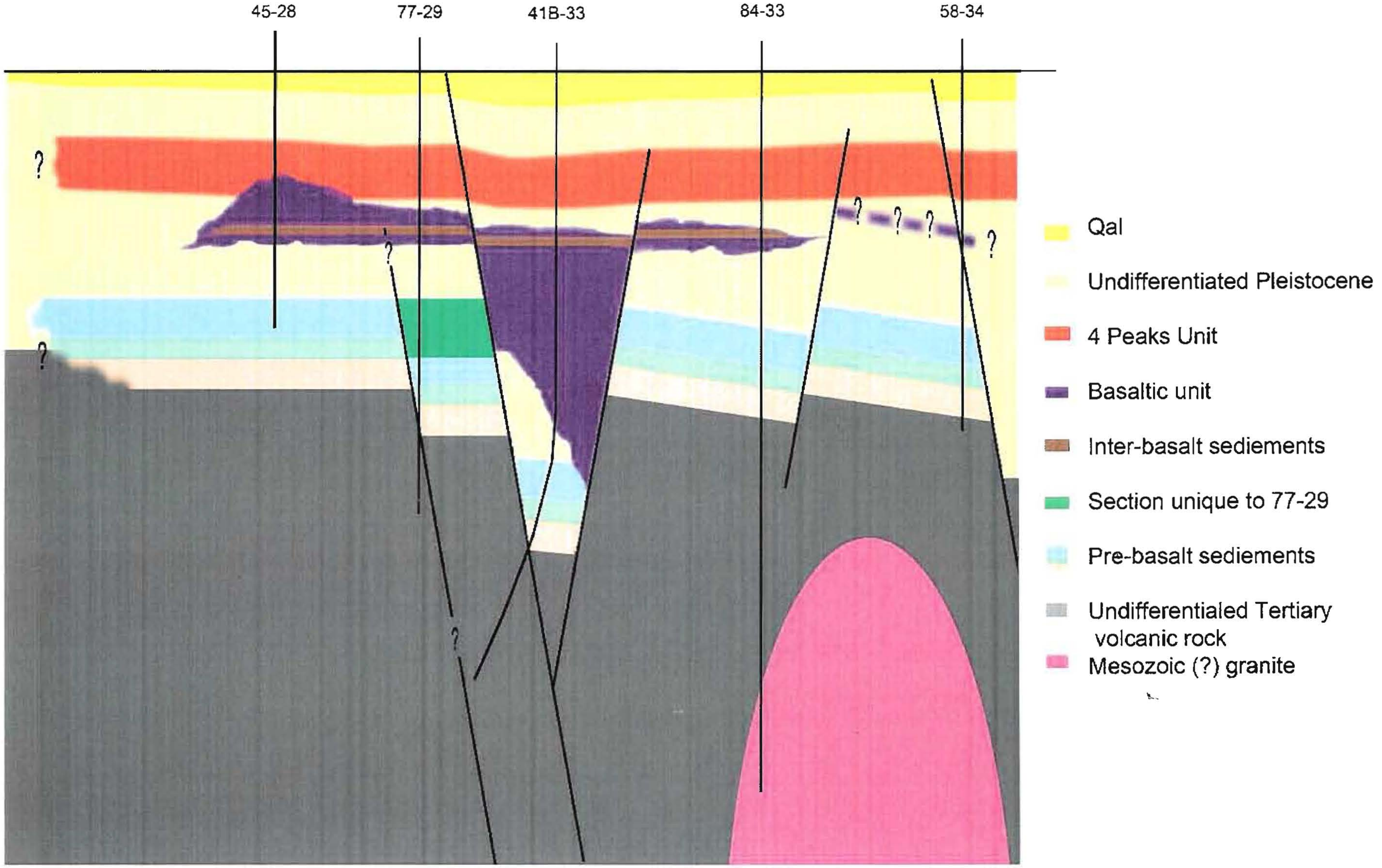


Figure 7: Geological cartoon showing generalized geological relationships interpreted from gamma ray logs

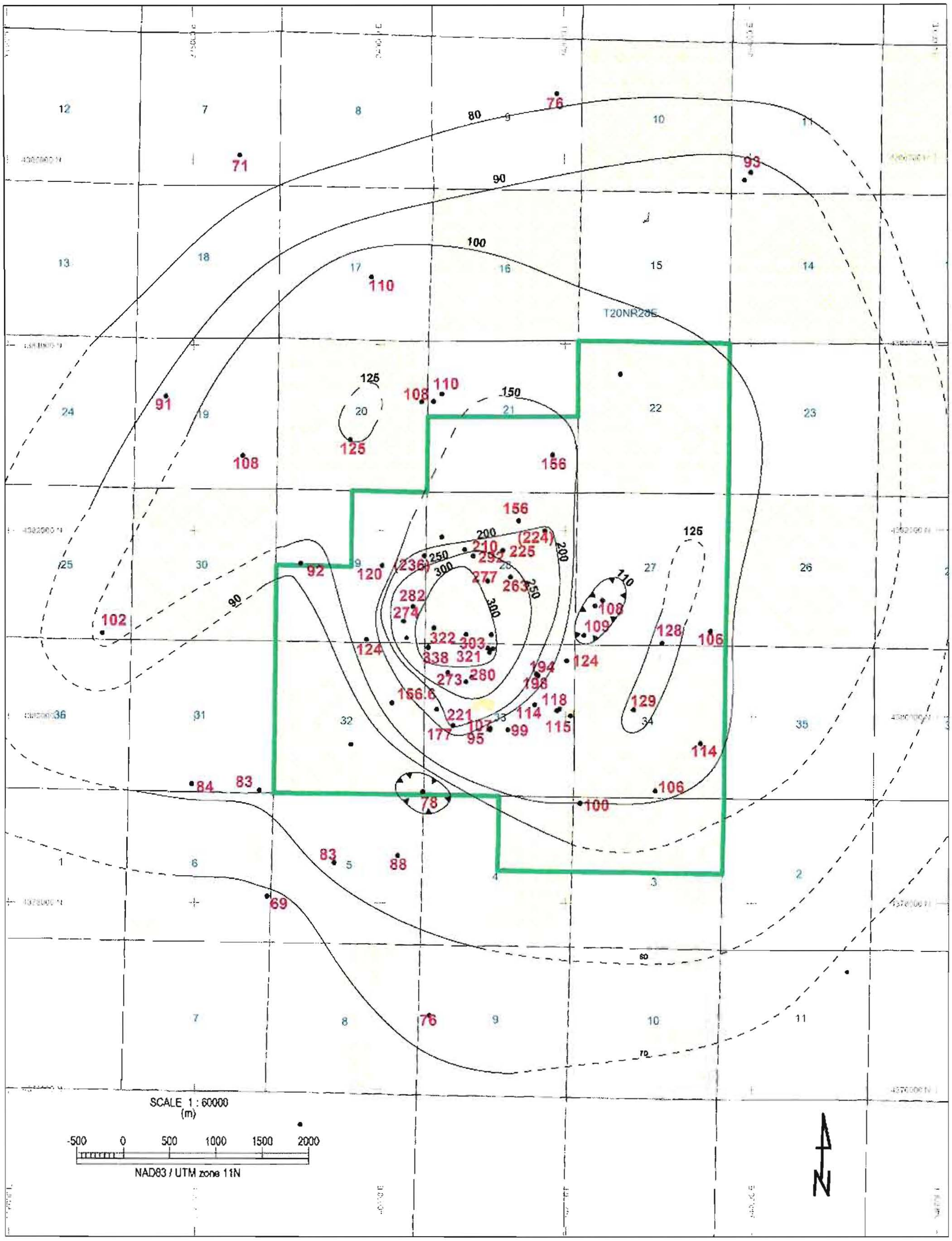


Figure 8: Measured Temperatures (°F) at a Depth of 500 Feet

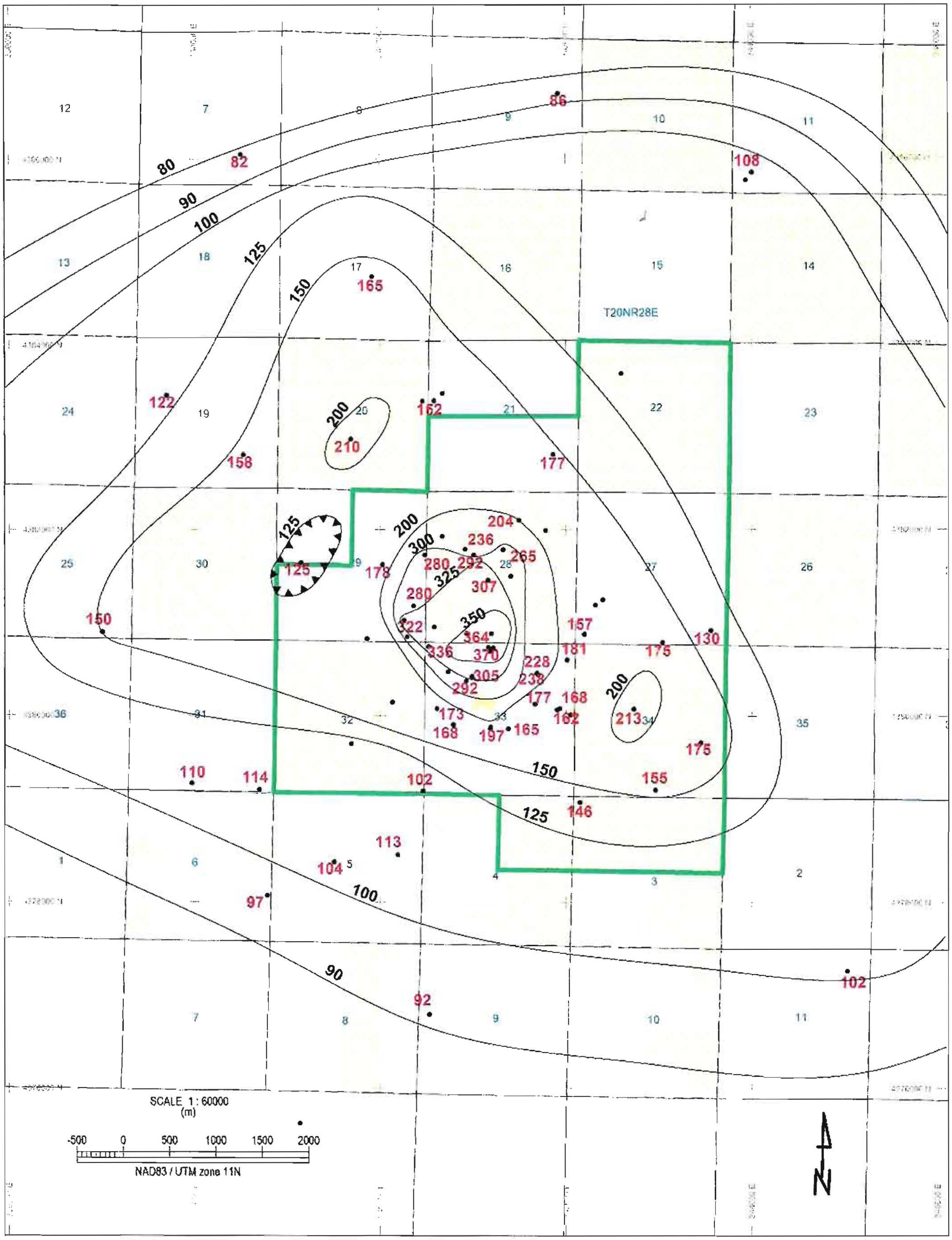


Figure 9: Measured and Extrapolated Temperatures (°F) at a Depth of 1000 Feet. All extrapolations are linear and are from a measured linear temperature gradient.

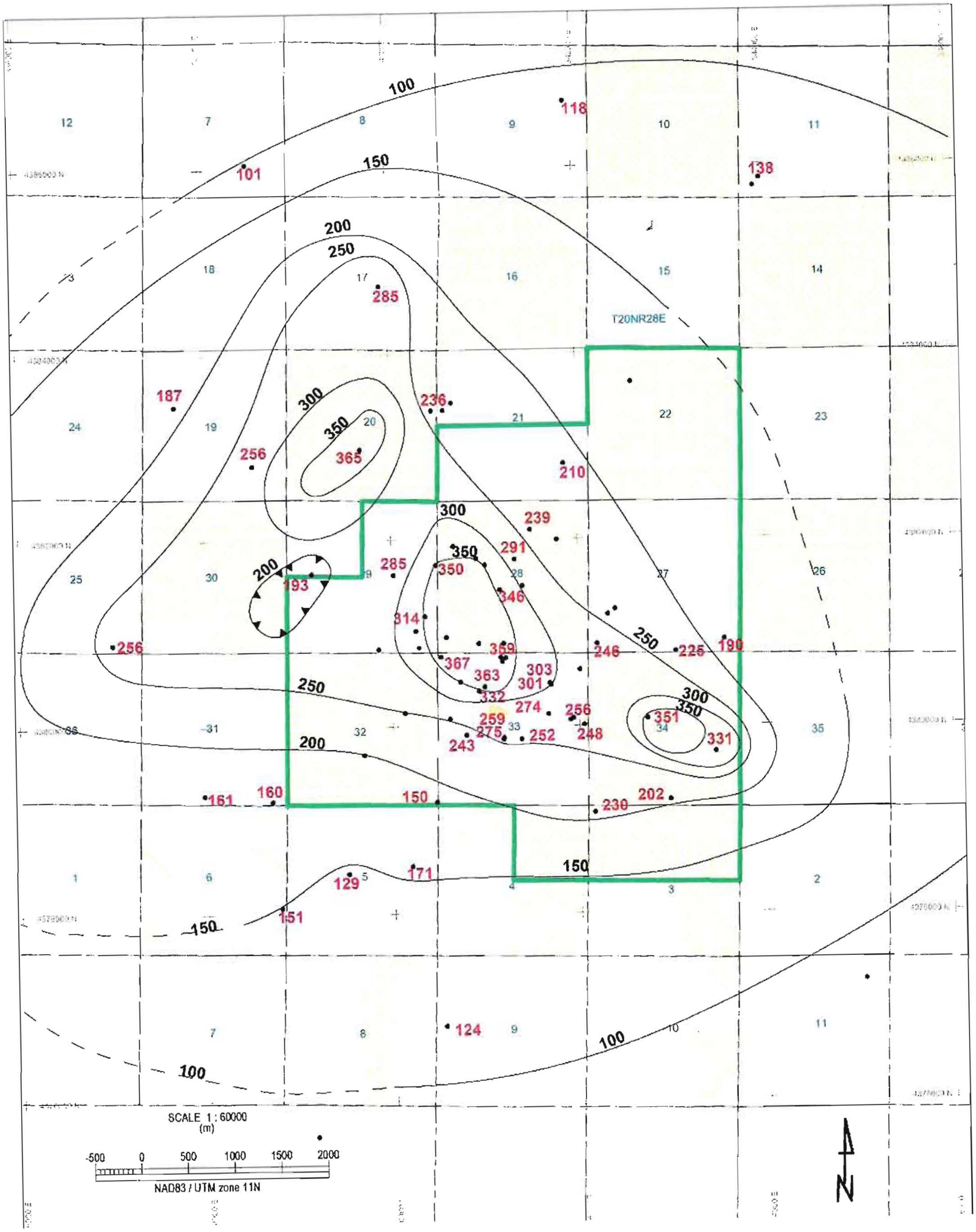


Figure 10: Measured and Extrapolated Temperatures (°F) at a Depth of 2000 Feet. All extrapolations are linear and are from a measured linear temperature gradient.

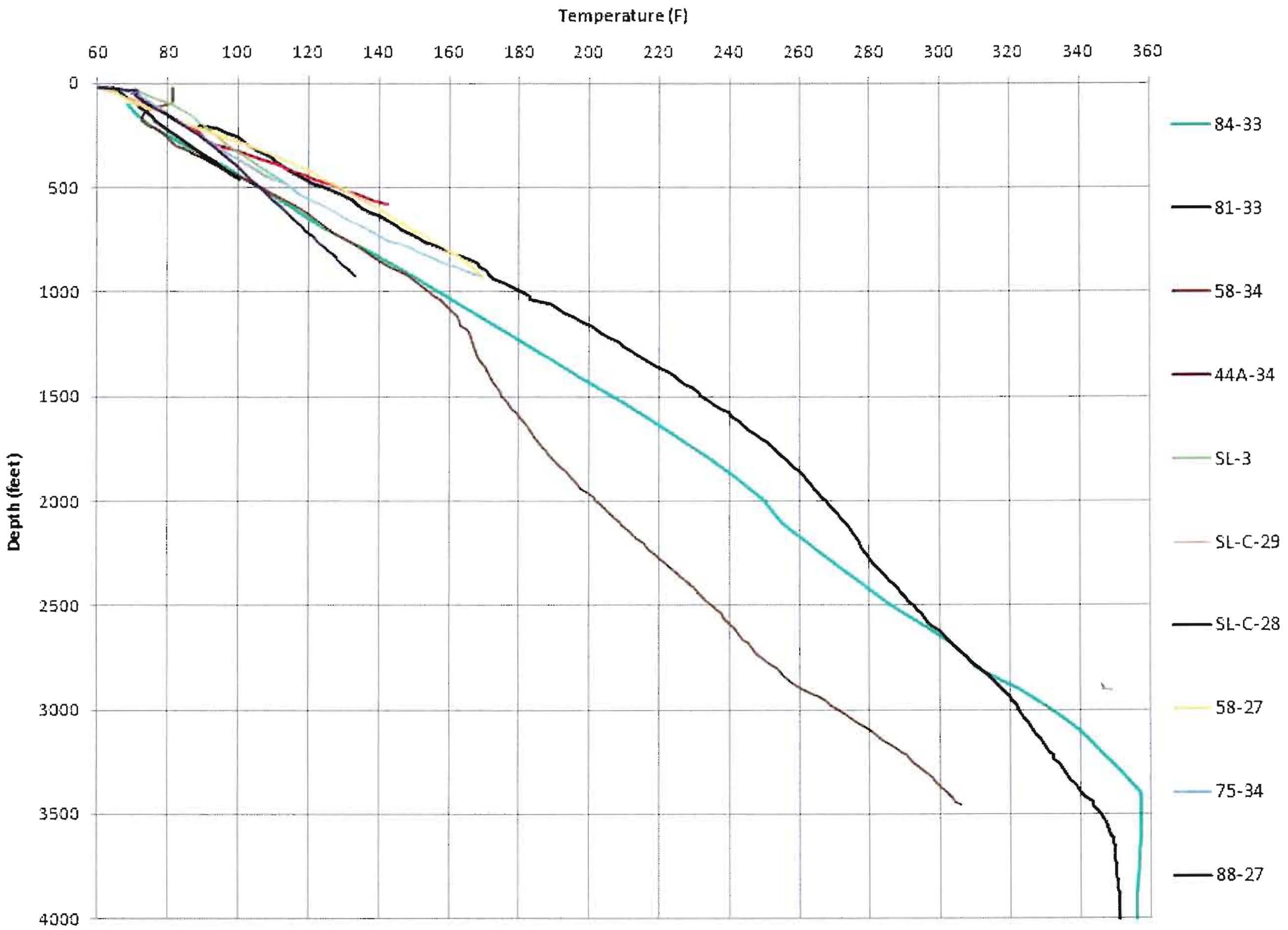


Figure 11: Section 34 Area Thermally Equilabrated Temperature Profiles.
These surveys were obtained with several different instruments.

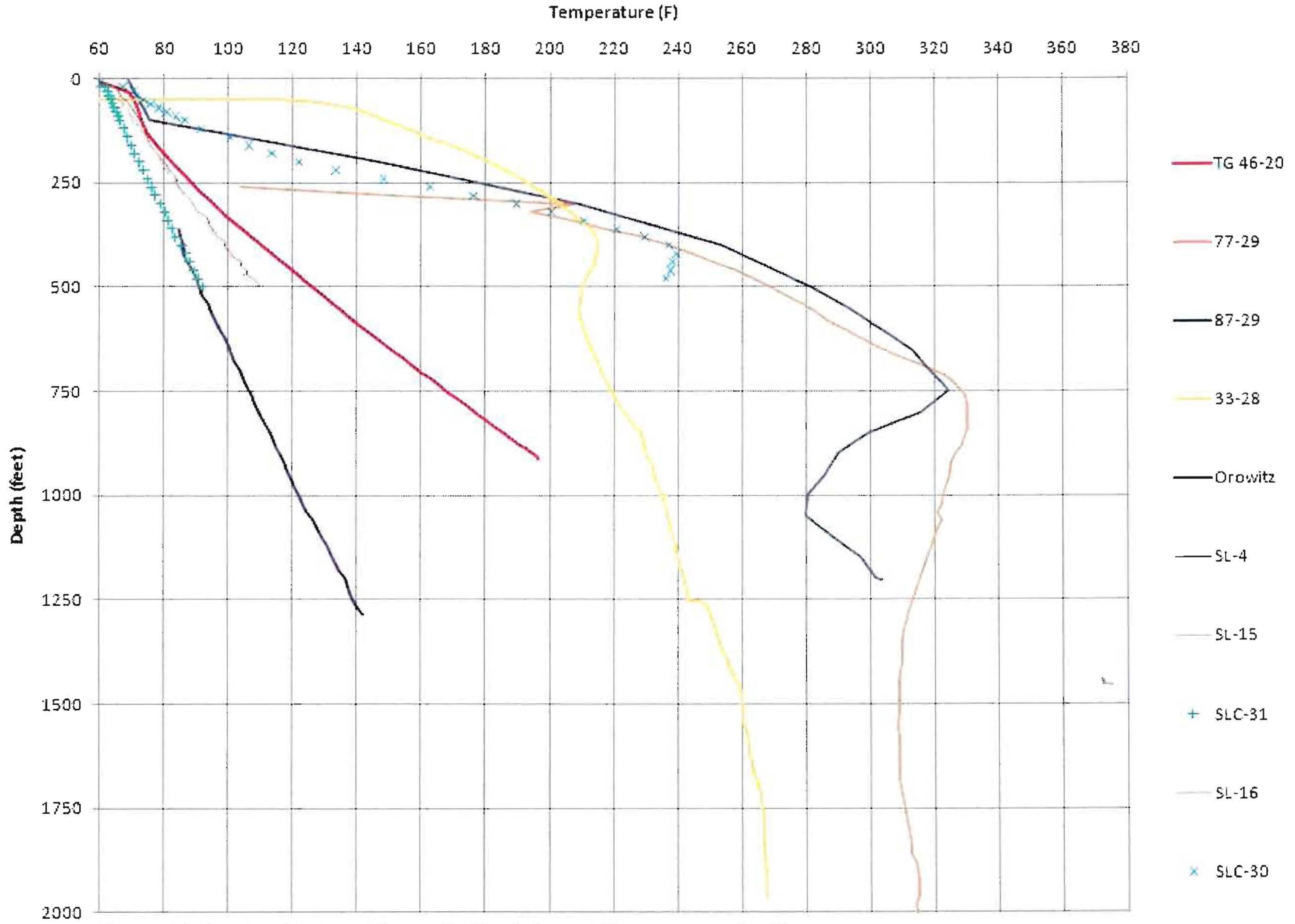


Figure 12: Section 20 Area Thermally Equilabrated Temperature Profiles.
These surveys were obtained with several different instruments.

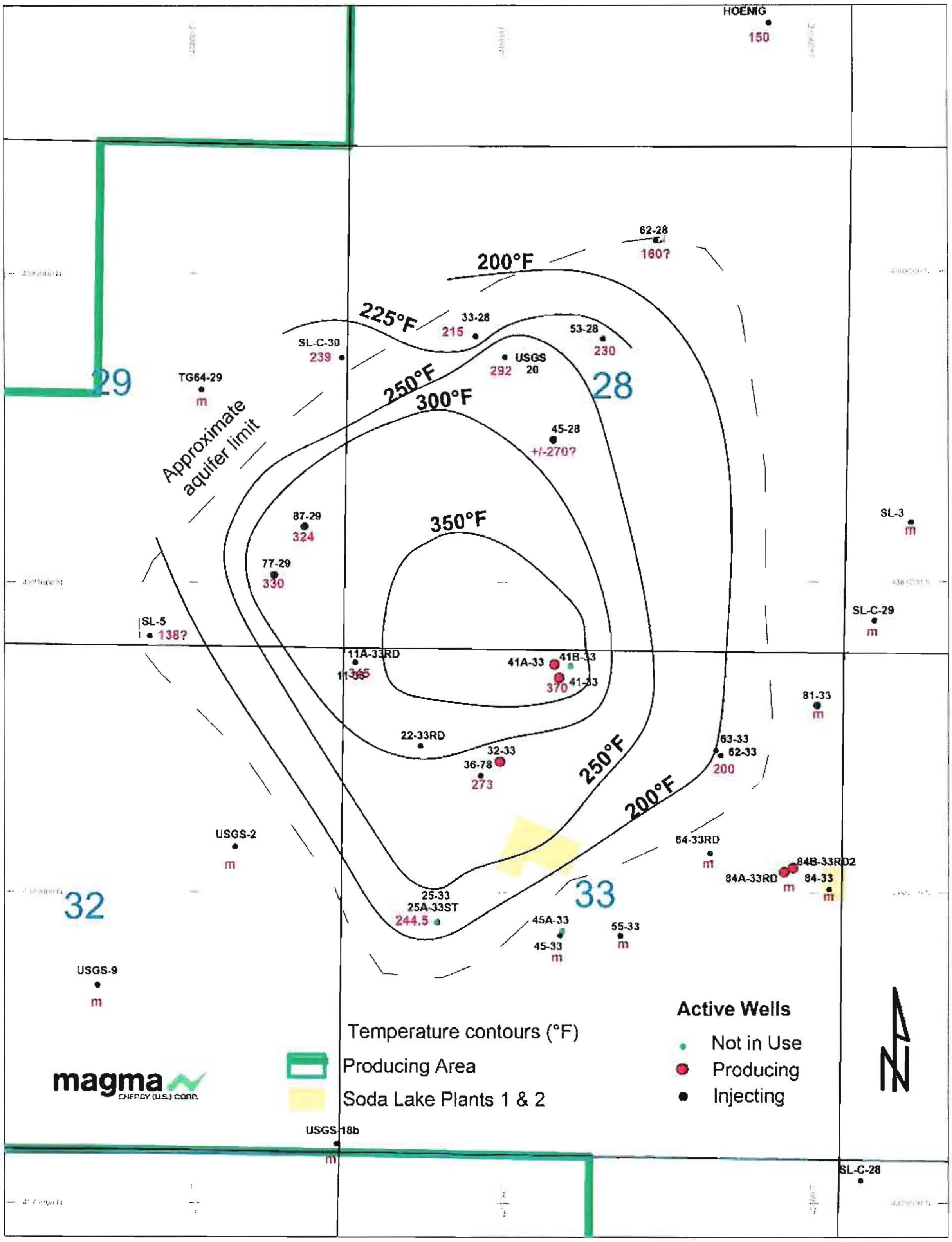


Figure 13: Shallow Thermal Aquifer Temperature at Depth of 400 to 1000 Feet
The contouring treats this as one aquifer but in reality there are probably multiple aquifers. Temperature maximum or changes to near isothermal conditions define the thermal aquifer(s).

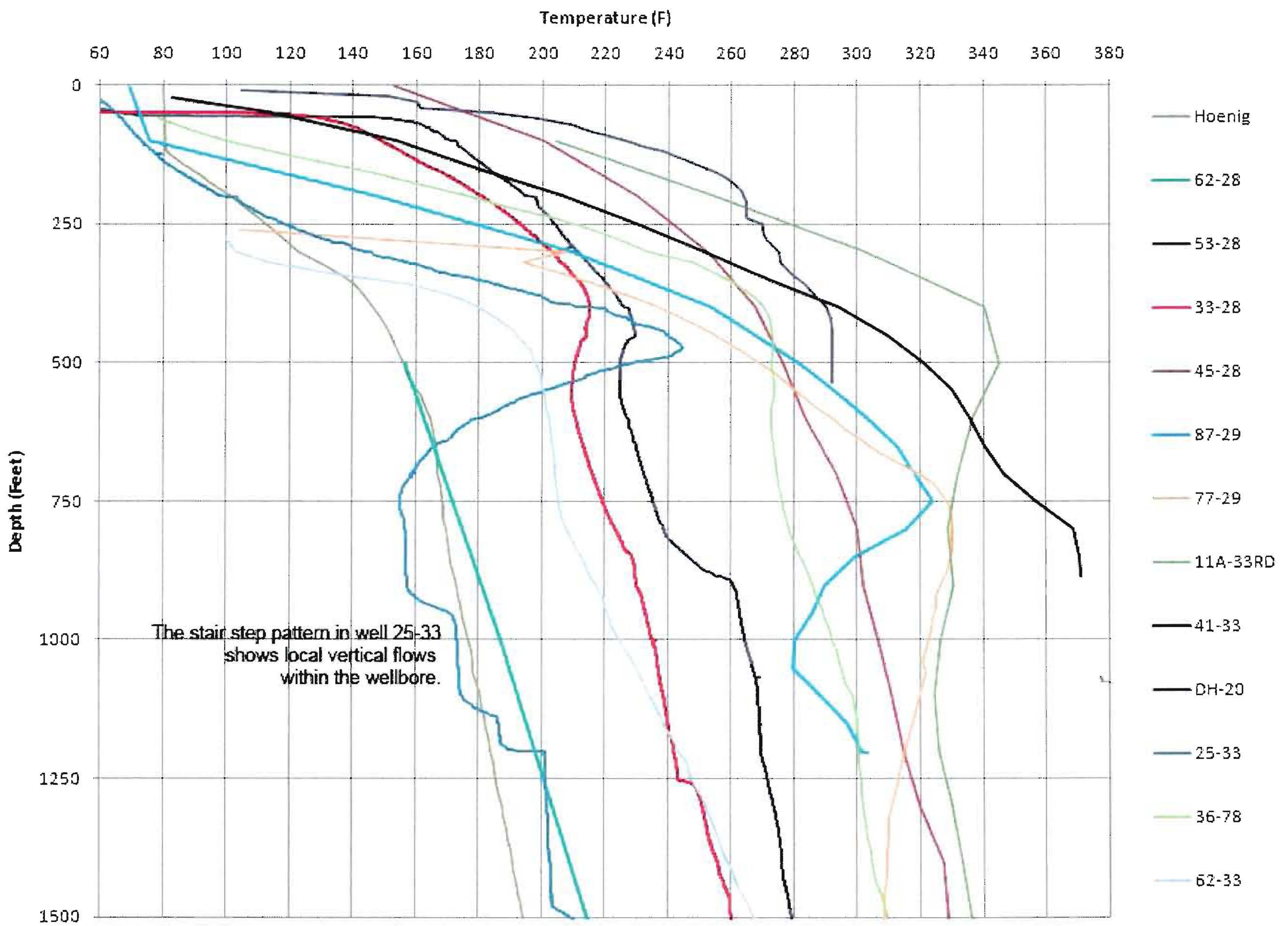


Figure 14: Temperature Profiles of Wells Showing Indications of the Shallow Thermal Aquifer Between Depths of 350 Feet and 1000 Feet

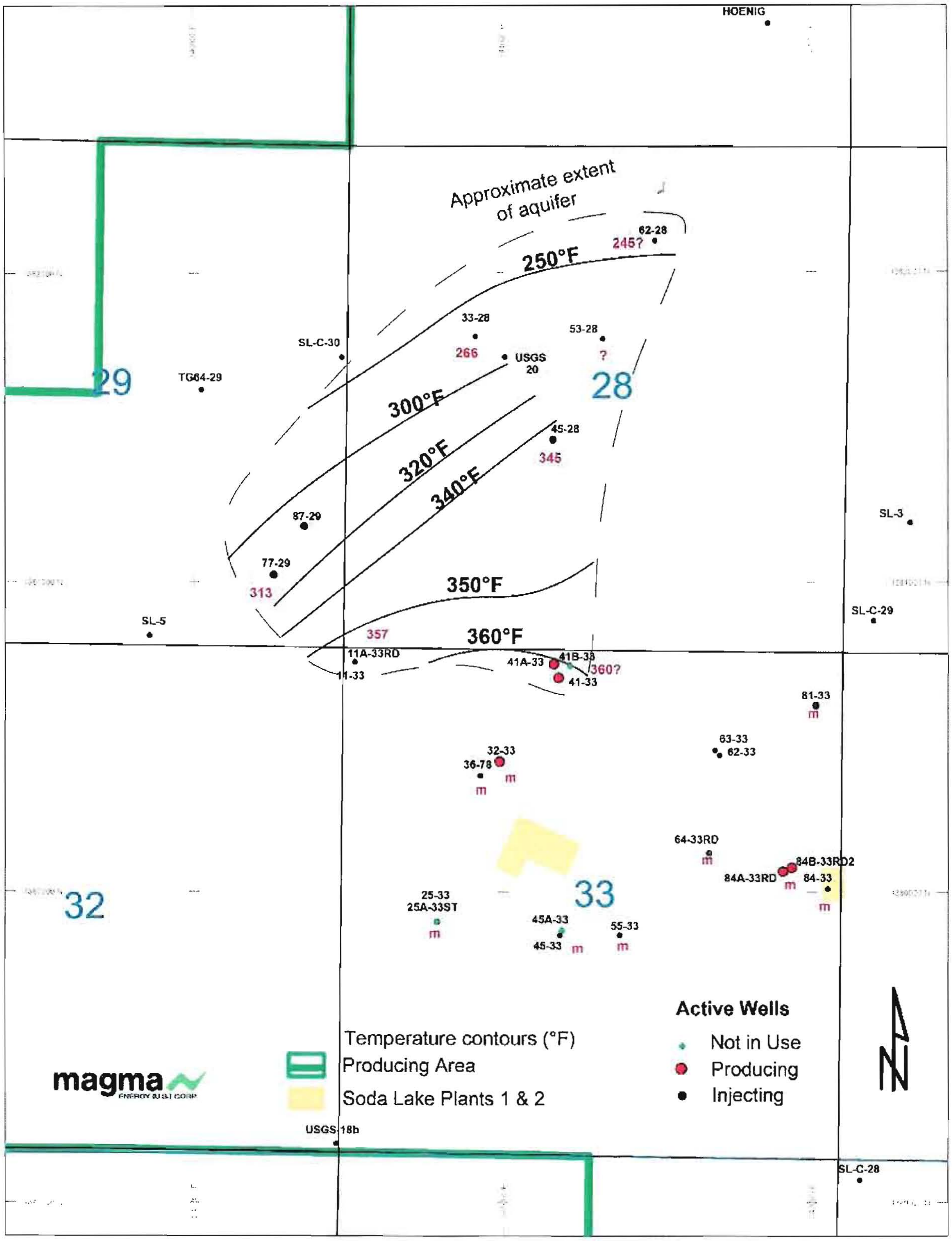


Figure 15: Intermediate Thermal Aquifer Temperature at Depths Near 2000 Feet

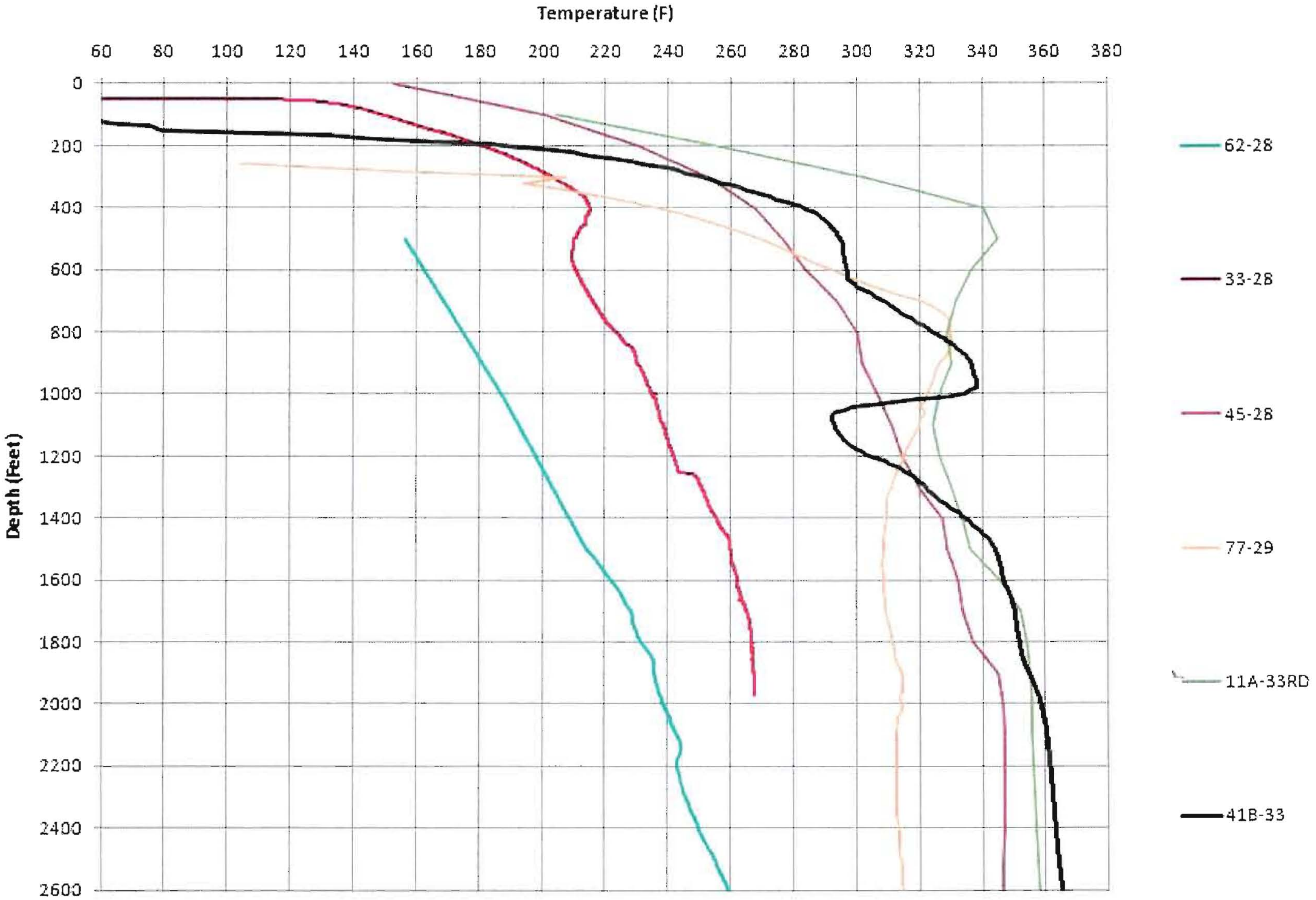


Figure 16: Temperature Profiles of Wells Showing Indications of the Intermediate Thermal Aquifer Near a Depth of 2000 Feet This aquifer is largely defined by a decrease in the temperature gradient near depth of 2000 ft.

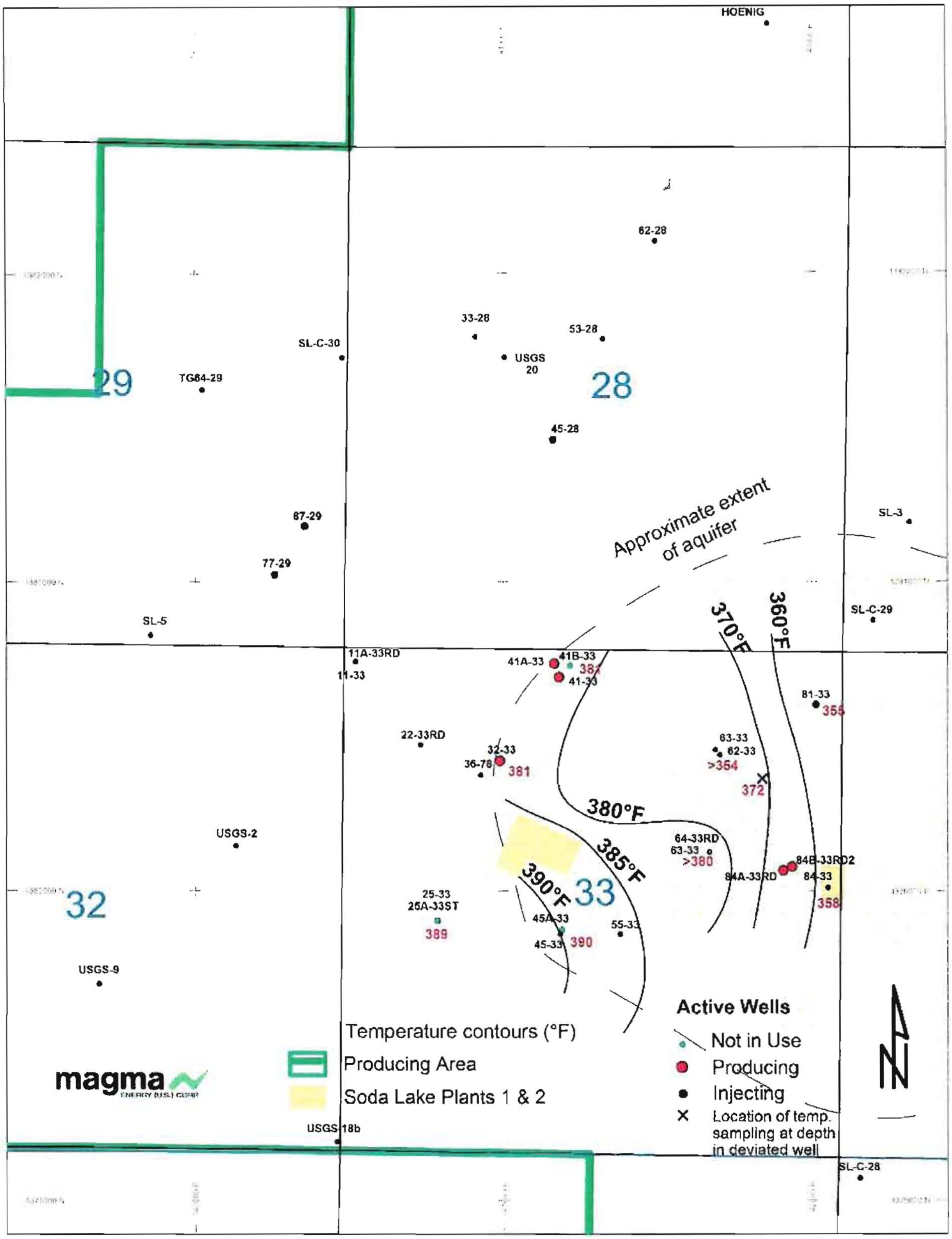


Figure 17: Deep Thermal Aquifer Temperature at Depths of 3300 to 5000 Feet

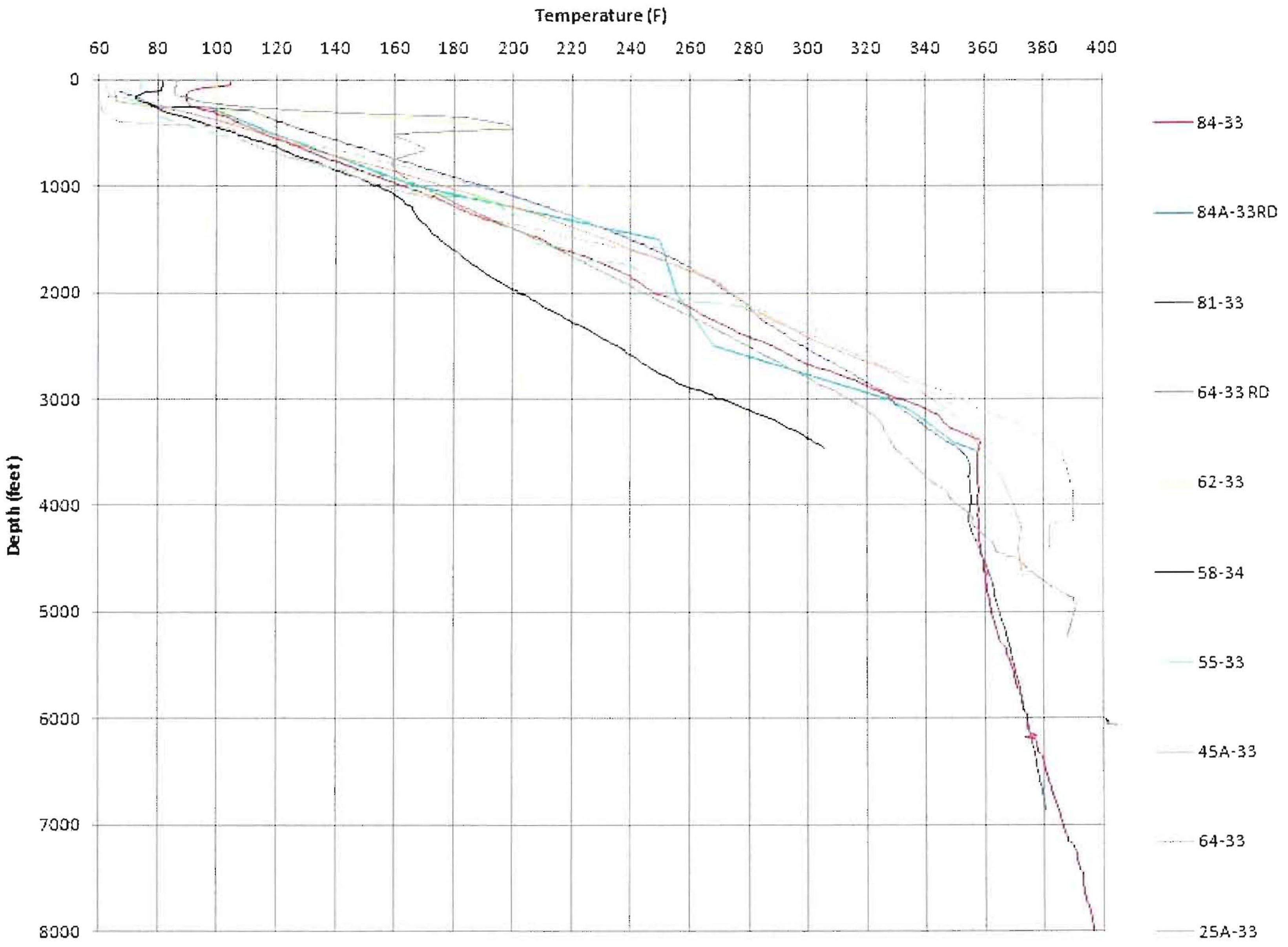


Figure 18: Temperature Profiles of Wells Showing Indications of the Deep Thermal Aquifer Between the Depths of 3300 and 5000 Feet. The aquifer is shown by the sharp decline in the temperature gradient near a depth of 3500 ft.

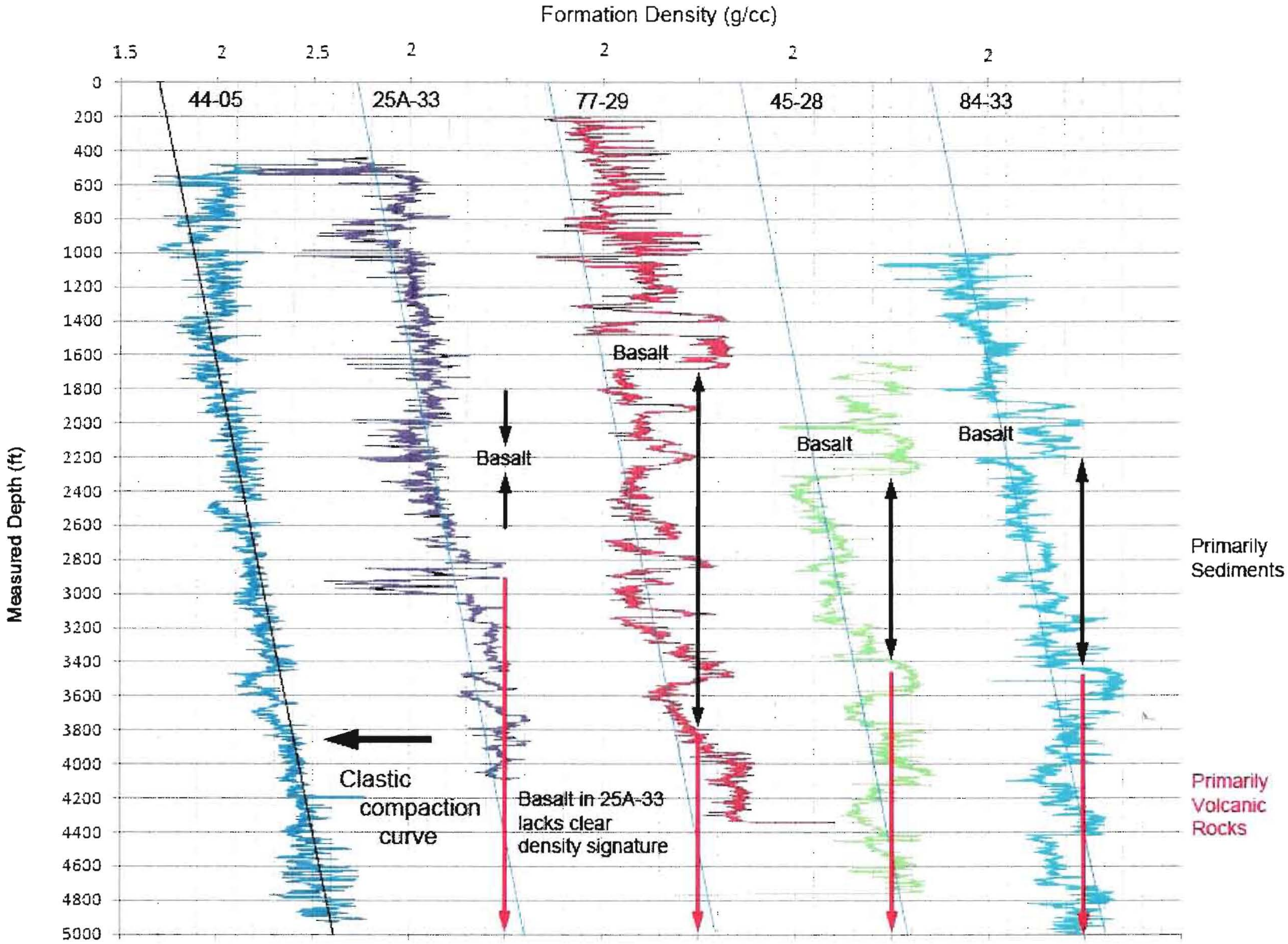


Figure 19: Density Logs. The "clastic compaction curve" is a simple, linear curve-fit to the density values with depth and is based on the relationship developed in soil mechanics between void ratio and vertical effective stress. This linear trend is also shown in the neighboring density logs to differentiate between sedimentary and volcanic rocks with depth.

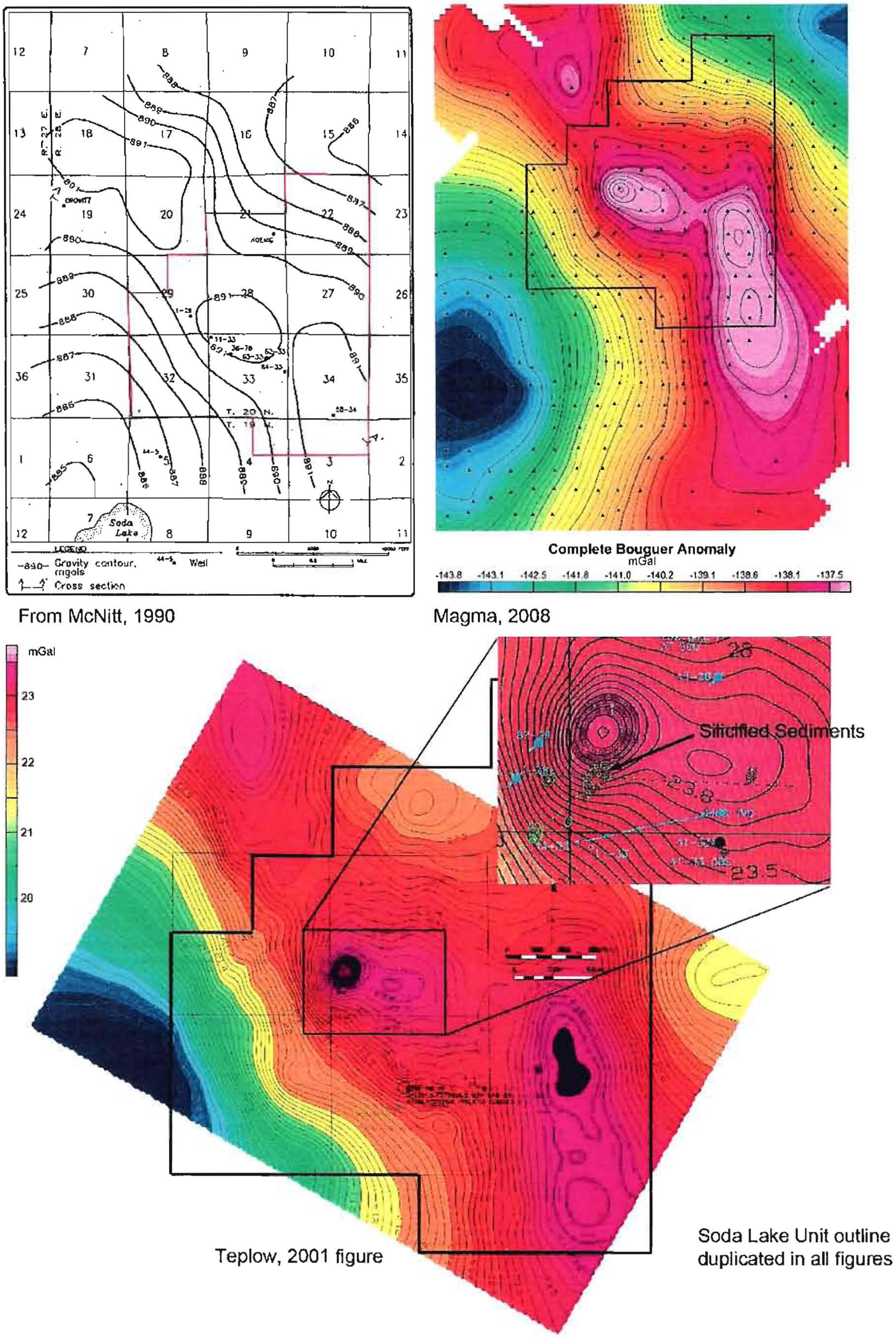


Figure 20: Gravity Surveys, 1990-2008. mGal values vary based on variables and assumptions in Bouguer correction.

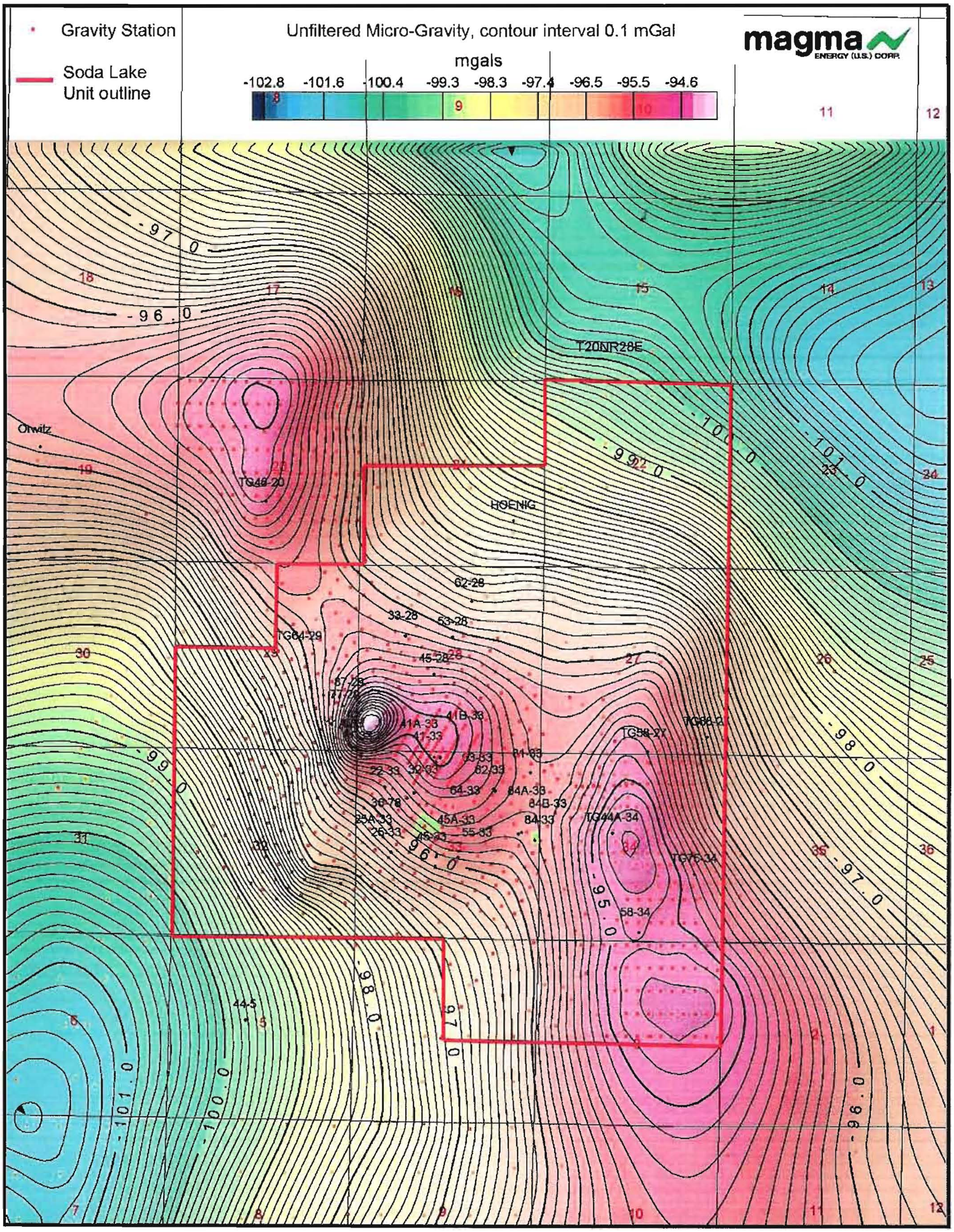


Figure 21: Complete Bouguer Gravity Anomaly, unfiltered. Data collected between 2008 and 2010.

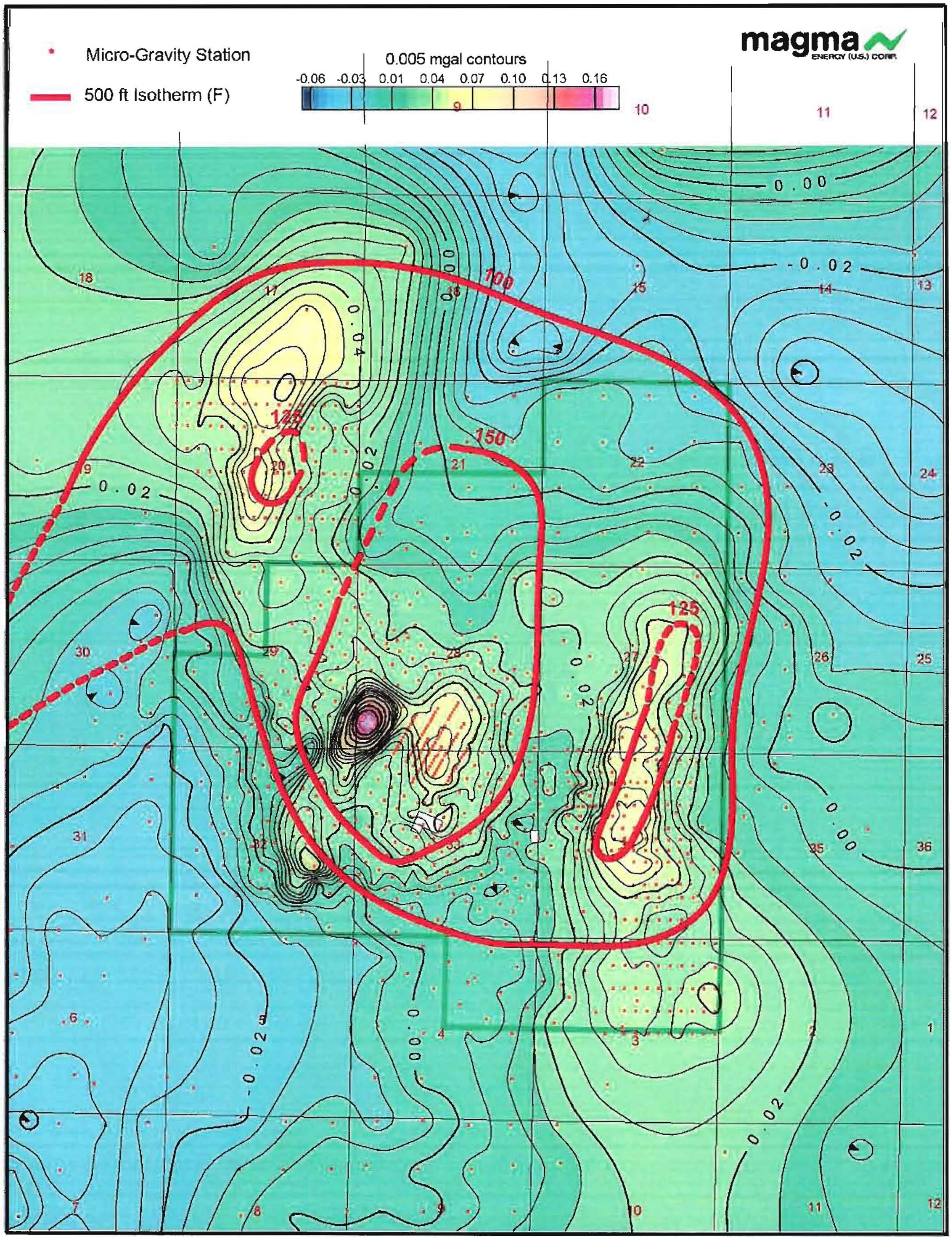


Figure 22: Residual Gravity Anomaly, 328 ft-164 ft, single-pole bandpass filter. Data collected between 2008 and 2010.

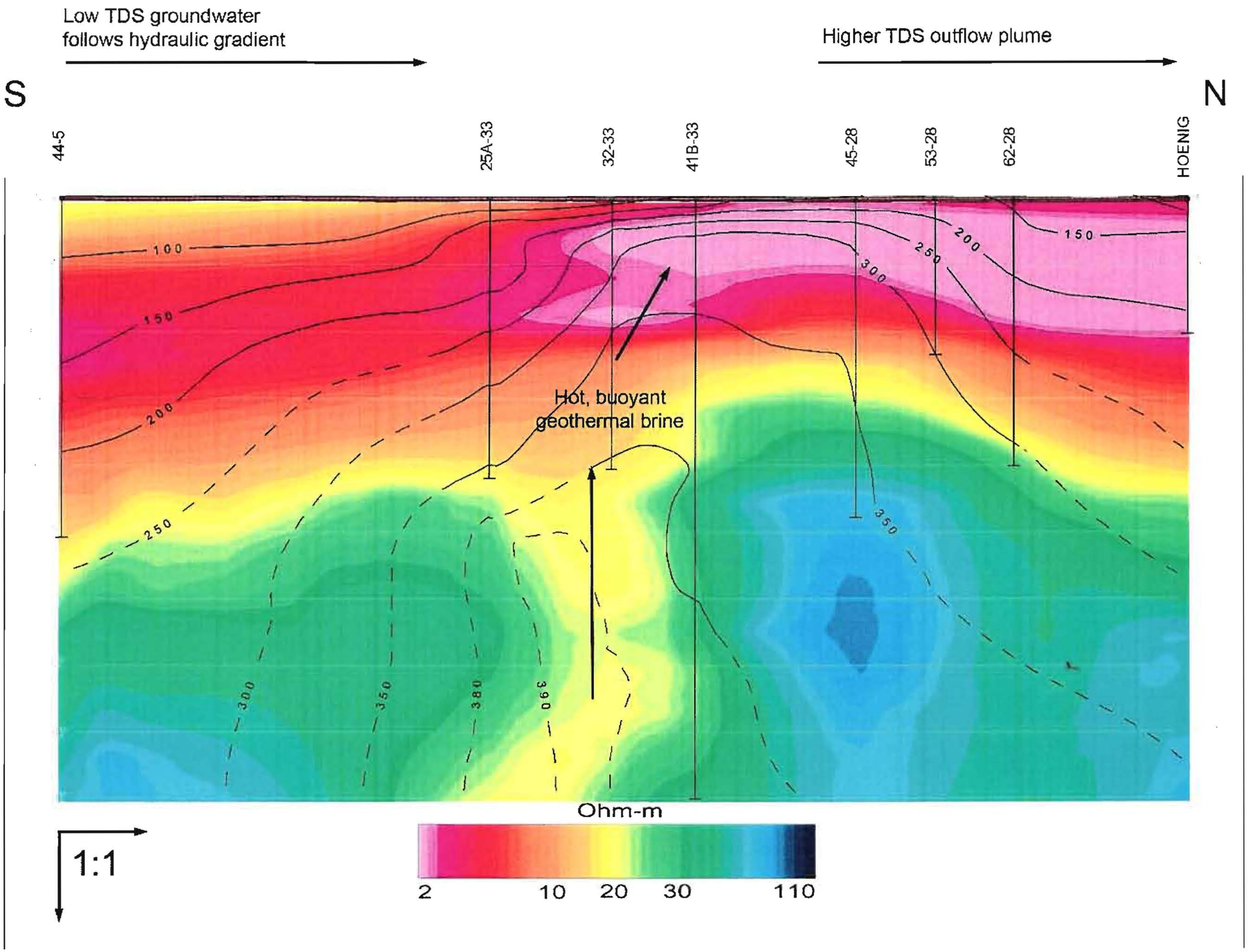


Figure 23: North-south MTprofile with temperature contours (°F)

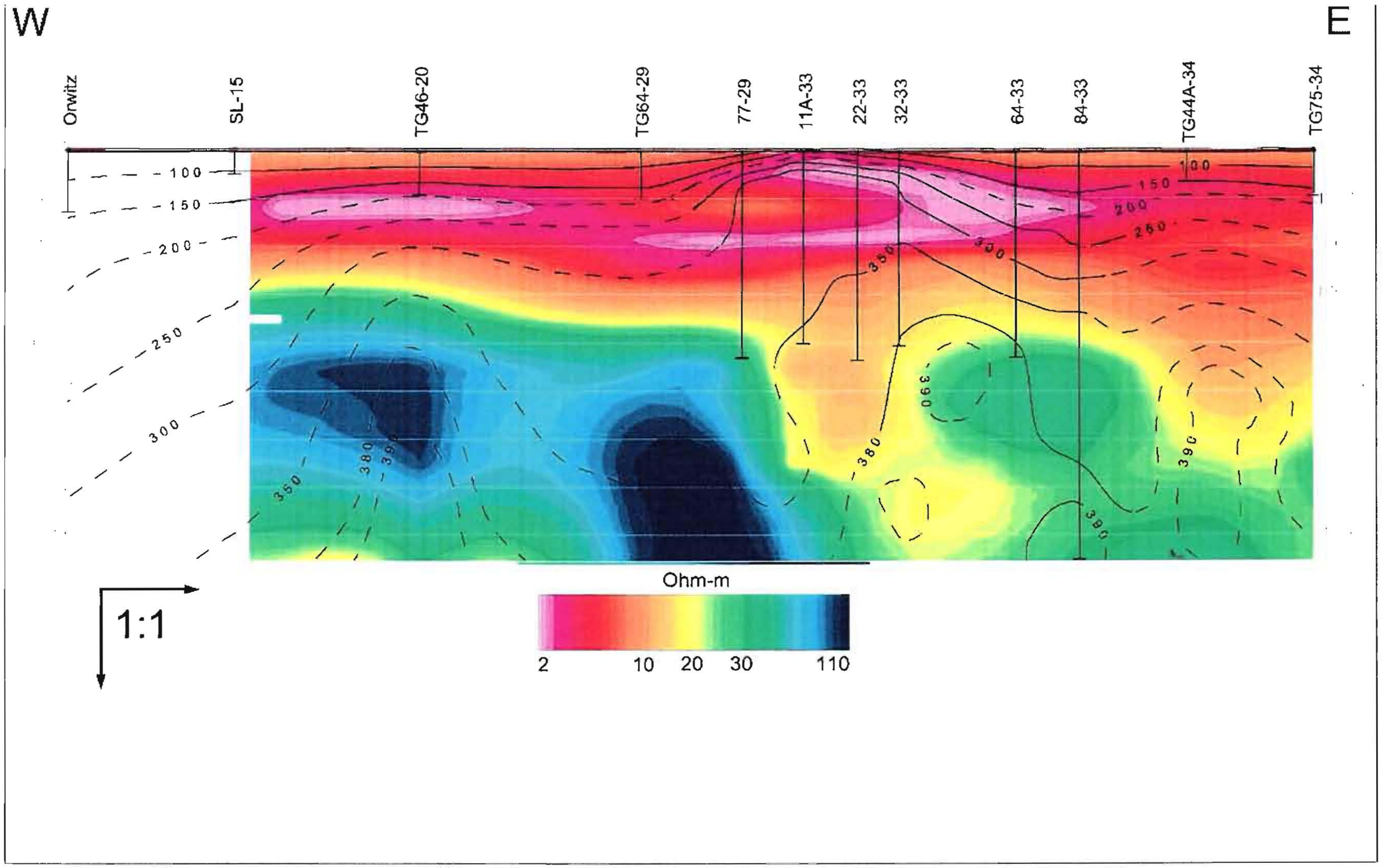


Figure 24: East-west MT profile wtih temperature contours (°F)

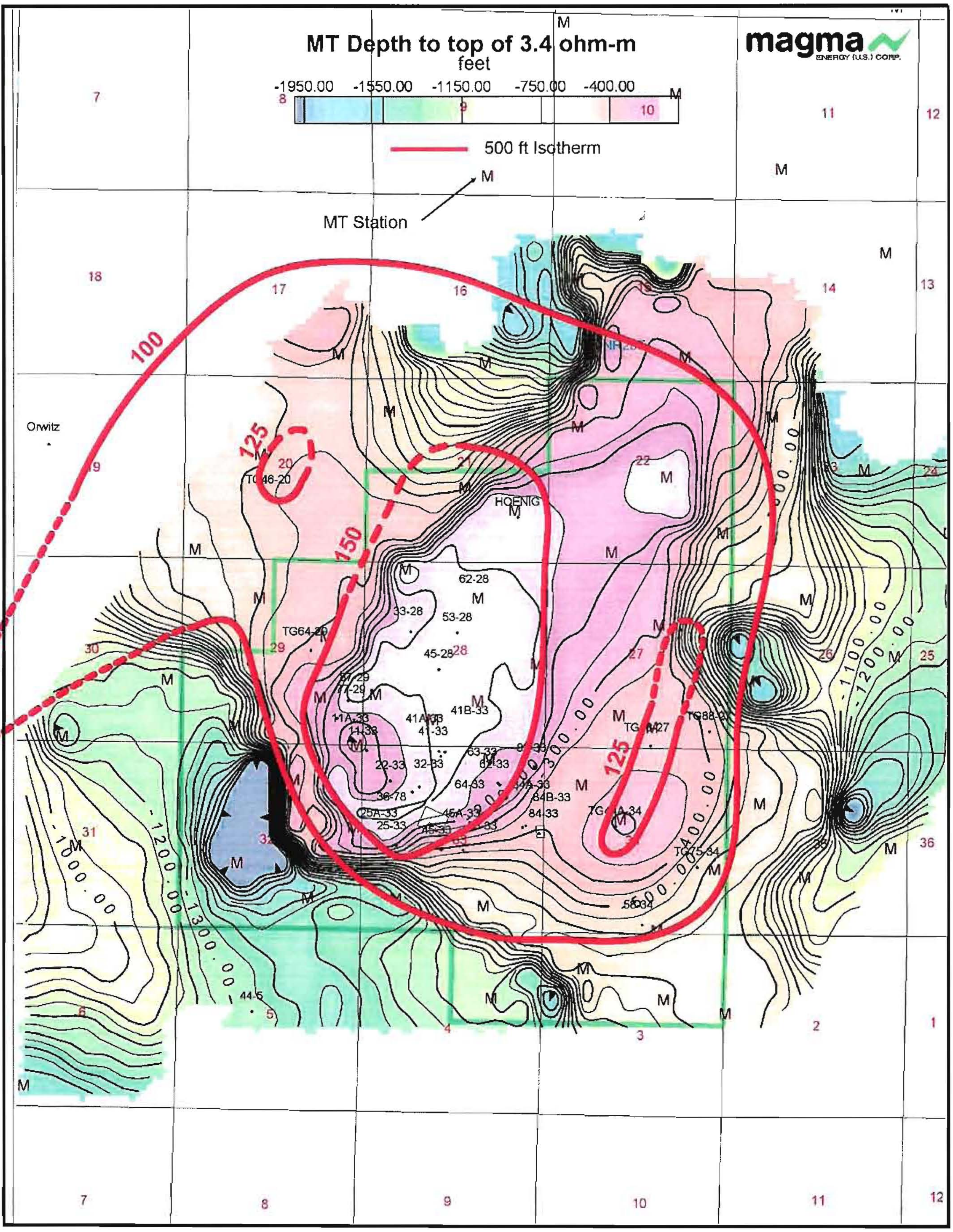


Figure 25: MT, depth to 3.4 ohm-m resistivity

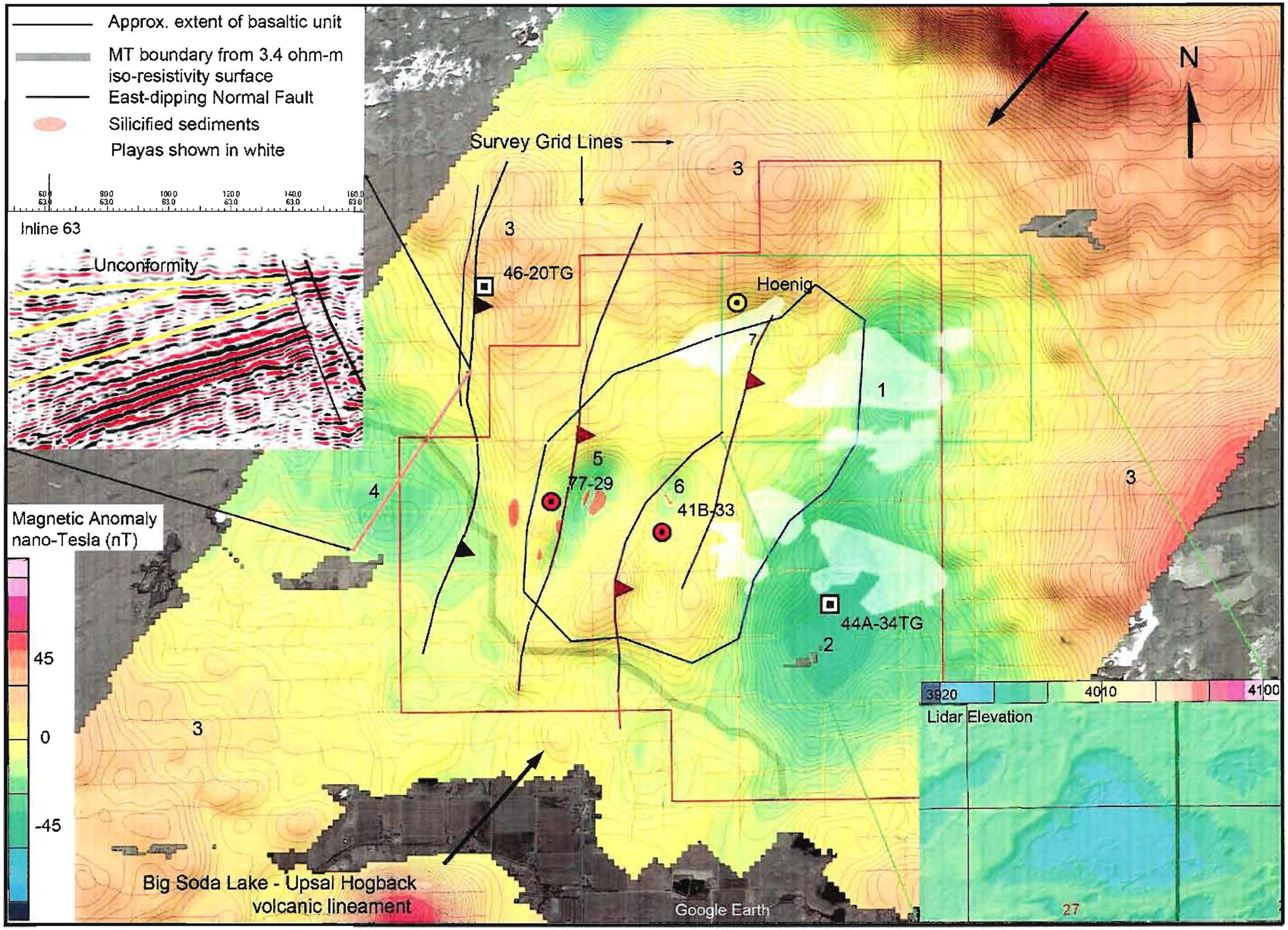


Figure 26: Ground Magnetic Survey. Magnetic anomalies can be associated with additional (3) or absence (1, 2, 4) of magnetic sediment or destruction of magnetite by hydrothermal activity (5, 6, 7). The two insets are examples where the absence of more magnetic sediment is associated with a low.

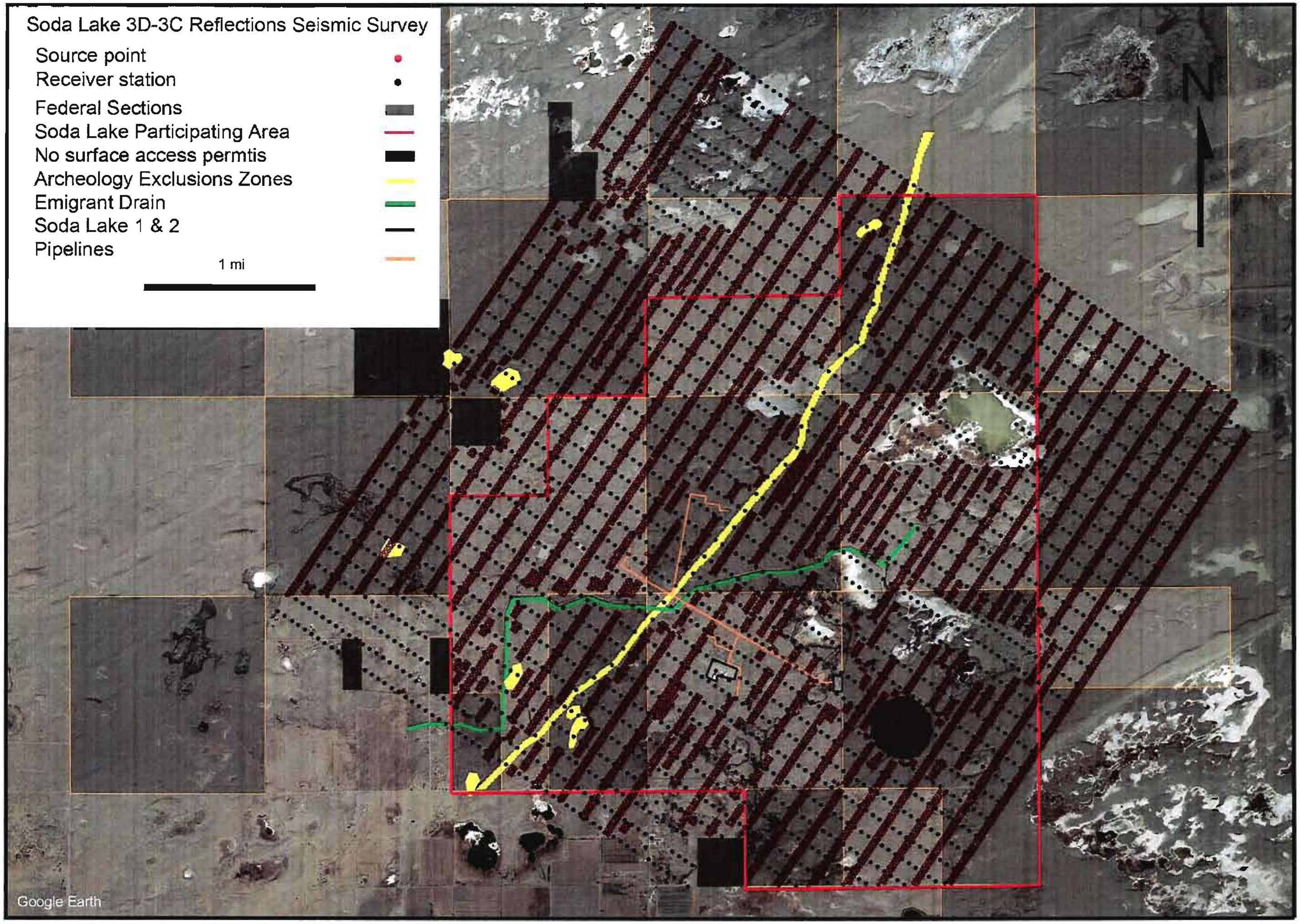


Figure 27: 3D- Reflection Seismic Survey. Area = 13.13 sq miles. 8,374 sourc points. 3001 receivers. Tandem source lines 110 ft apart,. Source interval is 110 ft and souce lines are 770 ft apart. Receivers are 220 ft apart and receiver lines are 550 ft apart. CDP bins are 55 ft.

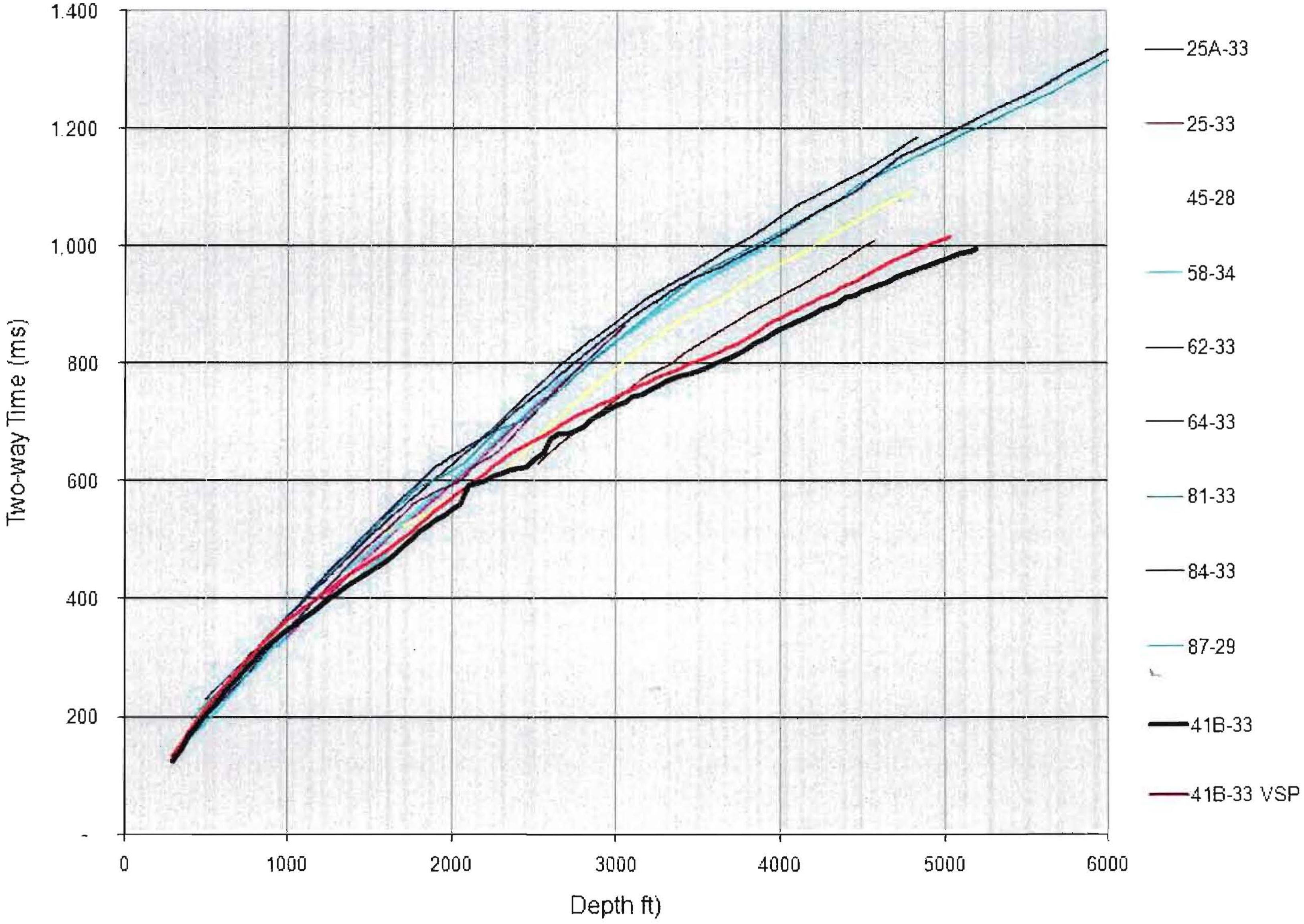


Figure 28: Time-Depth Curves from Synthetic Well Ties. The VSP curve is a direct measurement of time and depth. The other curves are indirect measurements using sonic and density (when available) logs to generate an impedance series to create a synthetic seismogram. Few geologic units in the upper 2000 ft correlated to wireline formation tops, creating uncertainty and non-geologic variations in the velocity model.

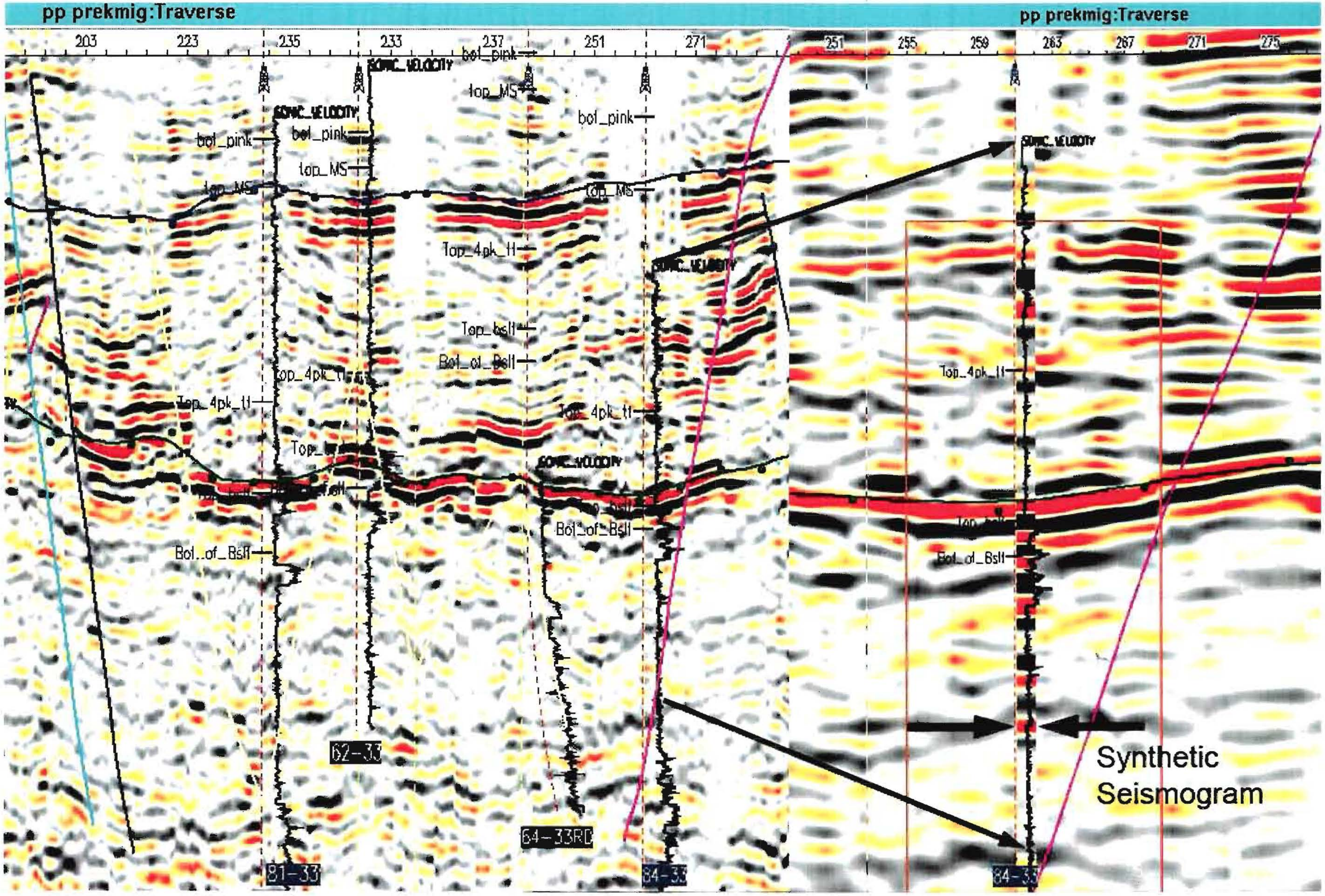


Figure 29: Arbitrary Seismic Line with Synthetic Seismograms. On the left side of the image, an arbitrary seismic line intersects four wells with sonic logs. Interpreted faults are shown as high-angled lines. Two early interpretations of seismic horizons, the mudstone (blue) and basaltic unit (green), are shown here. A line trace of the sonic logs are displayed to show major changes in acoustic impedance. Inset to the right, a synthetic seismogram for 84-33 is overlaid on the seismic data.

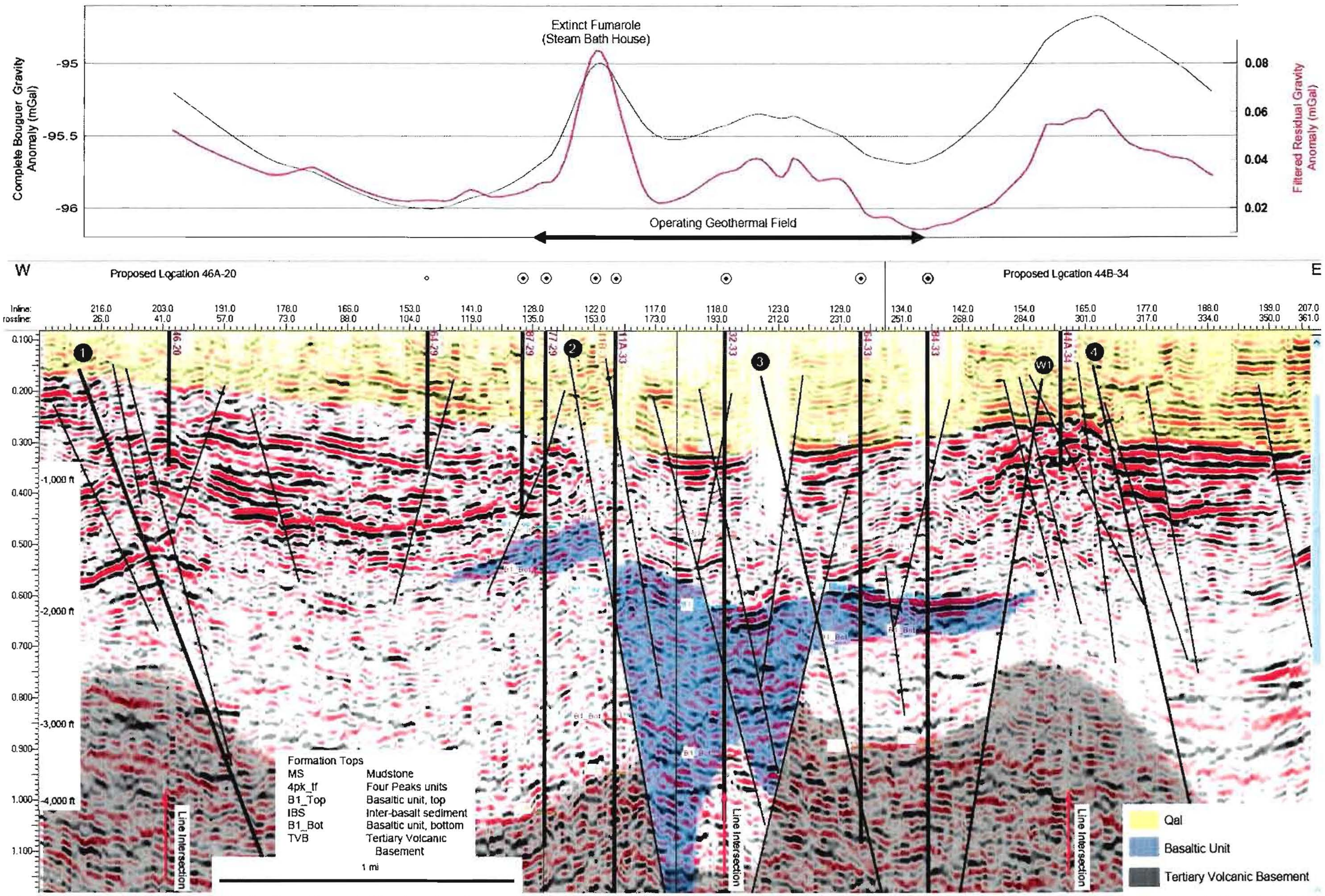


Figure 30: East-West Seismic Profile (See Figure 35 for locating this profile) This seismic profile connects existing production with the two thermal anomalies centered on TG wells 64-20 and 44A-34. Three significant wells are also shown where the thickness of the basaltic unit varies from 210' in 77-29 to >1000; in 32-33, to 320' in 84-33. The complete and filtered Bouguer gravity values along the profile are plotted above the seismic data to illustrate the correlation to structure.

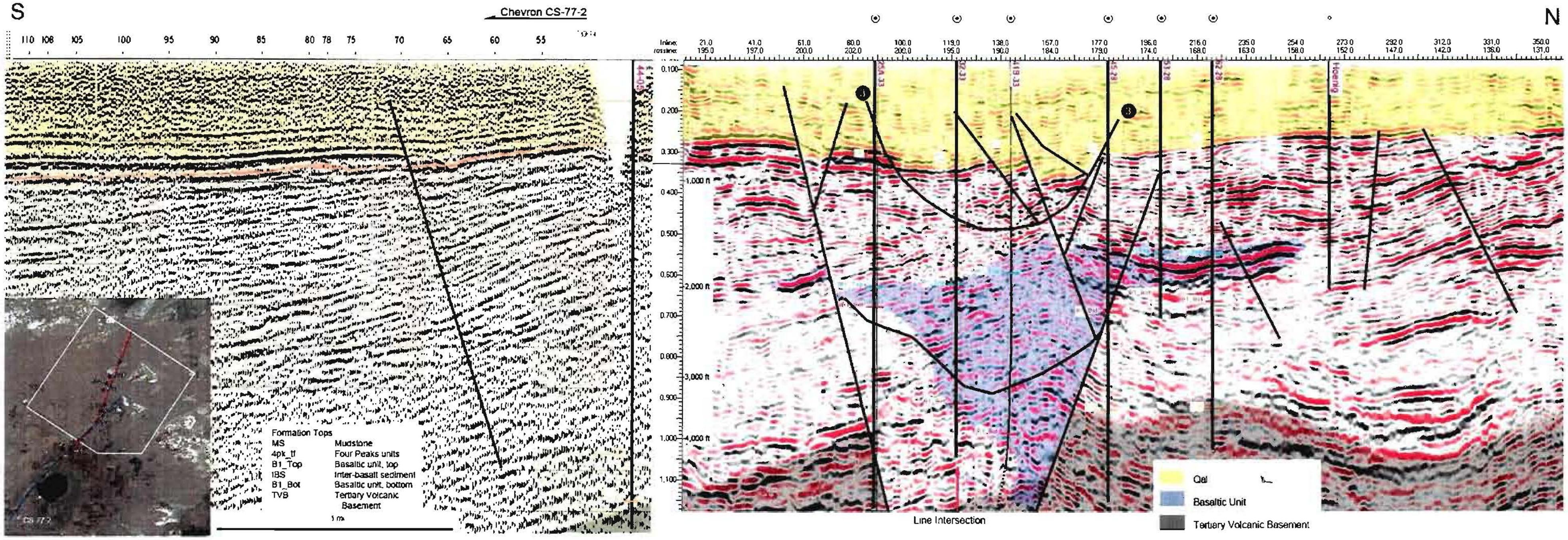
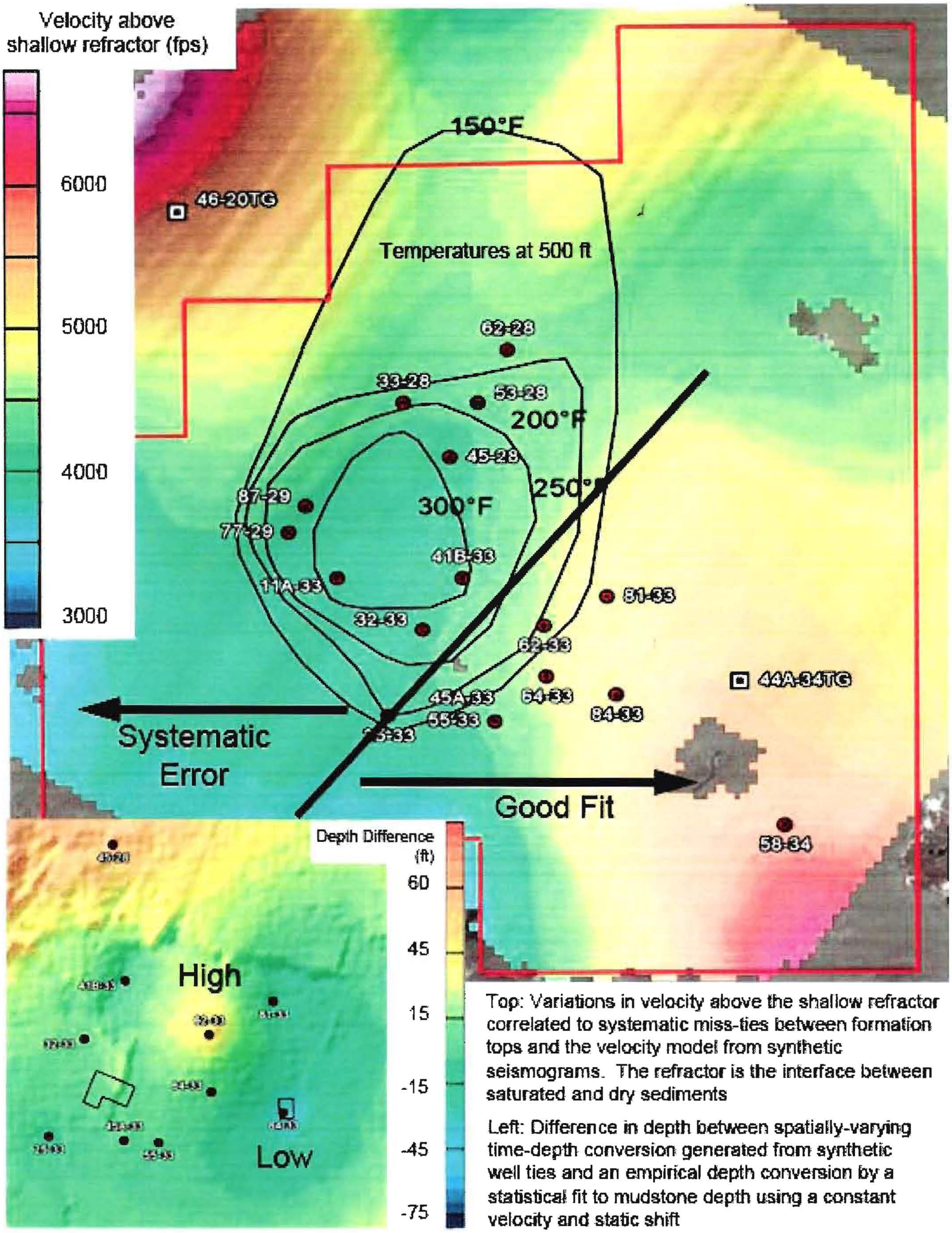


Figure 31: North-South Seismic Profile (See Figure 35 for locating this profile) The seismic profile intersects eight wells through the center of existing production. Merged with a 1977 Chevron 2D line, this profile shows the sedimentary section above the Tertiary Volcanic Basement thickens to the south and north to just beyond the Hoenig well This line is oriented on strike to the major faults. The fault segments forming the graben-like feature are essentially the same fault. The offset of Fault 3 is out of the plane.



Top: Variations in velocity above the shallow refractor correlated to systematic miss-ties between formation tops and the velocity model from synthetic seismograms. The refractor is the interface between saturated and dry sediments

Left: Difference in depth between spatially-varying time-depth conversion generated from synthetic well ties and an empirical depth conversion by a statistical fit to mudstone depth using a constant velocity and static shift

Figure 32: Mudstone Horizon Time-depth Conversion, Quality Control

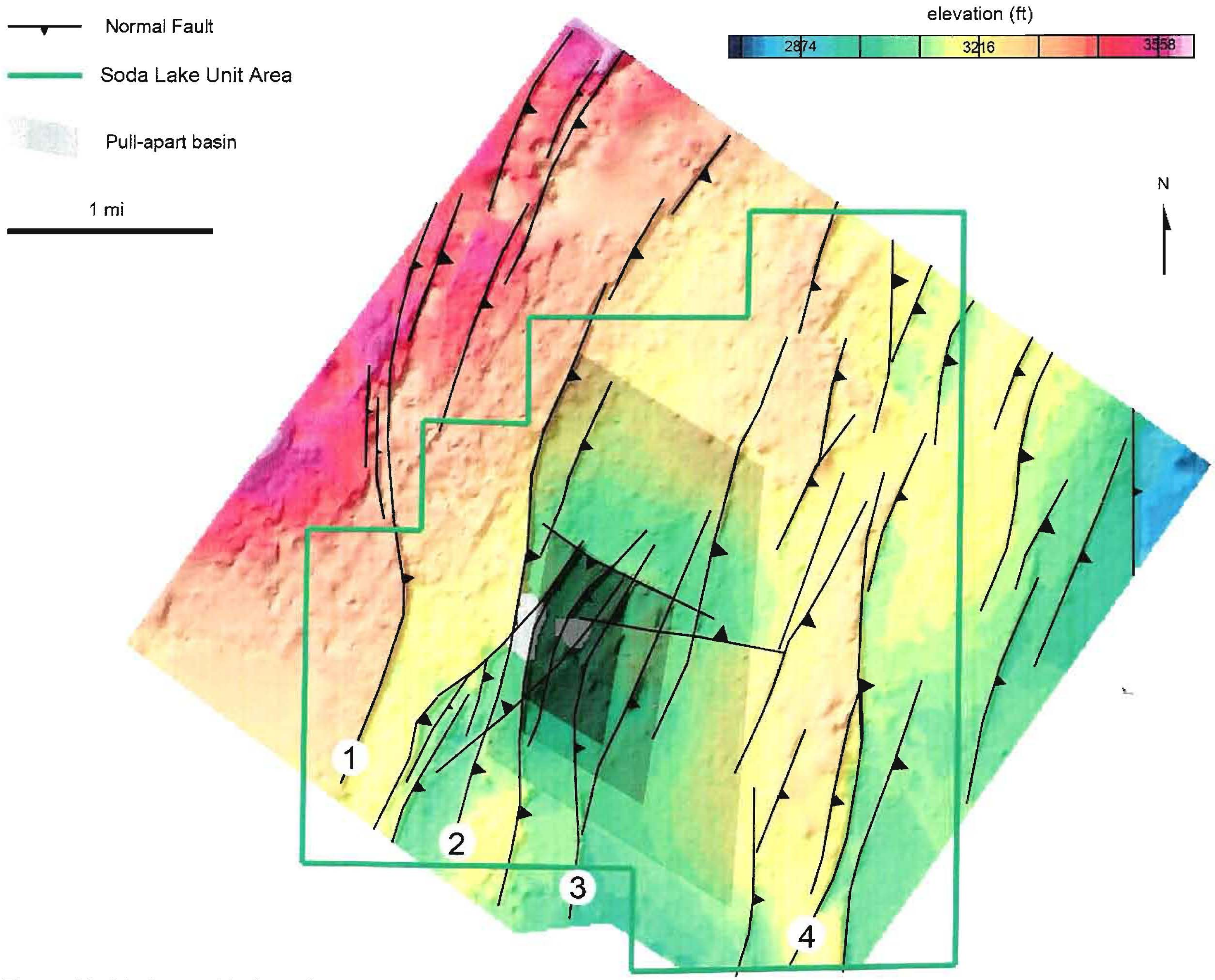


Figure 33: Mudstone Horizon Structure Map. Faults labeled 1-4 are referenced in the text and are consistent with other figures. The size of the down-thrown symbol is not related to throw. Not all faults penetrating this horizon are shown. Nested pull-apart basins are inferred from fault offsets and elevation of mudstone surface. Irregular white area inside the survey area indicates no data.

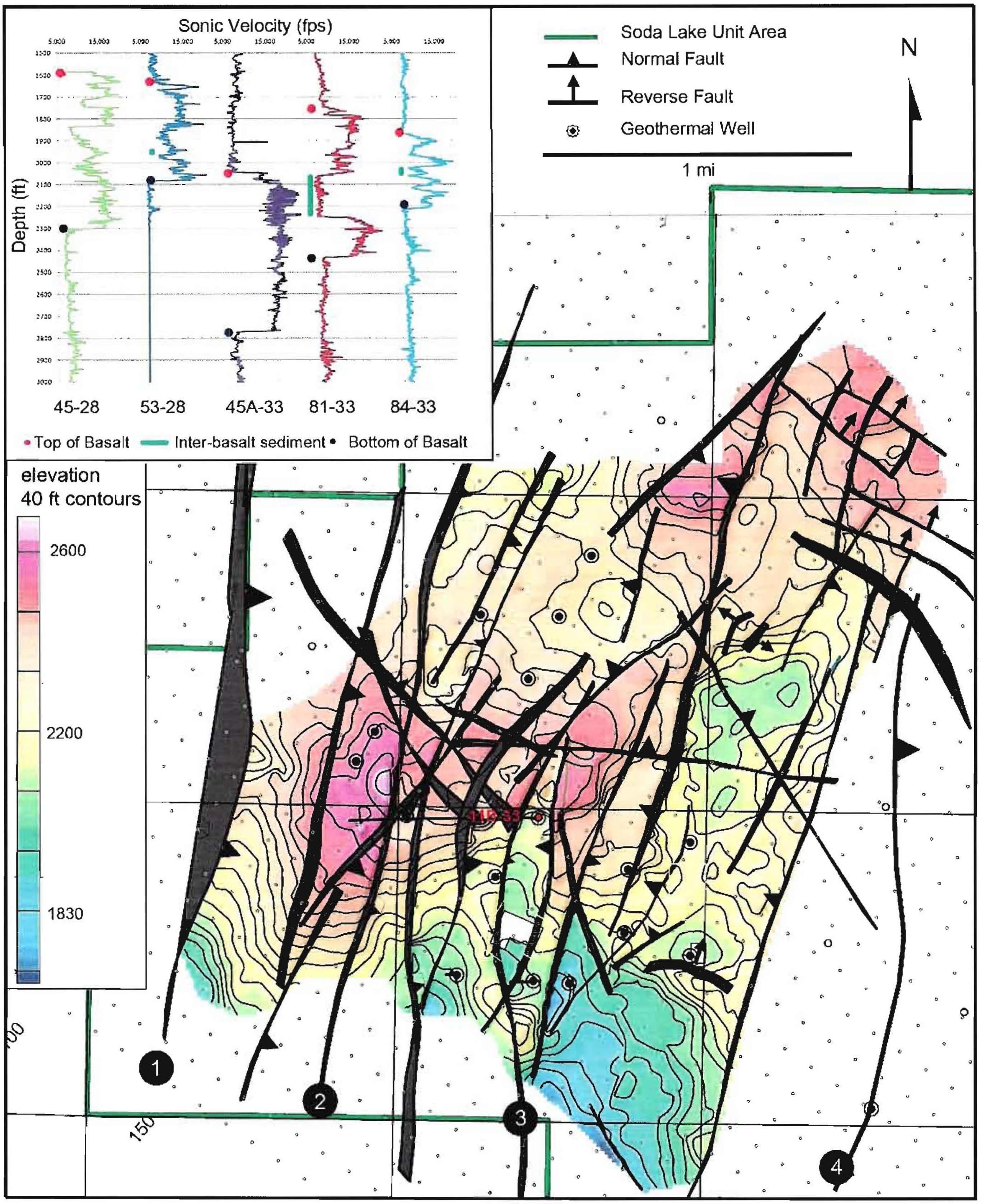


Figure 34: Basaltic Unit Structure Map. Faults labeled 1-4 are referenced in the text and are consistent with other figures. The reflectivity of the basaltic unit is highly variable. In the center of the field, well control is required to map the top of the unit. On the flanks of the gravity high (Fig. 35), the unit thickness is between 150'–600' and is a high amplitude event, but not necessarily coincident with the wireline formation top. In the inset, the sonic velocity shows a distinct bottom to the unit, but the top does not have a sharp acoustic response, perhaps due to weathering, erosion or brecciation.

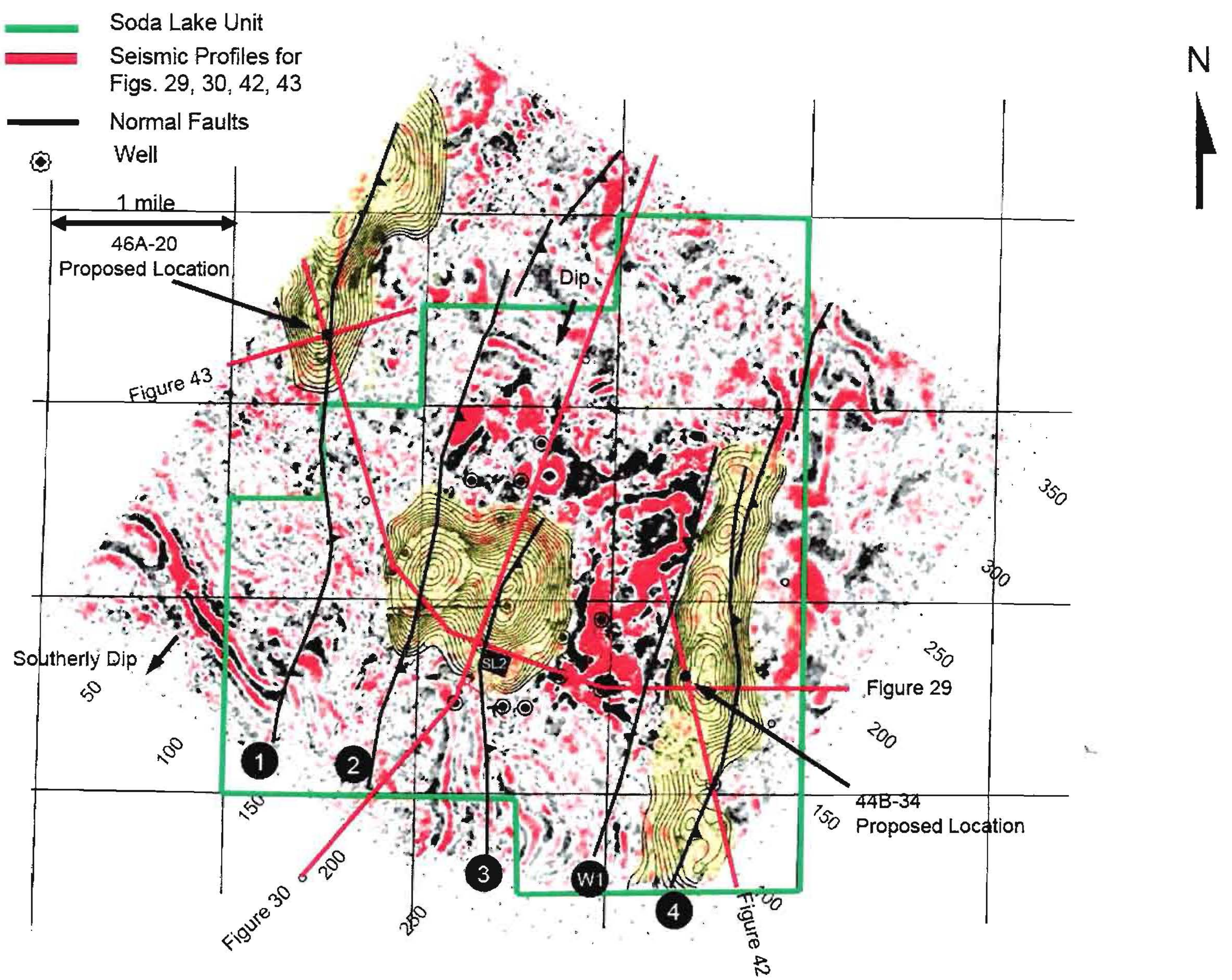


Figure 35: Seismic Profiles, Time-Slice, 600 ms. The numbered faults are consistent with the text and other figures. The broad, red and black bands correlate with the basaltic unit that has a strong reflector. The areas shaded yellow are the gravity contours that represent topography that existed at the time of basalt deposition. The aerial extent of the basaltic unit may be limited by an east-dipping fault to the west (2), a west-dipping fault or topography to the east (W1), and south-dipping beds to the north. (South-dipping horizons can also be seen in the southwest portion of the survey, truncated against Fault 1.)

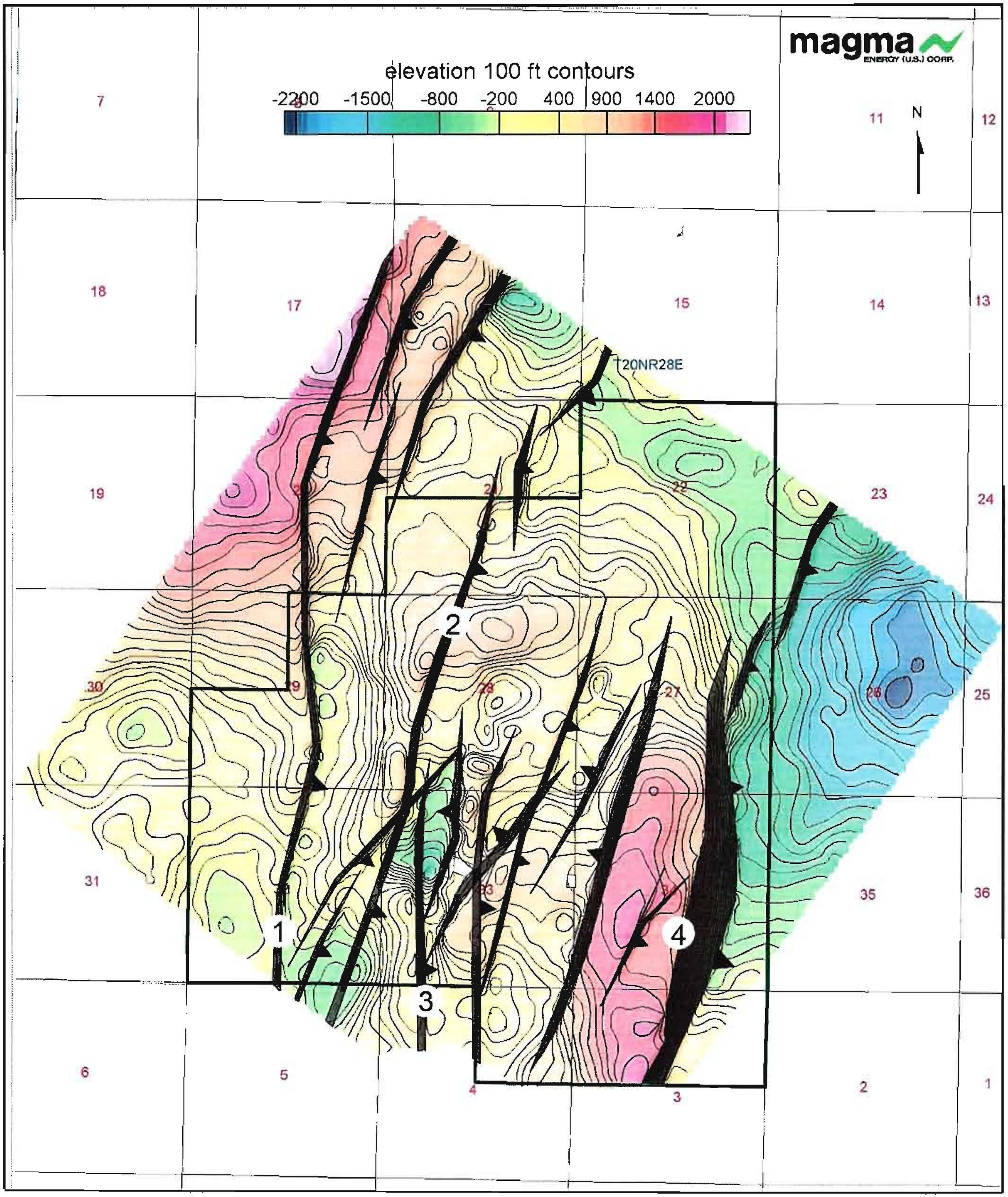


Figure 36: Tertiary Volcanic Basement Structure Map. The numbered faults are consistent with the text and other figures.

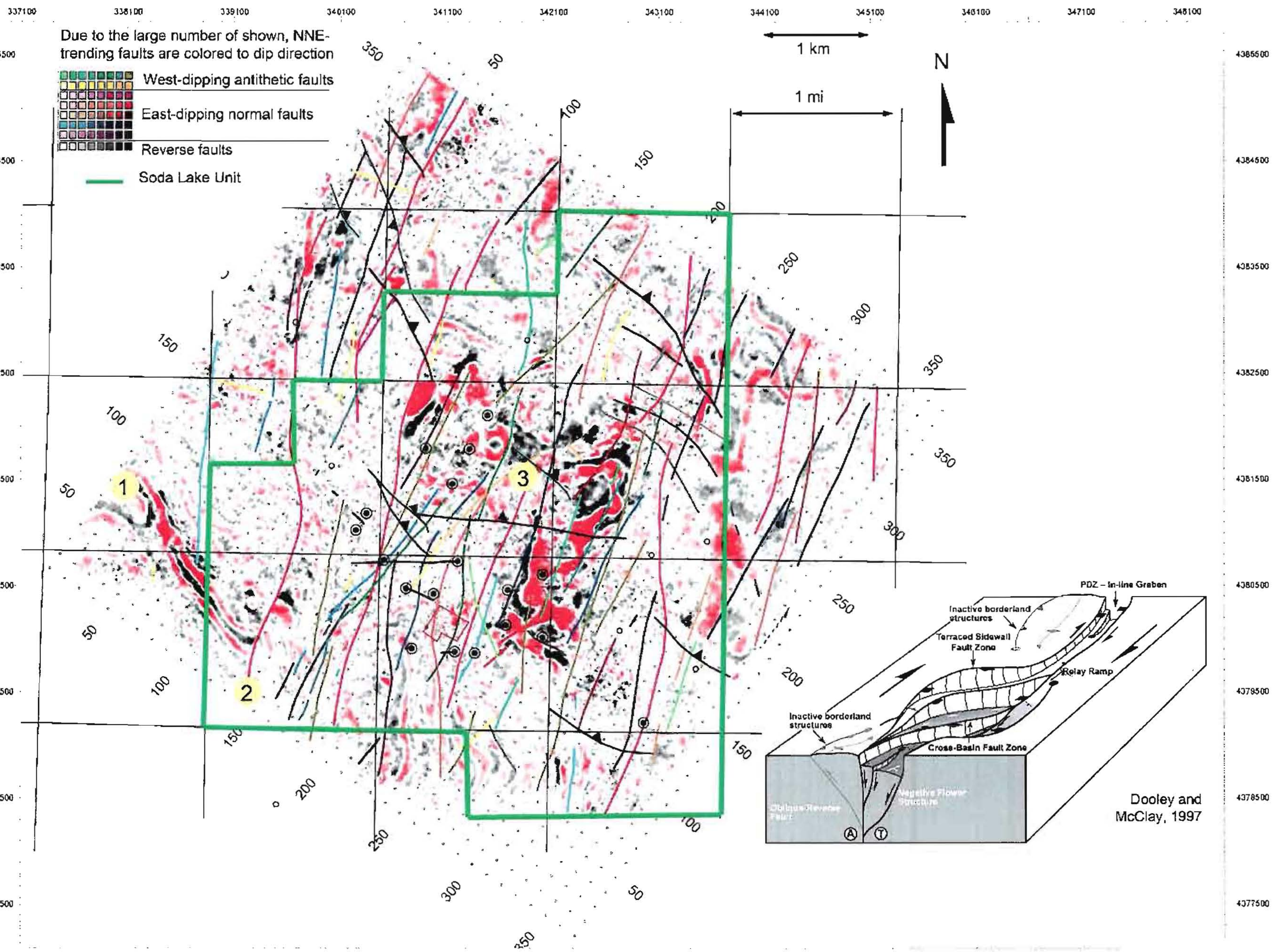


Figure 37: **Time-slice, 600 ms.** All faults penetrating 600 ms are displayed. Direction of throw shown by symbol or color. Numbers show features associated with a horizontal plane. 1) bands showing a dipping horizon; 2) event truncating against fault; 3) high amplitude event (basalt).
The inset is a diagram of a right-stepping, sinistral strike-slip fault system, a mirror-image of Soda Lake.

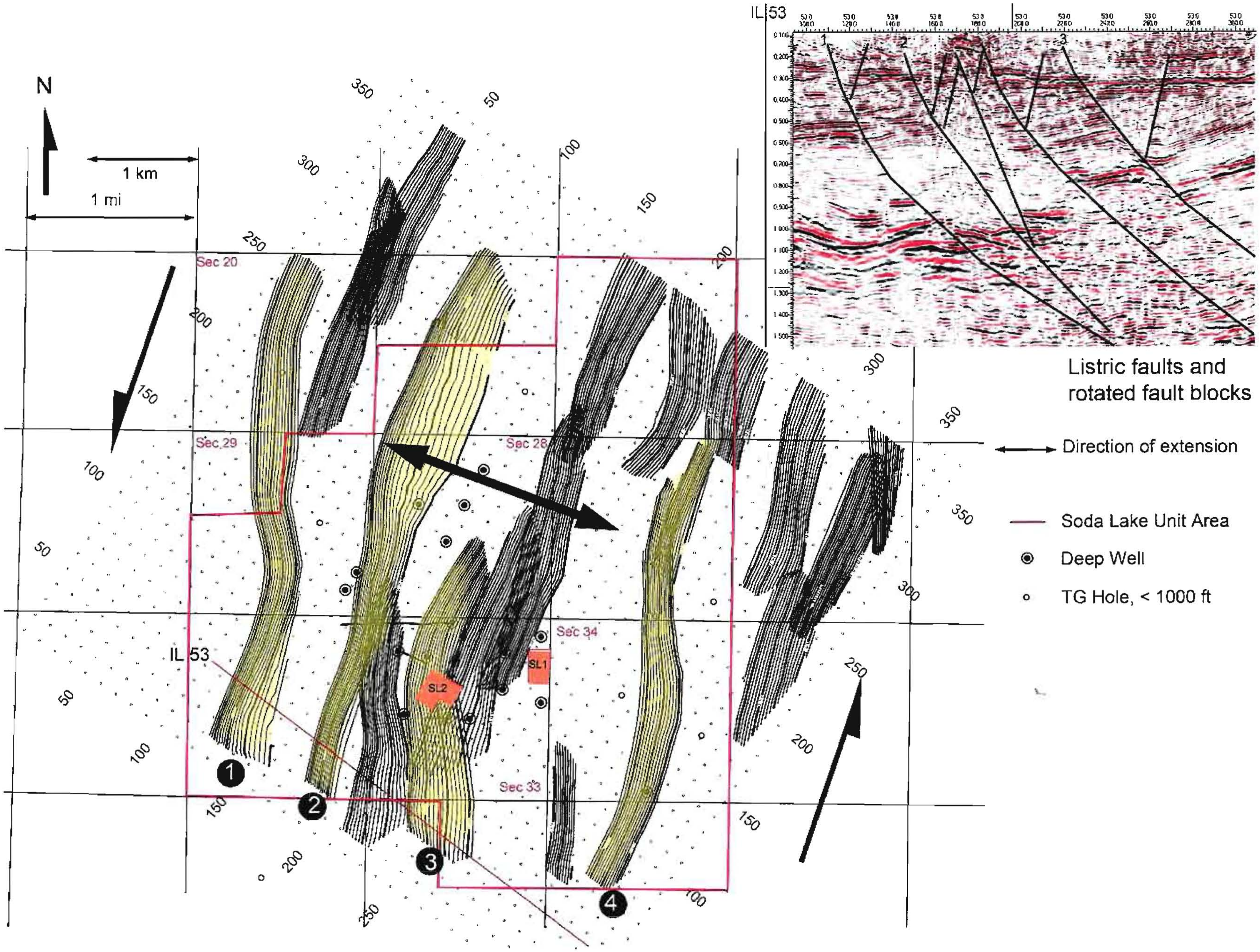


Figure 38: Fault Plane Map, 250 ms - 1000 ms (600 - 4000 ft) The contoured fault planes of nineteen east-dipping normal faults are shown. The numbered faults are consistent with the text and other figures. In this presentation, they are highlighted in yellow to show how the angle of faults planes respond to changes in stress fields. The inset is IL 53, an example of extesnsional faults becoming listric, with rotated fault blocks.

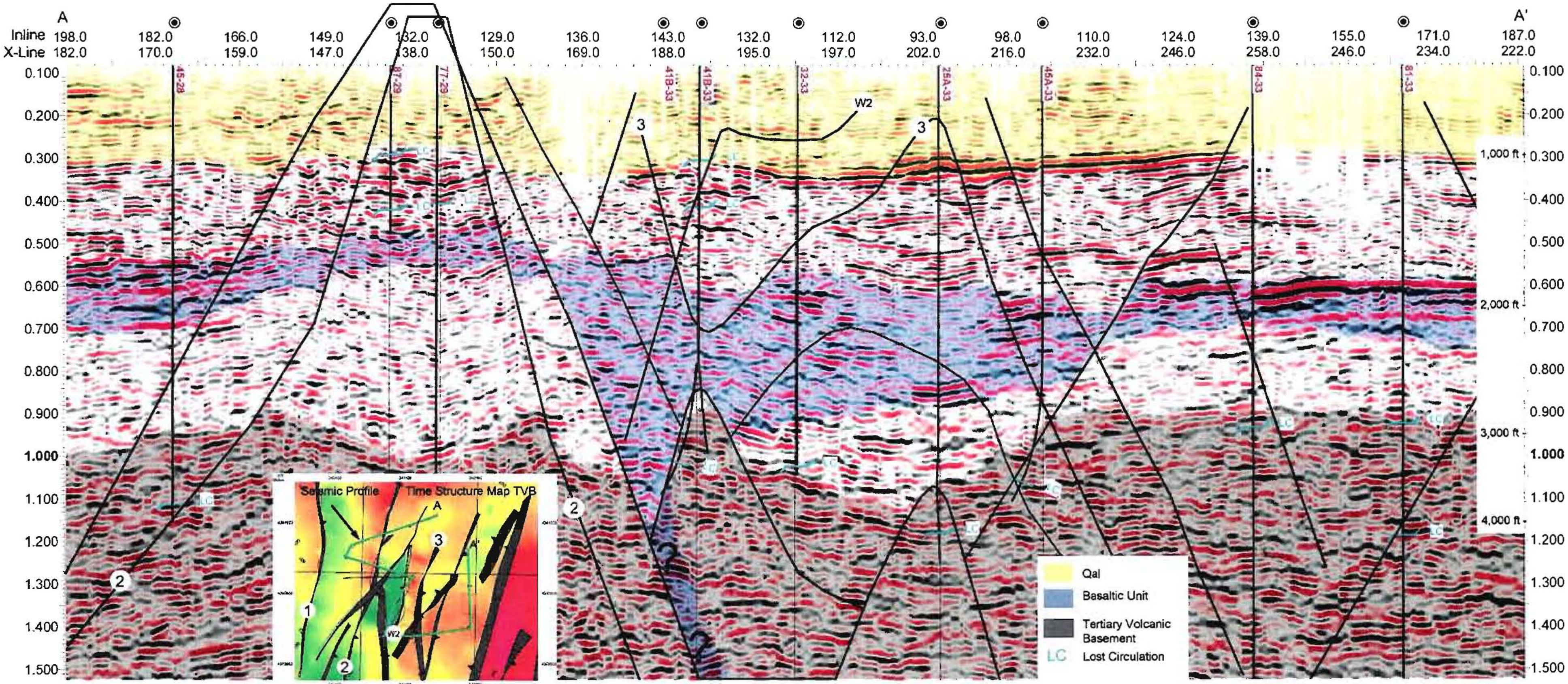


Figure 39: Seismic Correlation to Zones of Lost Circulation. Numbered faults are consistent with the text and other figures. A seismic profile through nine wells connects the production and injection wells. The inset is a time-structure map of the Tertiary Volcanic Basement with the location of the profile in green. The profile is not a continuous plane so fault planes intersect the seismic data is unusual pattern. Faults that continue in another plane are joined out of the section.

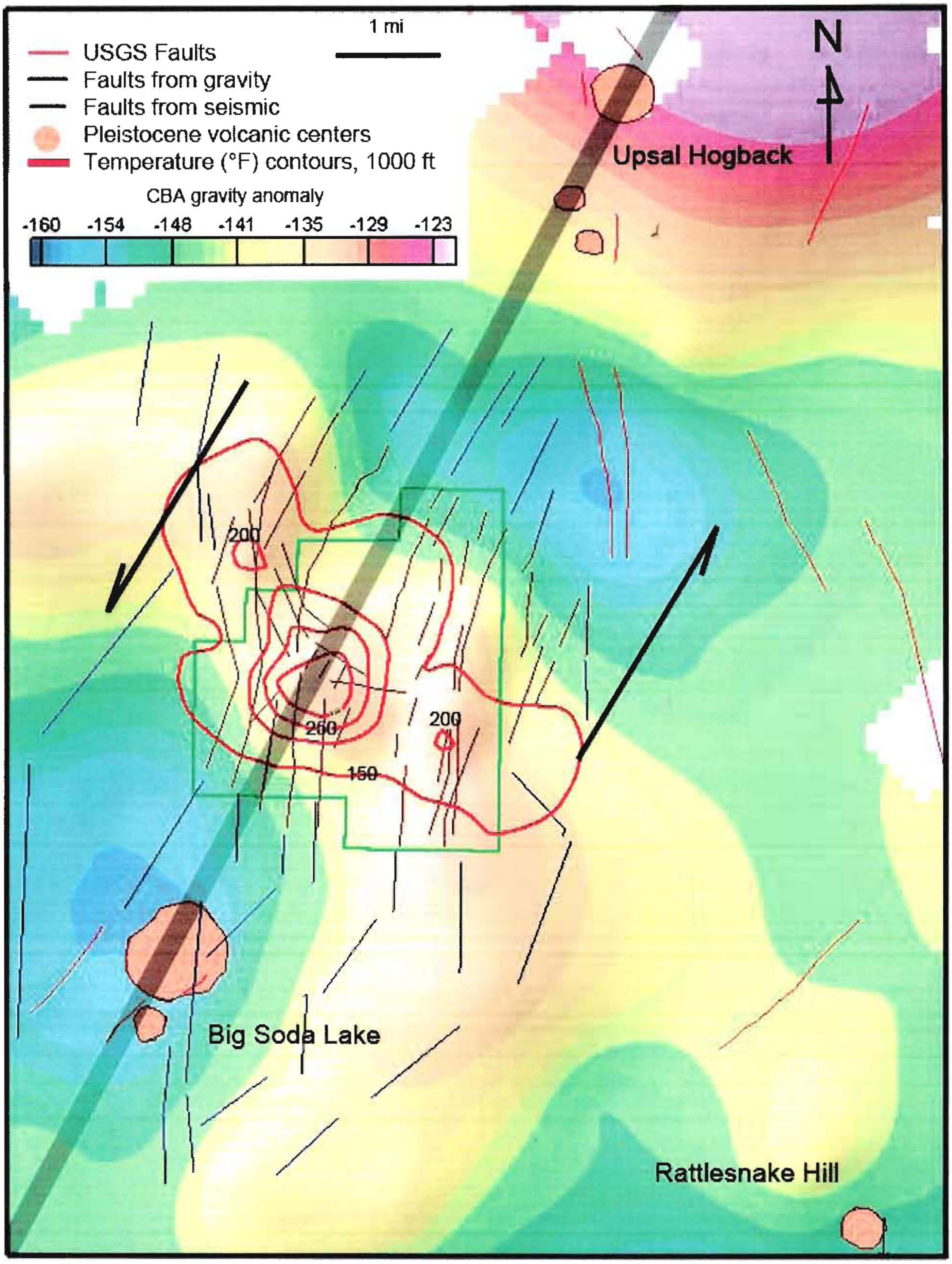


Figure 40: Regional Conceptual Structure Map. The surface location of faults and volcanic centers are shown on the regional gravity anomaly. The grey line represents a zone of crustal shear that links three volcanic centers. The black arrows represent the left-lateral shear.

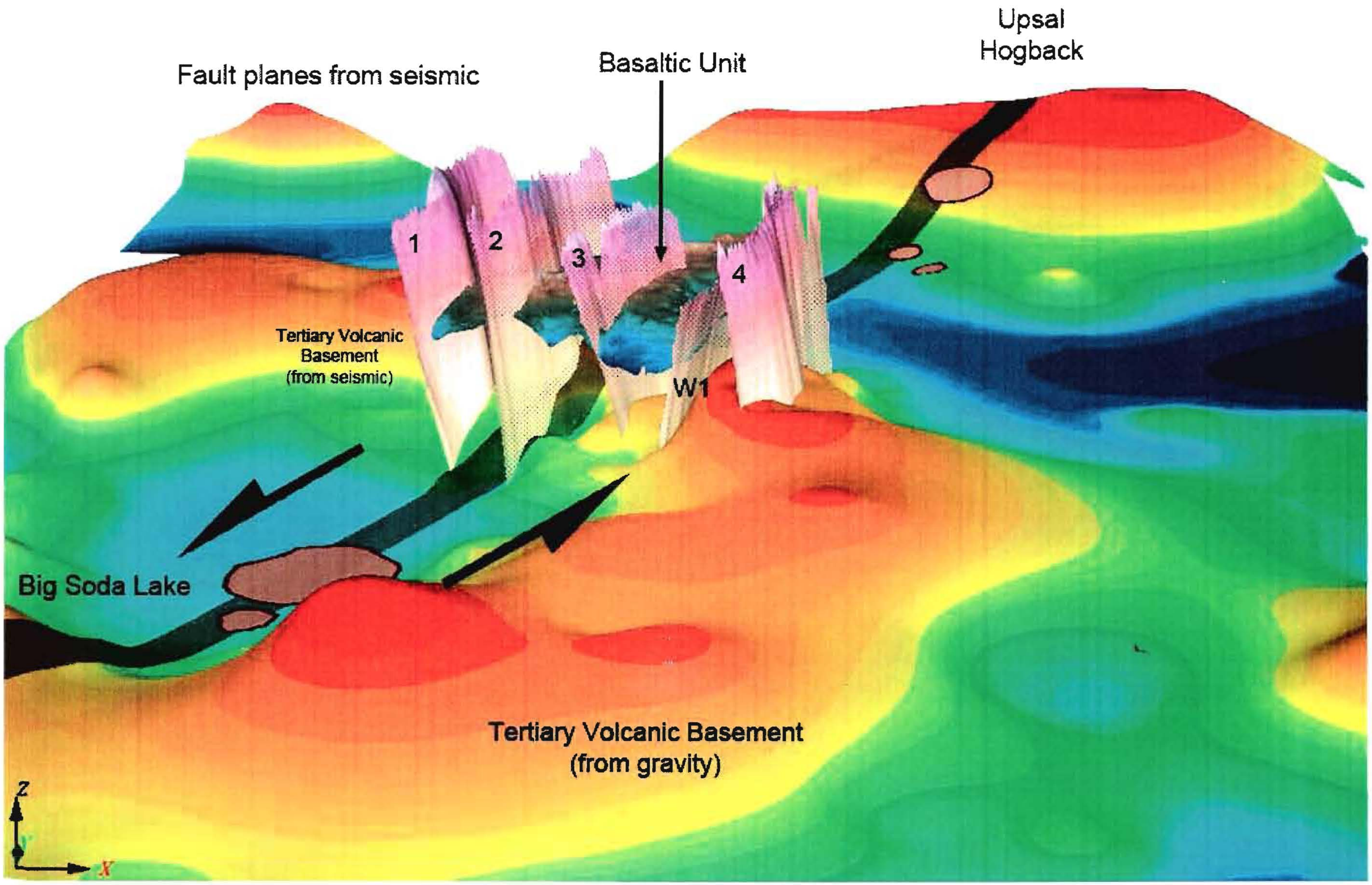


Figure 41: Conceptual Geologic Model, 3D oblique view. The numbered faults are consistent with the text and other figures. The volcanic features depicted on the surface in Figure 40 have been placed on the basement surface. While the sinistral strike-slip fault system is miles wide near the surface, at depth a wrench fault is near-vertical zone of crustal weakness providing pathways for deep fluids.

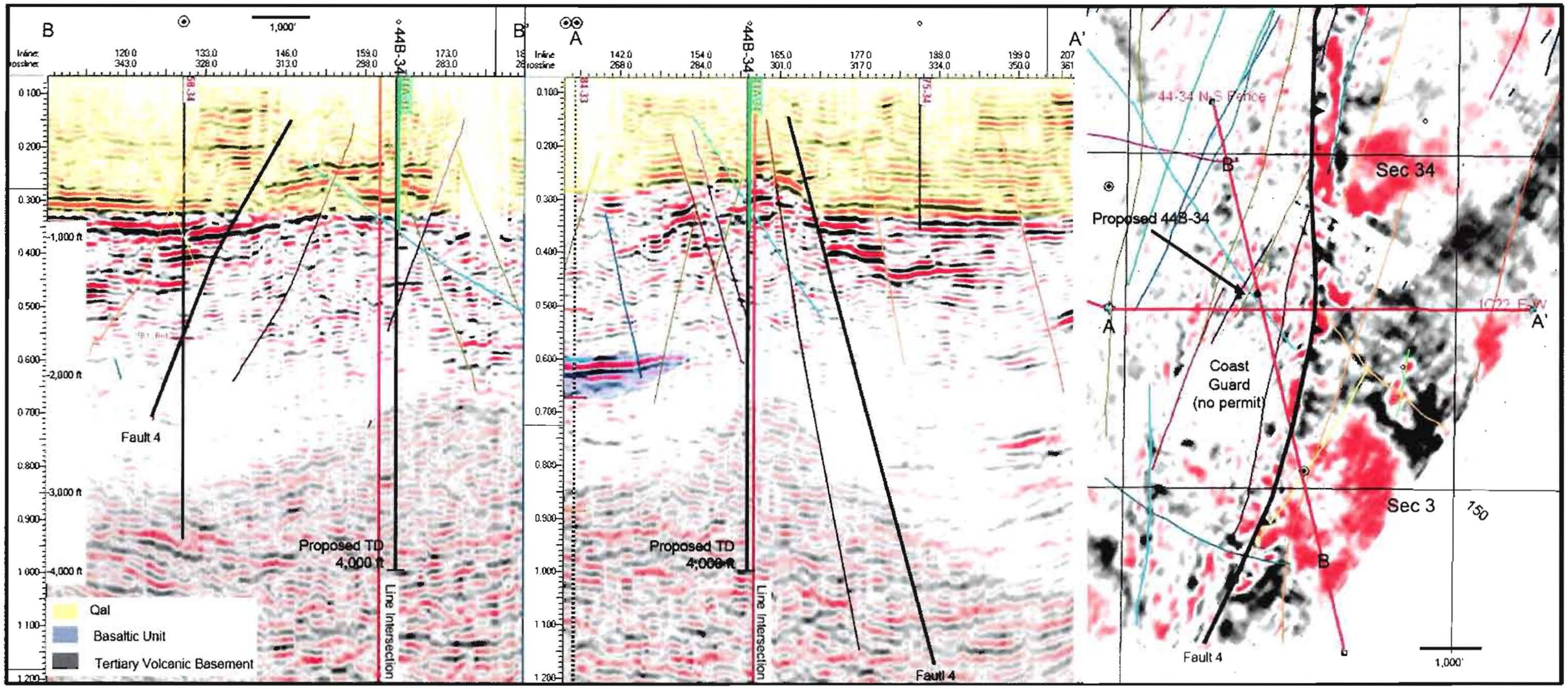


Figure 42: 44B-34 Seismic Cross-Section. The east end of the E-W seismic profile (A-A') intersects with arbitrary seismic line (B-B') near the proposed location. The depth of 44A-34 is the green line. The proposed location should test the Tertiary Volcanic Basement below 2000 ft.

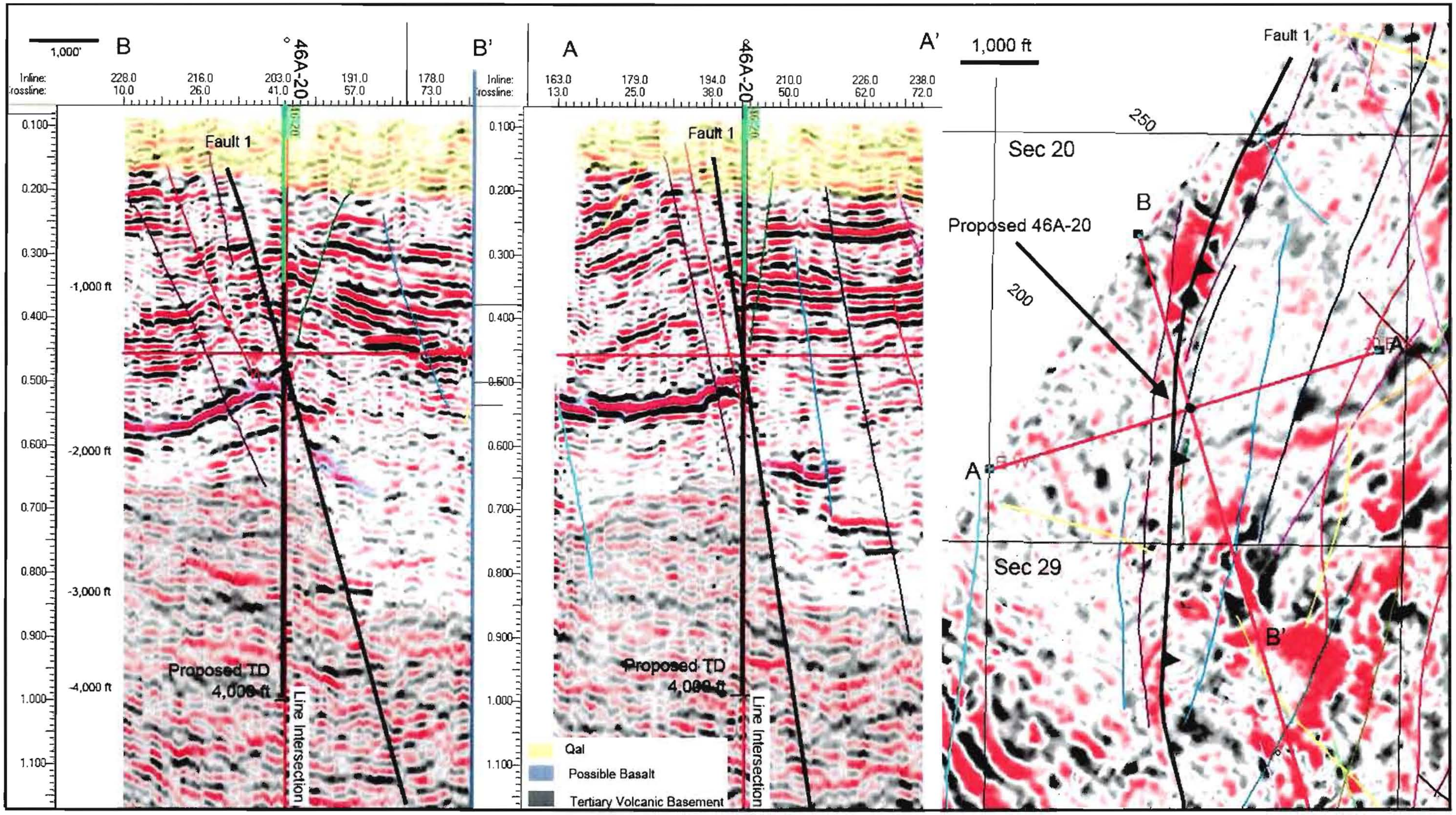


Figure 43: 46A-20 Seismic Cross-Section. The west end of the E-W seismic profile (B-B') intersects with arbitrary seismic line (A-A') near the proposed location. The depth of 46-20 is the green line. The proposed location should test the Tertiary Volcanic Basement below 2000 ft.

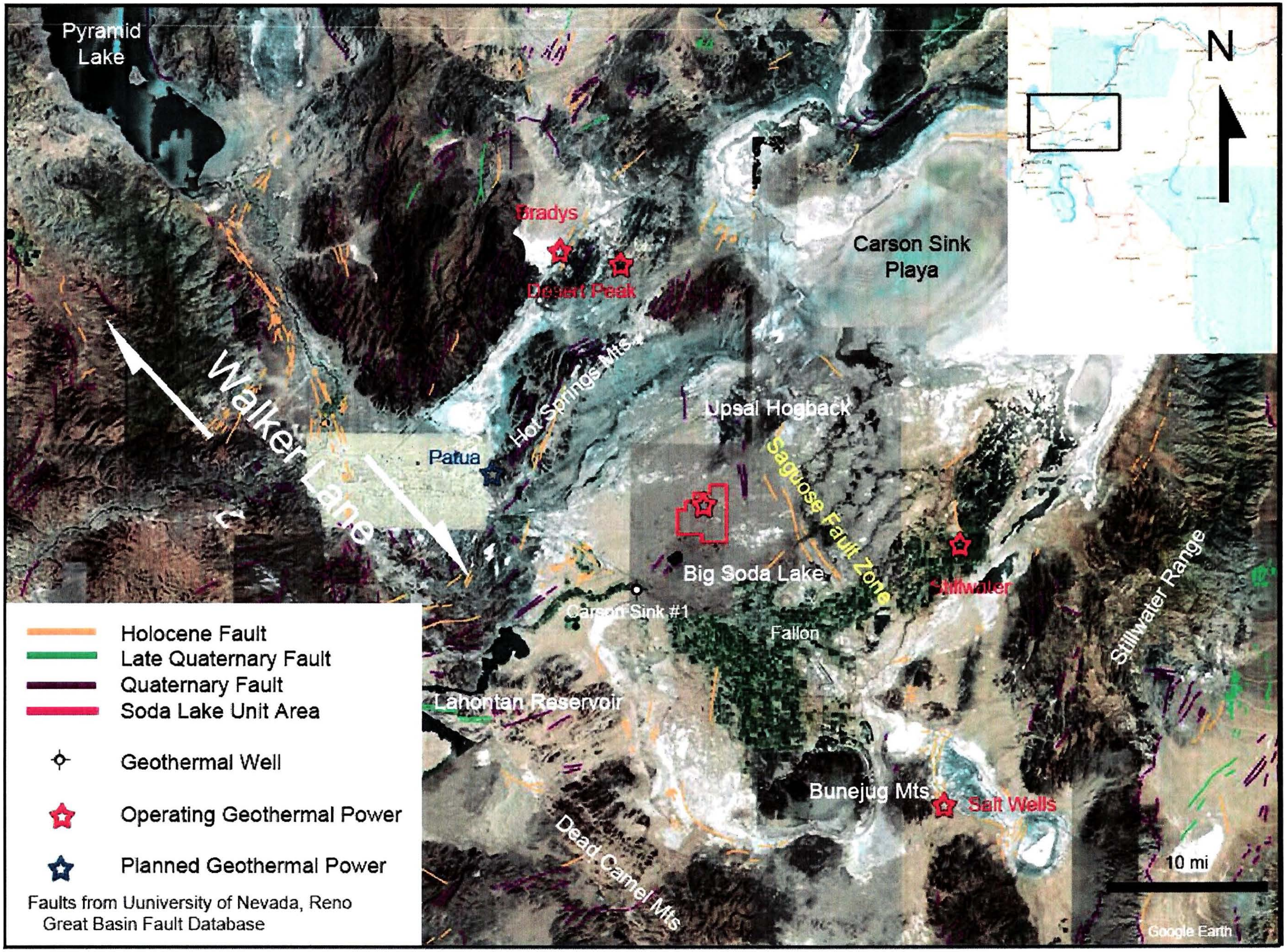


Figure 1: Soda Lake Project Location and Regional Setting

Appendix 1 - Vertical Seismic Profile

The VSP method evolved from zero-offset, check-shot surveys where a single geophone was lowered in a well to record the near-vertical, one-way travel-time from a surface-source to correlate time with depth. Stringing multiple geophones together in a vertical array reduced the number of surface sources. A "walkaway" VSP can image the vicinity around the well bore when surface sources are spaced along a line at frequent intervals up to the approximate depth of the deepest sensor.

A Vertical Seismic Profile (VSP) was acquired in well 41B-33 on June 15, 2010. Well 41B-33 is by far the deepest accessible well in the field with a one-year old uncemented liner known to be in good condition. A 28-day injection test in 41B-33 provided an opportunity to acquire a VSP due to cooling of the well to ± 170°F which is within the limitations of the geophone array. With the introduction of high temperature, three-component receivers, VSP technology has the potential to image fluid-filled fractures proximal to geothermal wells.

Survey Planning and Data Acquisition

A Two-Leg, Orthogonal Geometry (TLOG) Walkaway Vertical Seismic Profile (VSP) was designed to determine if fractures could be identified adjacent to a well bore (Figure 1-1). The Halliburton crew arrived on-site Monday, June 14, with two, on-road 50,000 lb. vibrators. The original plan was to acquire a Vertical Wave Test (VWT), a check-shot survey to 7000 ft, and a TLOG VSP. The planned walkaway legs had off-road source points that extended due south and due west, following the trajectory of the deviated 41B-33 wellbore, but the off-road source points could not be accessed by the Halliburton vibrators.

Assembling a 22-geophone array is a time consuming process where each geophone and 50 ft cable is connected one-by-one and lowered into the well. During the first trip into the hole, geophone #12 was intermittently communicating with the deeper geophones. After bring the array out of the hole, removing #12, and re-entering the hole, the real culprit was discovered to be #11. The array was again disassembled and reinstalled as the final 20-geophone array. This delayed the start of data collection until 4 PM on the day of the survey and provided time for the well to reheat following cessation of injection earlier in the day. This resulted in the planned VWT on the way in the hole being eliminated.

After the first recording at 1000 ft, the geophone array was lowered to 7000 ft, the deepest portion of the well that was expected to remain below 250°F at that time. Due to well deviation, the source points for the first two deep array set-ups were horizontally offset by 1750 ft (depths of 6050 ft-7000 ft) and 1000 ft(depths of 5150 ft – 6100 ft) to the west of the wellhead to be above the geophones. Each set-up had a two phone overlap for redundancy and QC. The shallower array depths were in the near-vertical to vertical portion of the hole. The "zero-offset" sources were actually 300 ft from the wellhead to minimize surface-generated noise propagating downhole along the casing and liner.

When the array reached the fourth set-up, between 3000 ft and 4000 ft, where the walkaway VSP would start, the first long-offset source point showed that a single vibrator per source point would not be sufficient, due to the background noise of the operating well field and power plant. Changing the program to accommodate 2 vibrators, guaranteed that most data would be acquired after dark. Turning the vibrators around on narrow dead-end roads after dark risked the entire program, so the program was reduced to a single walkaway profile from well 41B-33 to well 45A-33. VWT data and check-shot source points were acquired intermittently when the vibrators came back to the zero-offset location.

Results and Discussion

Prior to the survey, we understood that three-component geophones required full-elastic coupling with the formation for optimum results, primarily in cemented casing. Due to the cost of the geophone array, VSP's are rarely run in open hole due to the risk of collapse and other hazards. In the oil & gas industry, most of the well bore is cased due to the need isolate productive and non-productive horizons. Geothermal wells are not cased to total depth and are generally "bare foot" completions, e.g. open hole below casing, or a combination of blank, slotted or perforated liner. An arbitrary seismic line from the 3D reflection seismic survey is shown coincident with the well trajectory of 41B-33 (Figure 1-2) shows the casing strings (bold) and un-cased portion of the well. The geometry of the three source locations, the position of the receivers in the well bore, and the basaltic unit will be discussed later in the text. The corridor stack is generated from the up-going p-wave energy and is an alternative to a synthetic seismogram. In the section above the basalt and in the vertical portion of the hole, there is a good match to the waveform character of the reflection seismic data.

Three temperature profiles (Figure 1-3) are shown to describe the range of hole conditions. The green curve is a temperature log on Nov 25, 2009 and represents the best true formation temperature (TFT). The blue curve is from a temperature log on Jan 28, 2010 during a low rate injection test showing the intervals where fluid is exiting the well bore, 1) base of the casing, 2) perforations above 3980 ft, 3) slotted liner below 6962 ft.

Prior to the VSP, a temperature-pressure-spinner test was performed in 41B-33 to observe current temperature conditions and to determine whether inter-borehole flow existed under static conditions (Figure 1-3, curve 3). The red curve represents the temperature of the well immediately prior to the VSP after high volume injection. Since the well was perforated above 3980 ft, any vertical flow between zones inside the liner could produce enough turbulence around the geophones to overwhelm the surface source. No vertical flow was measured.

Vertical Wave Test

Prior to the acquisition of a reflection seismic survey, a series of tests are conducted to optimize certain acquisition parameters. A sweep test is a series of recordings where a vibroseis source imparts a range of frequencies (e.g., 8 Hz to 64 Hz) for a set period of time (sweep length). The duration and the number of sweeps per source point determine the total energy available for imaging. By placing the geophone array in the wellbore, one can observe the natural filtering occurring as the energy propagates through the overburden.

Sweep frequencies of 8-128, 5-80, and 6-48 Hz were tested with the 950 ft long geophone array deployed at the base of the lacustrine mudstone section (1000 ft – 1950 ft), within the basaltic unit (2450 – 3400 ft) and partially within and below the basalt (3350 – 4300 ft). For the most part, the response of the three sweeps is identical, with very little energy above 55 Hz in the 1000 ft – 1950 ft range. In the lower section most of the energy falls between 25-45 Hz (Figure 1-4).

Conflicting requirements will require a compromise in choice of sweep bandwidth. Prior to the seismic survey, two, 2D lines were acquired varying the source parameters, sweep frequency, sweep length, and two- and three-vibrators. The seismic data needs higher frequencies to better resolve recent faulting in the upper 1000 ft. The VWT showed there is strong attenuation of the higher frequencies in zone of interest. The resulting compromise was to have a high-end of 72 Hz for shallow resolution and three vibrators and two-sweeps per source point to maximize energy.

Check-shot Survey

The check-shot survey was performed to provide direct measurement of the time-depth relationship in the center of the field. To a depth of 5200 ft it provided the initial time-depth function (Figure I-5). One product of the check shot survey is an interval velocity series calculated from the differential arrival time times (Figure 1-5, center). These interval velocities compare closely with the sonic log velocities in the basaltic unit, due to a uniform hole diameter. Above the basalt, the hole diameter is ≥17 1/2" in softer sediments and has frequent cycle skips, giving erroneously high interval velocities. Below the basalt, borehole temperatures were consistently above 250°F which may have affected tool reliability. After incorporation of synthetic well ties from other wells, the 41B-33 time-depth conversion was the fastest in the field due the 2000 ft thick sequence of high-velocity basalt present between depths of 1835 ft and 3705 ft.

Figure 1-6 is a composite of all the data collected during the check shot survey, including the two vertical incident sources. The three panels are the three components, vertical, H1 and H2, and show the impact of not achieving full-elastic contact in the liner. The H1 panel shows the as-recorded data and H2 panel shows the 200 ft-5200 ft interval after horizontal rotation.

In the H1 and H2 images, down-going shear-waves can be seen propagating at a velocity just under 8000 fps versus a direct arrival velocity of 15,750 fps, agreeing within the range of the dipole sonic Vp/Vs. However, the signal is intermittent due to the vagaries of liner-formation contact. In processing, separation of the up-going shear-wave was not possible due to the coupling and attenuation of signal.

The differences in arrival times can be explained by the arbitrary seismic line profile in Figure 1-2. With two overlapping geophone locations for each array set-up, we were convinced that array depths were correct. The remaining cause had to be ray-path. The zero-offset sources penetrated the thickest portion of the basalt, while the two vertical incident sources had correspondingly thinner sections, giving the first indication of how the thickness of the basalt varies over relatively short distances.

Walkaway VSP

The original plan for the TLOG VSP was to collect two orthogonal walkaway profiles. Well 41B-33 is vertical to 2200 ft, and then deviated to the west at a maximum angle of 30°-40° to a measured depth of 8995 ft. One leg was to be oriented above the well bore, the other due south connecting 32-33 and 25A-33. The vibroseis source is a hydraulically-modulated mass that transfers energy to the ground. A significant portion of the energy from a p-wave vibrator is in the form of a vertically-polarized shear-wave. By using orthogonal source lines both components of the shear-wave can be measured in the wellbore. Alford rotation concepts can be applied to the crossed-shear vectors at specific target intervals and rotate the data to fast-shear and slow-shear directions, which is a great asset in interpreting fractures and stresses (Alford, 1986).

Unfortunately, the TLOG VSP was replaced by a single walkaway profile between 41B-33 and 45A-33. A 3D representation of the source ray-paths and well trajectory is shown in Figure 1-7. The first source for the walkaway profile was acquired at 21:00. With the array between 2450 ft-3400 ft, four source locations were acquired, 45A3 (3000 ft offset), 45A2 2000 ft offset), 45A1 (1000 ft offset) and the zero-offset (300 ft offset). The array was moved to the interval of 1550 ft-2500 ft. After recording the first source at 45A2, it became apparent that having geophones in the cemented portion of the hole and the liner set up an unacceptable noise environment. The array was moved to the range 1100 ft-2050 ft, above the liner hanger, with source location at 45A1 and the zero-offset. The last set-up was from 200 ft-1150 ft with the same source location.

On the VSP display, the area under the arrow, (1), shows the refraction of energy along shallow horizons, leading to the 200 ft-1050 ft being discarded for further efforts. The "no data" zone between 2100 ft and 2400 ft was discussed earlier. An arbitrary Seismic line between 45A-33 and 41B-33 (Figure 1-5) provides cross-section of the structure between the wells.

The Vertical Seismic Profile provided a valuable direct measurement of time versus depth (T-D) from a surface source. We discovered as the project progressed, that a velocity model constructed from indirect sources, synthetic seismograms and seismic stacking velocities, can introduce uncertainties when formation tops picked from wireline data do not coincide with distinct velocity and density contrasts. The 41B-33 VSP was the first survey-wide T-D function used to convert the depths of formation tops to seismic time. This T-D function was also the fastest in the entire survey due to the thickness of the basaltic unit. As more indirect T-D functions were introduced other inconsistencies were observed which required iterations of T-D functions and formation top depths. Having one direct measurement eliminated a lot of "what-if" scenarios.

Lessons Learned

Vertical Seismic Profiles in high-temperature geothermal wells will have limited applications. The windows of opportunity are currently limited to relatively cool wells outside of the thermal anomaly or immediately following periods of active cooling associated with drilling or injection testing. Full elastic coupling is vital for good signal-to-noise. Unless a geothermal well is cased and cemented to near the zone of interest, the geophone array inside an uncemented liner will be reduced to a check-shot survey, where an expensive geophone array is not necessary.

One potential use of the VSP is to identify fluid-filled fractures adjacent to the impermeable wells. Since a large part of the cost of a geothermal well is the large diameter hole to the casing point, it would be advantageous if a VSP could orient a redrill to permeability by use of walkaways in multiple directions. In addition to controlling wellbore temperatures and achieving full elastic coupling, the general volcanic geology of most geothermal resources will continue to challenge the seismic method.

In light of the experience with the 41B-33 VSP, this application will not be something that could be accomplished with a rig on stand-by. The Halliburton crew was mobilized from New Iberia, Louisiana. They arrived with 50,000 lb vibrators that were limited to travelling on hard-packed surfaces, even though all through the planning, it was clear that off-road source points were needed. The turnaround for a finished product is one the order of months, not hours.

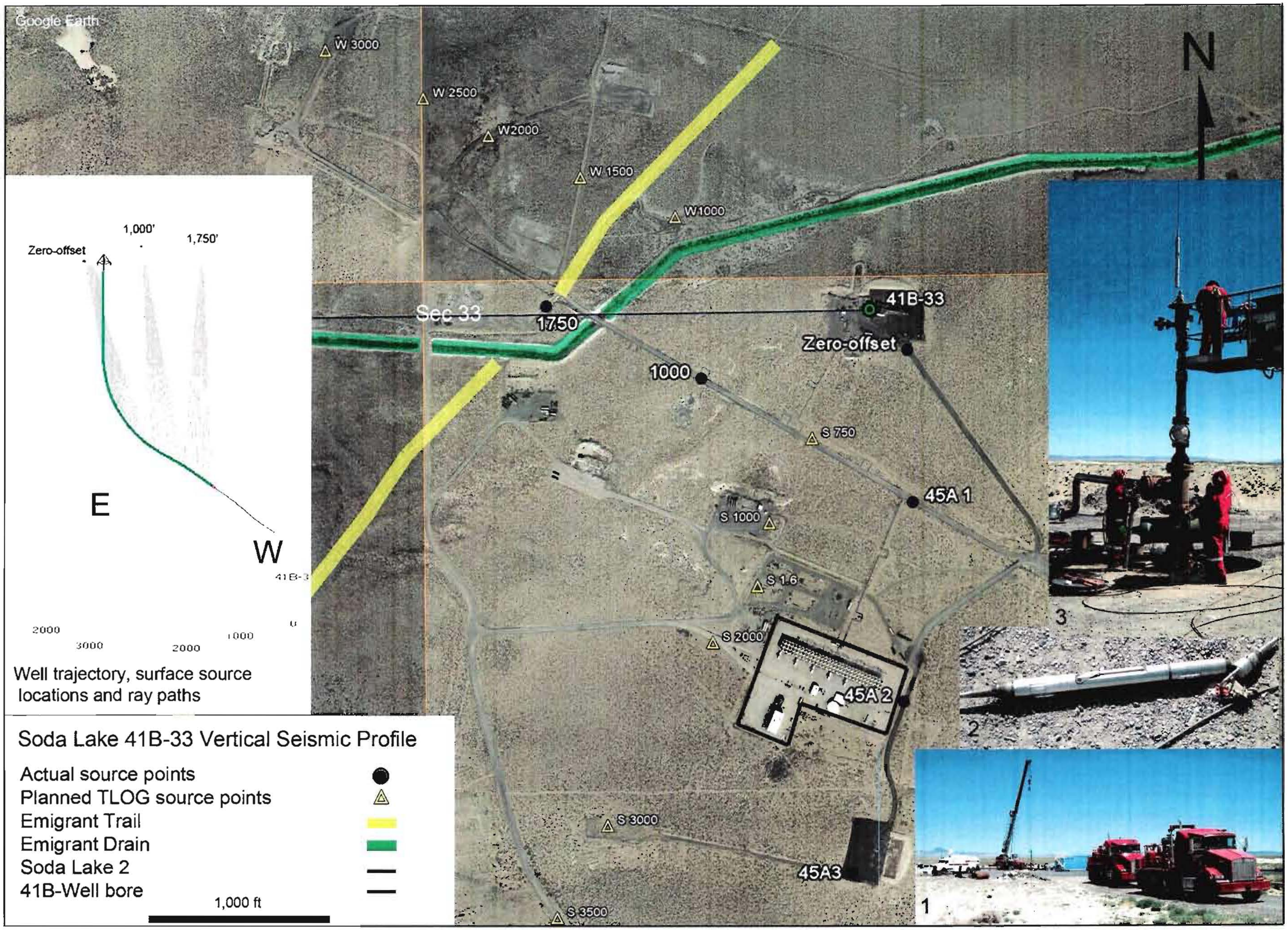


Figure 1-1: Vertical Seismic Profile Plan Map. Insets: 1) vibrators at the zero-offset source point, with the Halliburton logging truck and crane over 41B-33 in the background; 2) one geophone of the array; 3) assembly of the array at the wellhead.

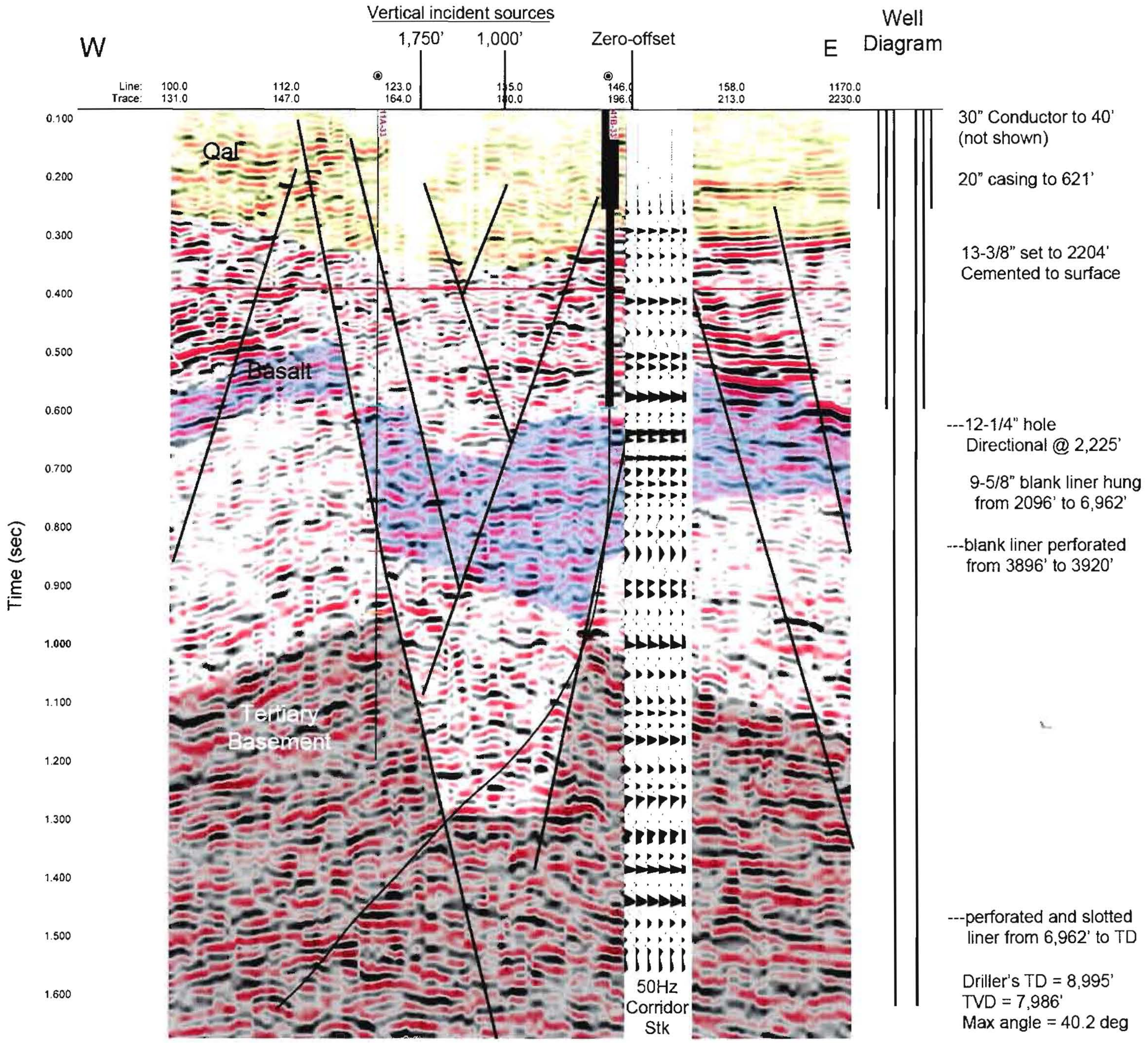


Figure: 1-2: Arbitrary Seismic Line Along 41B-33 Well Path and VSP Corridor Stack

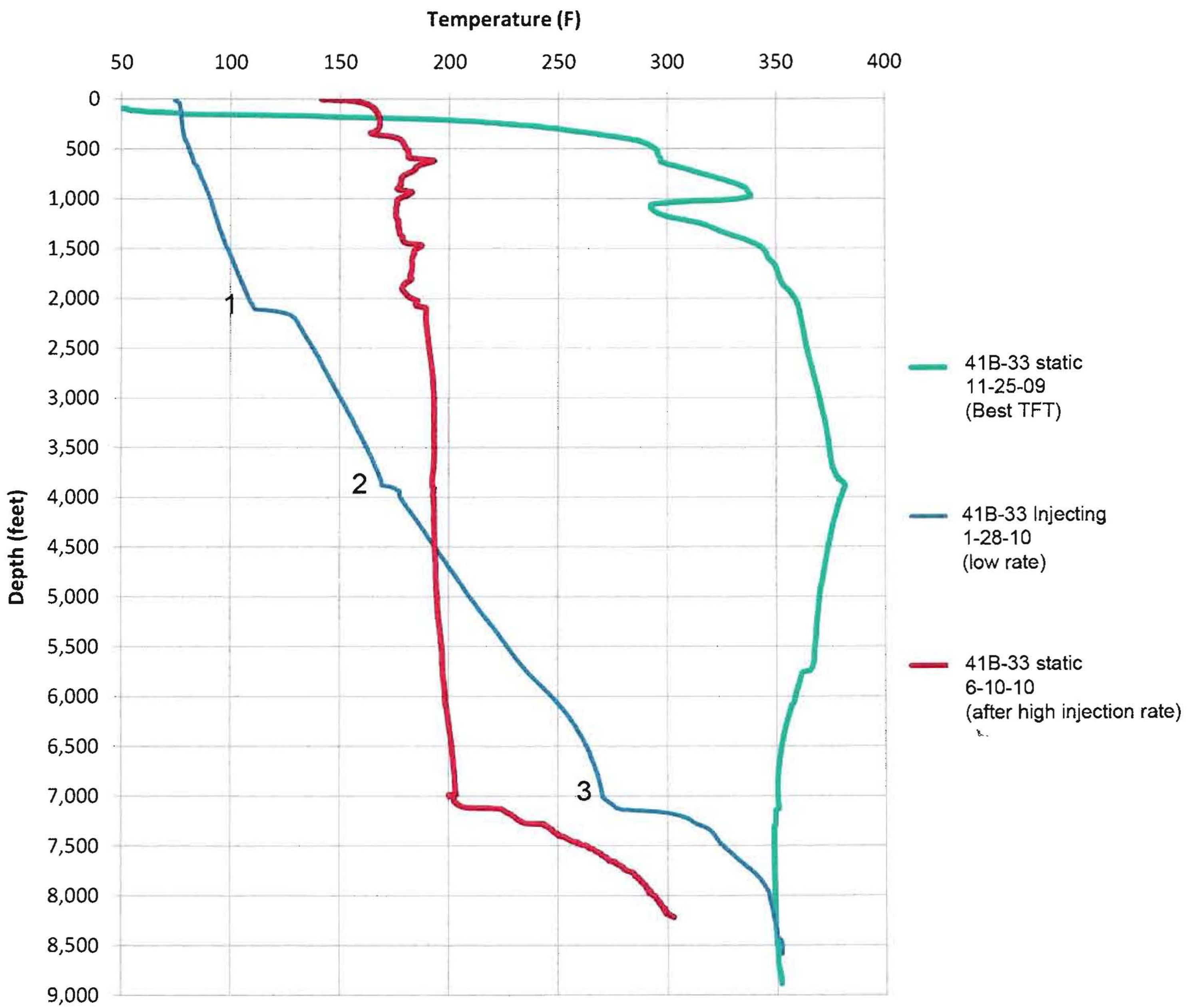


Figure 1-3: Temperature Profiles Under Various Hole Conditions

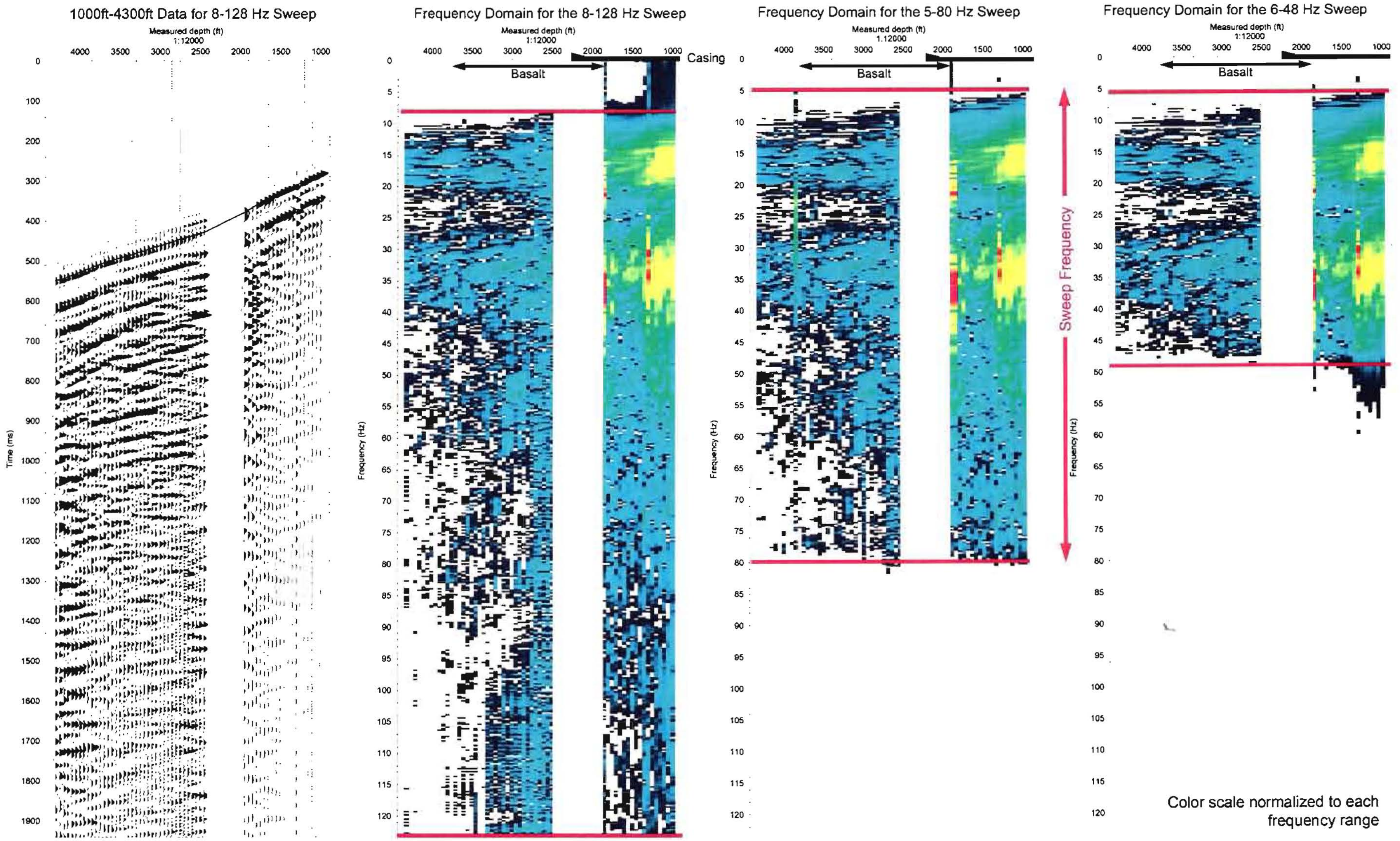


Figure 1-4: Vertical Wave Test. Left: data with Automatic Gain Control (AGC) of the three 8-128 Hz sweeps from the depths listed above, with a gap between 2000 ft and 2400 ft. Right: frequency analyses of the three sweeps without AGC. The strength of signal is color-coded, violet (low) to red (high) and normalized for each sweep.

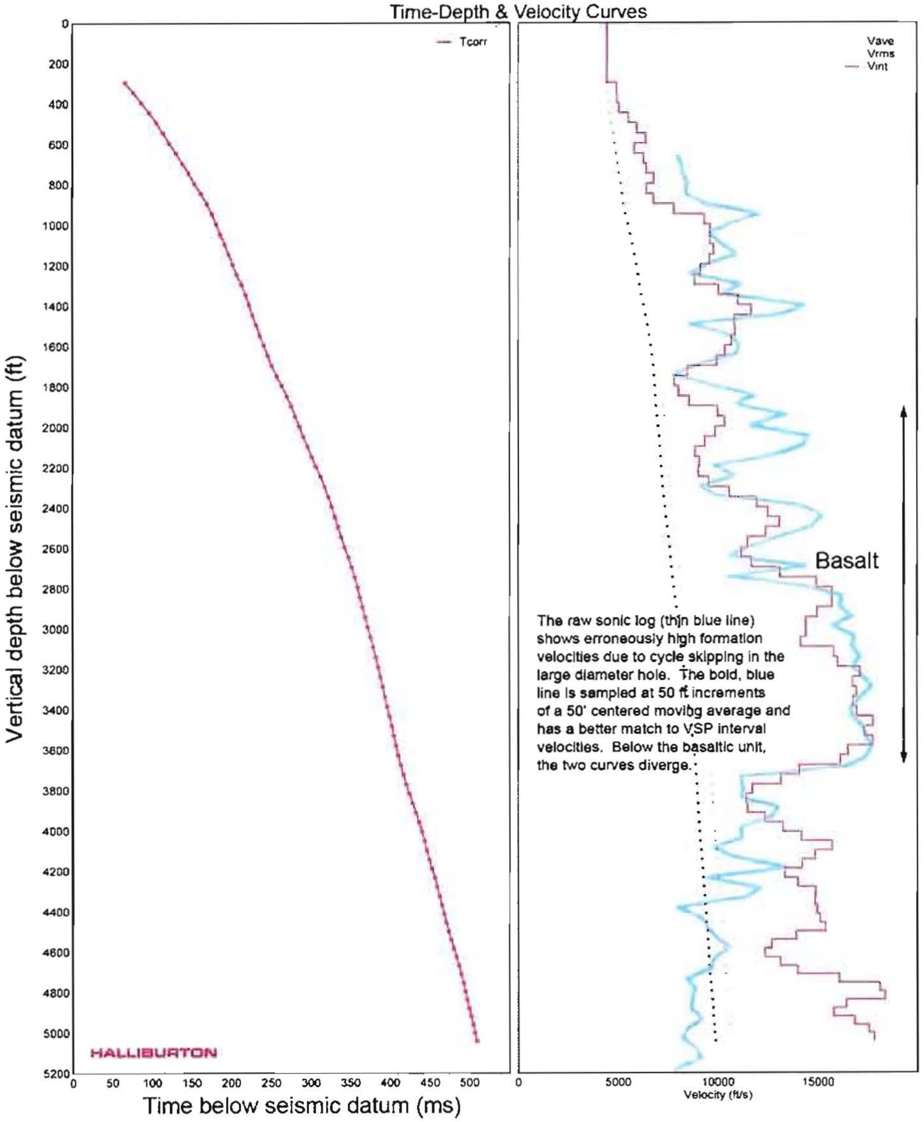
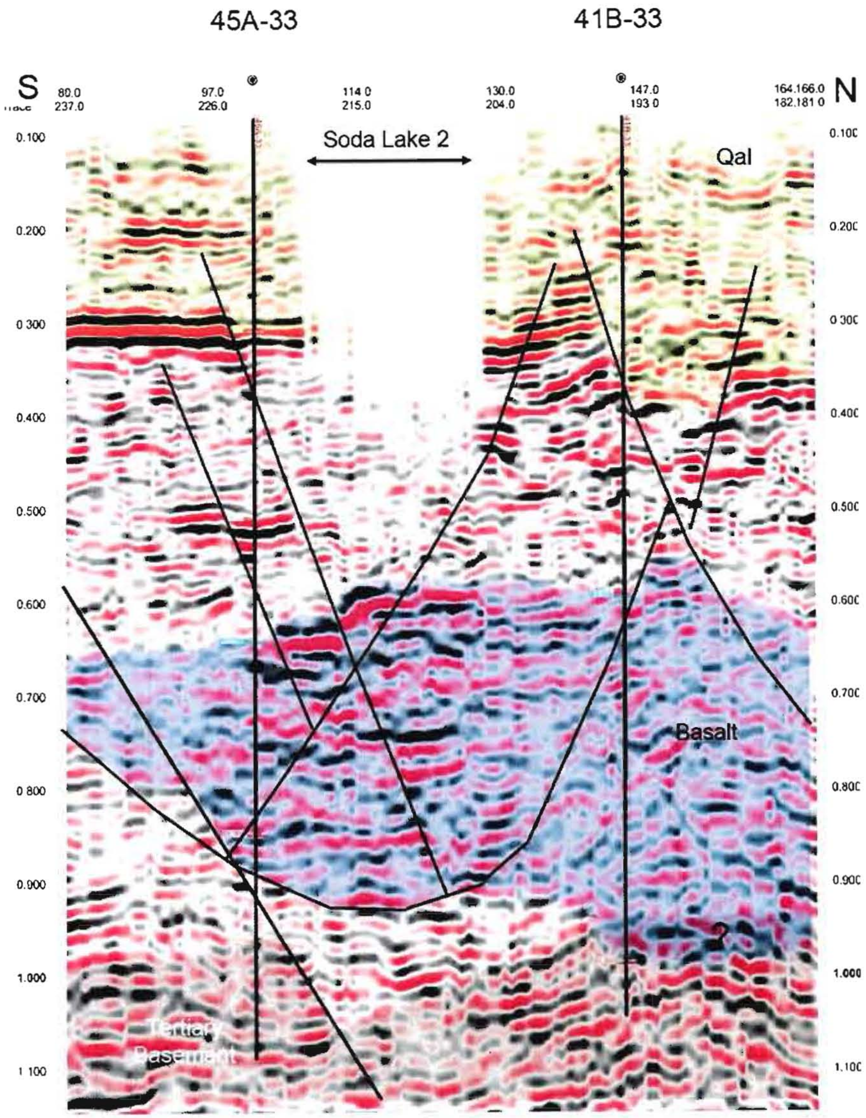


Figure 1-5
Check Shot Survey, One-Way Time vs Depth and Interval Velocities



Arbitrary Seismic Line between 41B-33 and 45A-33

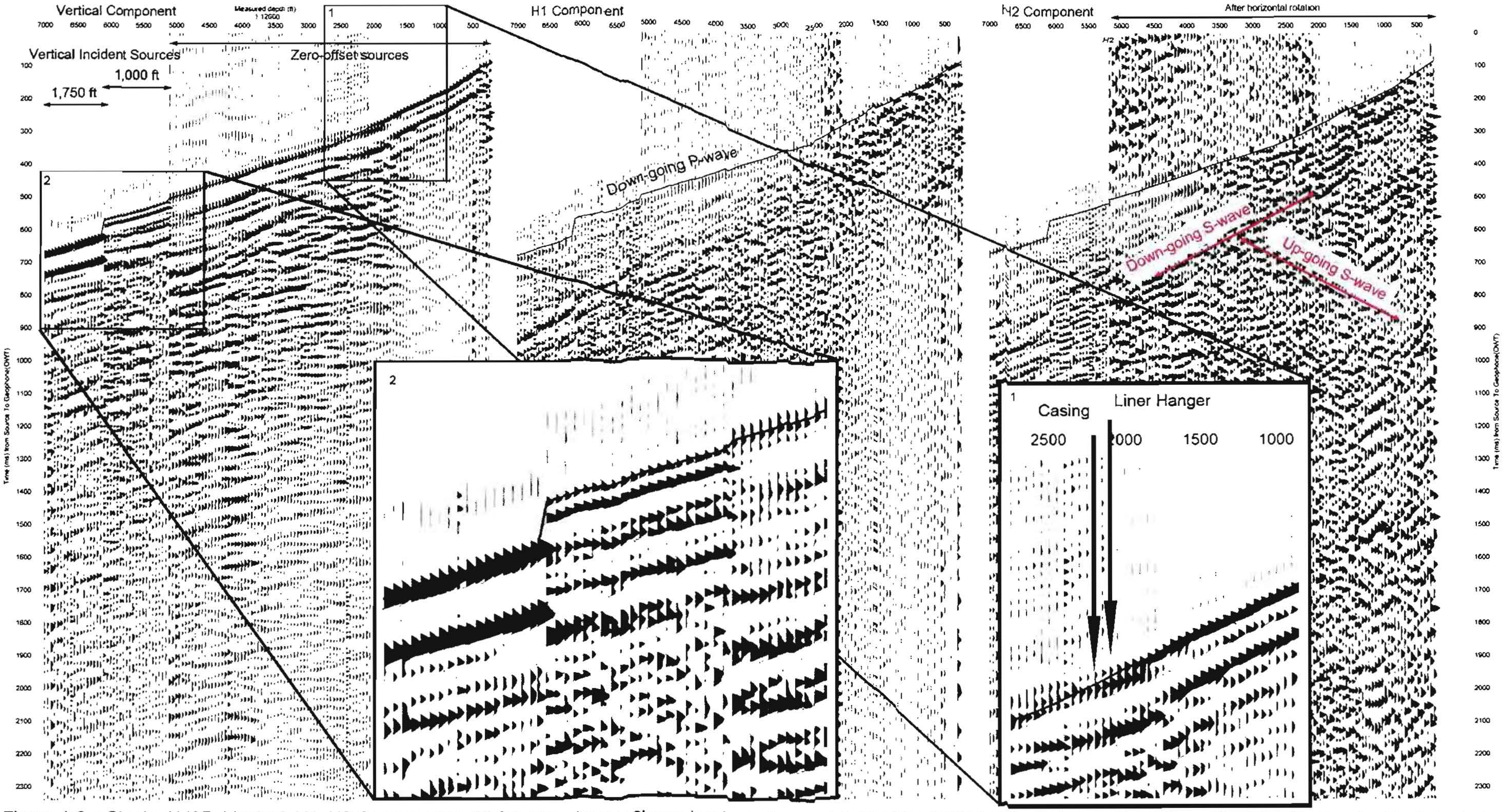


Figure 1-6 : Stacked VSP, Vertical, H1, H2 Components, All Sources. Inset 1: Change in seismic character between the cemented casing and open-hole with liner. The well defined trough of the first arrival becomes smeared due the destructive interference of the fluid-filled annulus and the liner. Inset 2: Discontinuities in the first-breaks between the zero-offset and vertical incident sources, in both arrival times and first-break character. The zero-offset and 1000 ft source points were located on the hard-packed gravel roads of the Soda Lake facility. The 1750 ft source point was located on soft sand, producing a much lower frequency signal.

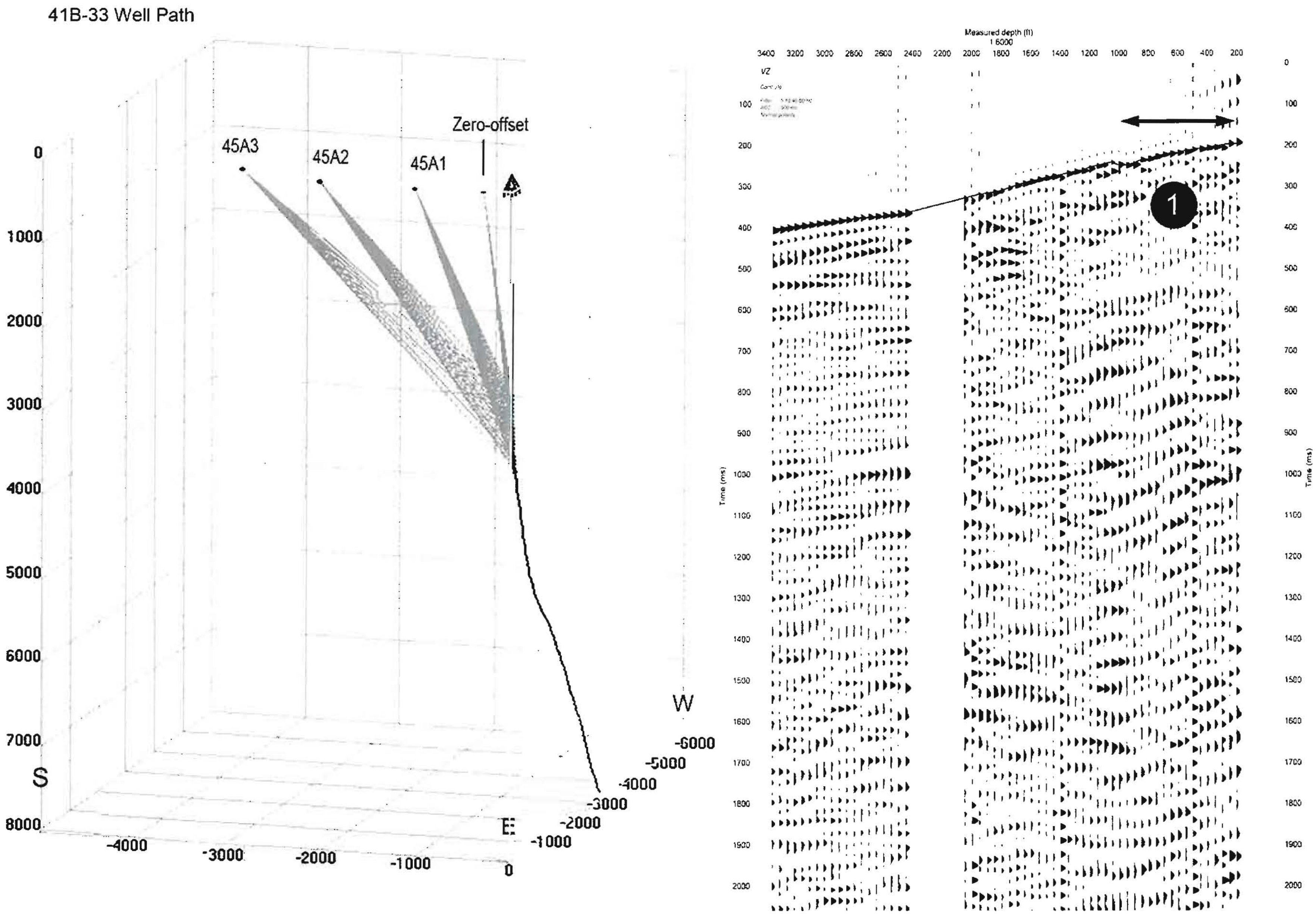


Figure 1-7: 45A-33 Walkaway Profile. Left: Well trajectory with surface sources and ray paths. Right: Composite source data

Appendix 2 - 3D-3C Reflection Seismic Survey Data Acquisition

Reflection seismology has historically had limited application in geothermal fields. In Nevada, data quality is degraded by the combination(s) of complex structure, colluvial aprons, volcanic rocks at the surface, discontinuous strata, near-surface alteration and shallow boiling, and high lateral and vertical velocity changes, etc. The Soda Lake geothermal system is overlain by upwards of 2,000 ft of Quaternary lacustrine and deltaic sediments and the data quality in this interval appears to be average to good. The 1977 2D seismic data were acquired with shot-hole dynamite which placed the source beneath the aeolian sand dunes. The 3D survey used a vibroseis surface-source.

When the survey was originally planned, standard vertical geophones would be connected by cables to a mobile recording system. In the time between the NOI was filed to data acquisition, the acquisition parameters described above were modified to three-component geophones and a cable-less, continuous recording system. Without the need to transport thousands of pounds of cables and troubleshoot cable continuity and connections, productivity greatly increased.

The complete acquisition specifications follow in this Appendix. The basic specifications are: receivers spaced on a 220 ft interval; 550 ft receiver lines; 110 ft tandem source lines; 110 ft source interval; 770 ft source lines. The active patch is 28 lines (770 ft interval) x 46 stations (220 ft interval). This configuration yields 55 ft bins and high fold in the 2,000 ft–4,000 ft area of interest.

In Figure 26, the even-numbered sections (1 sq mi, 640 acres) colored light gray are under the jurisdiction of the Bureau of Land Management (BLM) and the Bureau of Reclamation (BOR). Under an agreement between the agencies, the Carson City District Office of the BLM acts as lead federal agency for permit compliance. Federal approval is required under Section 106 of the National Historic Preservation Act (NHPA) (36 CFR 800). Cultural resource investigations for the Soda Lake area follow methods and procedures outlined in the Cultural Resource Inventory General Guidelines (BLM 1989) as well as the 2009 State Protocol Agreement between BLM, Nevada and the Nevada State Historic Preservation Office (SHPO) for implementing the NHPA. An archeology contractor performed this investigation to identify and record cultural resources within the Area of Potential Effects (APE), asses the significance of identified resources according to the NHPA, and recommend procedures for avoidance or mitigation of adverse effects.

The private lands have 91 mostly-absentee, individual land owners. Each one must be contacted and agree to surface access to their property. Permit agents required about two months of phone calls, mail correspondence and door-to-door visits to secure landowner permission. Only 130 acres of private land were not permitted. All private land owners declined permission to conduct a cultural inventory.

The survey has 36 receiver lines, each line averaging 18,250 ft long, with a cumulative length of 124.7 miles. There are 8,374 sources on 52 lines, each line averaging 19,000 ft long, with a cumulative length of 190.6 miles. Once landowner permits were in place, a land survey crew marked the source and receiver lines. The locations of individual points are recorded using a high accuracy global positioning system (GPS). Surveying the source and receiver locations required almost 40 days.

In many parts of the country, a reflection seismic survey is considered "casual use," activities ordinarily resulting in "no or negligible disturbance of the public lands or resources." In Nevada, casual use extends to vehicles weighing less than 10,000 lbs. The Vibroseis sources are 62,000 lb machines on large diameter, two-foot wide tires. Under the sandy conditions of the survey area, compression of the soil is on the order of two or three inches.

Assuming half of the source and receiver lines fell on public lands, the 500 miles of shot and receiver lines required 250 miles of transects that identified, recorded and evaluated twenty-one isolated artifacts and forty-nine archeological and historical sites within the APE. Of these, 10 of the sites were considered eligible for the National Register. As such, the boundaries to these sites, plus a 30m buffer were clearly marked with coded flagging tape. No project activities would occur within these areas, with the exception of foot traffic to plant receivers. Travel routes around the sites were also inventoried to ensure no additional sites were affected.

Seven of the sites were pre-historic lithic scatter or historic debris and ranged in size from two to ten acres. Among the remaining sites were 20,000 ft of the Carson River Route of the Emigrant trail, a 19th century migration route to California, 16,000 ft of the Emigrant Drain and an elaborate irrigation canal and ditch system of the Newlands Project. The final Class III Inventory was 434 pages and completed in May 2010. The NOI was approved June 7, 2010.

In July 2009, Magma Energy submitted a proposal to the Geothermal Technologies Program under the ARRA FOA Topic 1, Validation of Innovative Exploration Technologies, to conduct a 3D-3C reflection seismic survey. At the time, it was generally assumed that the awards would be announced in November and the Environmental Assessment would be completed about the same time. Six months of delays associated with the completion of the Cultural Resource Inventory created additional expenses for permit agents and surveyors. By the time the seismic crew arrived on site, the permit from the Coast Guard expired, removing twenty-two receiver locations in Section 34. Much of the flagging marking source and receiver locations had disappeared, requiring re-surveying of thousands of locations.

The topography of the Soda Lake survey is relatively flat with sage brush-covered sand dunes. The maximum elevation difference is 70 feet. The articulated vibrators are four-wheel drive and very maneuverable, but the steep grades of a dune field (200 ac) and the seasonal lake beds (363 ac) eliminated important source points. The geothermal field created numerous obstacles with two power plants (100 ac), four injection wells and five production wells, and over four miles of pipeline. Other no-source zones included the Emigrant Drain (130 ac) and a recently decommissioned Coast Guard LORAN tower (50 ac). The Emigrant Trail ran almost parallel to the shot lines so most of those sources were offset parallel to the track. An additional 250 acres of sources were eliminated in a residential area in the southwest corner of the survey.

Dawson Geophysical Company Party 29 arrived on site on June 16. The crew received safety training according to company policy and prepared for the next day's field parameter testing. The major question to be answered on the first day of field testing was how much energy needed to be input into the ground? Results from the VWT showed that the frequency content in the zone of interest fell below 45 Hz, so an 8-128 Hz sweep was chosen to determine if the shallow section would respond to the higher frequencies. A 2D line was laid out along a previously permitted source line (2178) beginning on the western Section 33 section line. The source tests consisted of one- and two-eight second sweeps, and one- and two-sixteen second sweeps. Overnight, a Unix-based field processing system generated a suite of stacked sections with the four source parameters. Upon reviewing the data, better results were obtained with longer sweeps and multiple vibrators. Frequency analysis of the data showed that the data in the shallow section did benefit from higher frequencies.

On day two of the testing, another 2D line, roughly perpendicular to Line 1, was shot along the pipeline road, running diagonally between receiver lines 6196 and 6201, using three vibrators and an 8-72 Hz sweep. Following overnight processing, it was clear that three vibrators produced better results. Two additional vibrators were ordered from Midland, TX and arrived on the third, full-day of shooting to provide two sets of three vibrators and one in reserve.

On June 19, production shooting began starting on the east side of the project. In this survey, receiver lines are approximately east-west, and source lines perpendicular. Under normal conditions, a seismic crew acquires data in rectangular patches following the pattern of receiver lines, where whole receiver lines are picked up "behind" the sources and relocated "ahead" of the sources. This requires the vibrators to traverse between source lines along receiver lines. One condition of the NOI required the sources to minimize ground disturbance, acquiring the data in a "lawnmower" fashion along the long source lines. This required rolling groups of receivers across the 36 receiver lines, complicating acquisition logistics. Instead of recovering all 86 receivers along a line, the crew recovers a small number of receivers spread across 36 separate receiver lines.

Figure 2-1 is a composite of acquisition activities. 1) Two sets of three vibrators averaged almost 700 daily source points over a twelve day shoot. Each source point consists of two, sixteen second sweeps with a several second pause between sweeps. While one set of vibrators moves into position, the other set vibrates a source station. On average, a source location was acquired on one-minute intervals. 2) Three vibrators in position at a source station. 3) The tracks left by three vibrators in typical Soda Lake soil conditions. 4) A receiver location is marked by a pin flag. The OYO Geospace continuous recording system consists (from top to bottom) a battery, a recorder with clock, and 5) three-component geophone. During placement, field personnel orient the horizontal component, represented by the big arrow in-line with the sources and the little arrow in-line with the receiver line. The vertical component has a bubble level. During QC, this observer did not see a single geophone misaligned. 6) The Dawson field camp consisted of (L-R) navigation equipment, AC generator, office trailer and data collection, crew vehicles, four-wheel drive ATV, crew facilities and more vehicles. The crew of 28 included a party manager, a party clerk, vibrator operators, vibrator mechanic, navigation specialists, surveyors, data processors, geophone handlers, and a fuel truck driver.

After the final source point, the field crew spent two days collecting the remaining 2,000 receivers on the ground. Each receiver may have up to 140 hours of uncorrelated recordings. The four channels of data on each recorder have to be downloaded, correlated and each four second trace assigned to a source location. Once all the traces are collected for a given source point, that collection is given a unique Field File Identification (FFID) number that has the location of the source and all the location of the receivers. During the collection of the final receivers and for several days after, all the survey flagging was removed from the survey area.

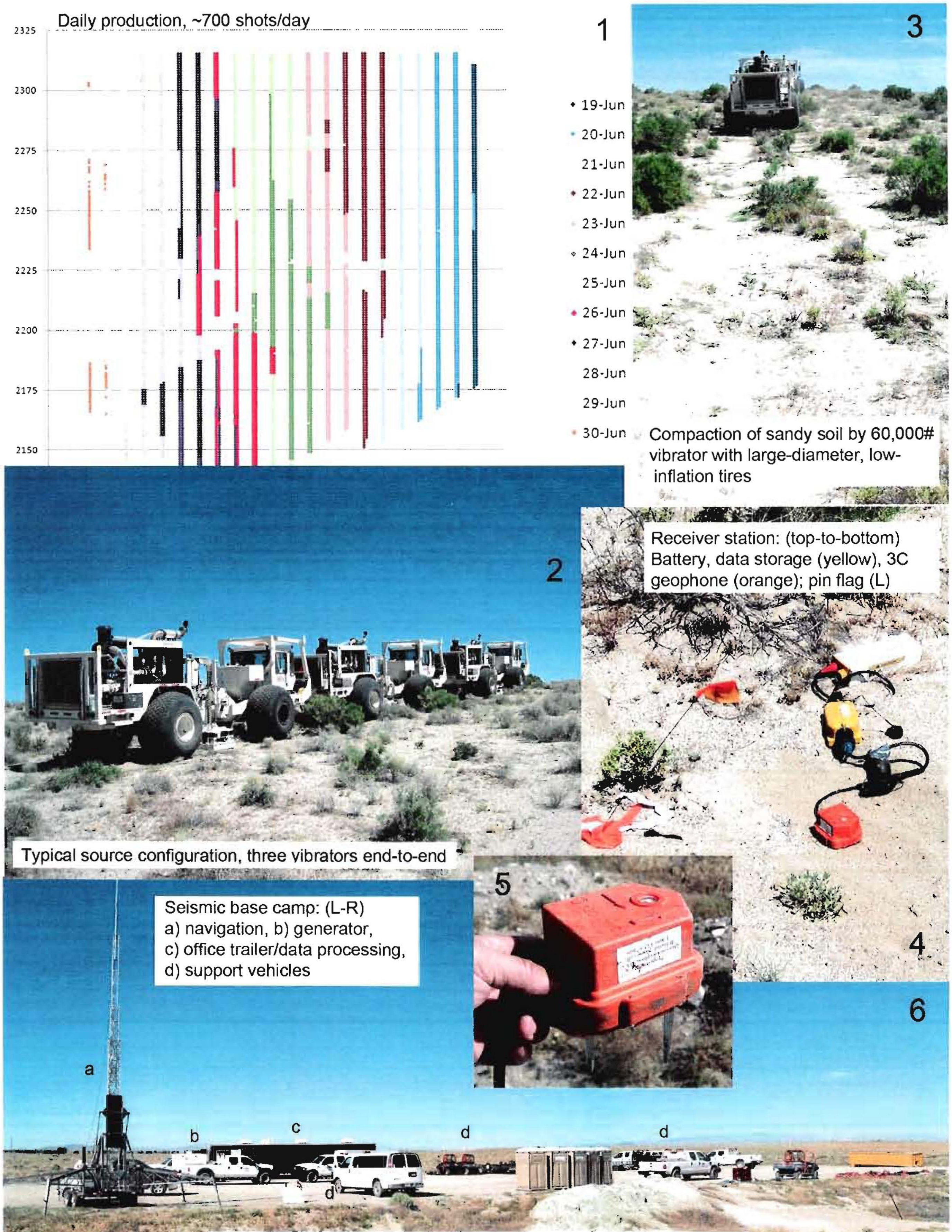


Figure 2-1: 3D-3C Seismic Acquistion Composite

Form 3200-9
(August 2007)

UNITED STATES
DEPARTMENT OF THE INTERIOR
BUREAU OF LAND MANAGEMENT

FORM APPROVED
OMB No. 1004-0132
Expires: July 31, 2010

NOTICE OF INTENT TO CONDUCT GEOTHERMAL RESOURCE EXPLORATION OPERATIONS

Applicant(s)	Address *(include zip code)*
Richard Hoops Magma Energy (US) Corp. 775-787-7050	9740 S. McCarran Blvd., Suite 103 Reno, NV 89523
Operator *(name and telephone number)* include area code	Address *(include zip code)*
Contractor(s) Dawson Geophysical CO.	Address *(include zip code)* 10200 Richmond Ave., Suite 120 Houston, TX 77042

hereby apply for authorization to conduct exploration operations pursuant to the provisions of 43 CFR 3250 now or hereafter in force across and upon the following-described lands *(give description of lands by township, attach map or maps showing lands to be entered or affected).*

T.19N, R27E., secs 1, 2, 11, 14; T19N, R28E, secs 2-11, 15-20; T20N, R27E., scs 25, 36; T20N, R28E, secs. 14-17, 20-23, 25-36;

Type of operations to be conducted *(give brief description).*
See Attached Plan of Operations

Exploration operations will be conducted during the period *(date)* from 03/15/2009 to 06/30/2009

Attached ☐ $ Surety bond ☐ Rider to Nationwide bond ☑ Rider to Statewide bond ☐ Bond to be furnished

Upon completion of exploration operations, the undersigned agrees to notify the Bureau of Land Management (BLM) that authorized exploration operations have been completed in conformance with the general and special terms and stipulations of the notice.

The undersigned hereby agrees (1) that he will not enter upon the described land until he has been informed in writing whether there are special stipulations applicable to his Notice of Intent, as to either time or method of operation or otherwise, and if there are such stipulations, what those stipulations are, (2) that he will comply with those special stipulations, if any; and (3) that he will not enter upon the described lands until his entry has been approved by the BLM.

The undersigned agrees to be bound by the terms and conditions of this notice to conduct exploration operations when approved by the BLM.

The undersigned agrees that the filing of this *Notice* under the regulations (43 CFR Subpart 3250) does not vest or confer any preference right to a geothermal resources lease.

The undersigned agrees further that all exploration operations must be conducted pursuant to the following terms and conditions:

1. Exploration operations must be conducted in compliance with all Federal, State, and local laws, ordinances, or regulations which are applicable to the area of operations including, but not limited to, those pertaining to fire, sanitation, conservation, water pollution, fish, and game. All operations hereunder must be conducted in a prudent manner.
2. Due care must be exercised in protecting the described lands from damage. All necessary precautions must be taken to avoid any damage other than normal wear and tear to improvements on the land including, but not limited to, gates, bridges, roads, culverts, cattle guards, fences, dams, dikes, vegetative cover, improvements, stock watering, and other facilities.
3. All drill holes must be capped when not in use and appropriate procedures must be taken to protect against hazards in order to protect the lives, safety, or property of other persons or of wildlife and livestock.
4. All vehicles must be operated at a reasonable rate of speed and, in the operation of vehicles, due care must be taken to safeguard livestock and wildlife in the vicinity of operations. Existing roads and trails must be used wherever possible. If new roads and trails are to be constructed, the BLM must be consulted prior to construction as to location and specifications. Reclamation and/or seeding of new roads and trails must be made as requested by the BLM.
5. Upon expiration, conclusion, or abandonment of operations conducted pursuant to this *Notice*, all equipment must be removed from the land, and the land must be restored as nearly as practicable to its original condition by such measures as the BLM may specify.
All geophysical holes shall be safely plugged. The BLM must be furnished a *Notice of Completion of Geothermal Resource Exploration Operations* (Form 3200-10) immediately upon cessation of all such operations and must be further informed of the completion of reclamation work as soon as possible.
6. Location and depth of water sands encountered must be disclosed to the BLM.

(Continued on page 2)

7. Operator must contact the BLM prior to actual entry upon the land in order to be appraised of practices which must be followed or avoided in the conduct of exploration operations pursuant to the terms of this *Notice* and applicable regulations.
Operator will conduct no operations on the land unless the attached bond is in good standing.

8. Due care must be exercised to avoid scarring or removal of ground vegetative cover.

9. All operations must be conducted in such a manner to avoid (a) blockage of any drainage systems; (b) changing the character, or causing the pollution or siltation of rivers, streams, lakes, ponds, waterholes, seeps and marshes; and (c) damaging fish and wildlife resources or habitat. Cuts or fills causing any of the above-mentioned problems will be repaired immediately in accordance with specification of the BLM.

10. Vegetation must not be disturbed within 300 feet of waters designated by the BLM, except at approved stream crossings.

11. Surface damage which induces soil movement and/or water pollution must be subject to corrective action as required by the BLM.

12. Trails and campsites must be kept clean. All garbage and foreign debris must be eliminated as required by the BLM.

13. Operator must protect all survey monuments, witness corners, reference monuments, and bearing trees against destruction, obliteration, or damage. He must, at his expense, reestablish damaged, destroyed, or obliterated monuments and corners, using a licensed surveyor, in accordance with Federal survey procedures. A record of the reestablishment must be submitted to the BLM.

14. Operator must make every reasonable effort to prevent, control, or suppress any fires started by the operator, and to report, as soon as possible, to the BLM location and size of fires, and assistance needed to suppress such fires. Operator must inform the BLM as soon as possible of all fires, regardless of location, noted, or suppressed by independent action.

15. No work must be done within one-half mile of a developed recreation site without specific written authority from the BLM. Any tavel within one-half mile of a recreation site must be over existing roads or trails.

16. Use of explosives within one-half mile of designated waters is prohibited unless approved, in writing, by the BLM.

17. If operations conducted under the provisions of this *Notice* causes any damage to the surface of the national resource lands, such as, but not limited to, soil erosion, pollution of water, injury or destruction of livestock or wildlife, or littering, operator must, within 48 hours, file with the BLM a map showing exact location of such damage and a written report containing operator's plans for correcting or minimizing damage, if possible.

18. Violation of, or failure to comply with any of these terms and conditions will result in immediate shutdown of field operations until deficiency is corrected. Failure to correct deficiency within the time period allowed by the BLM will result in forfeiture of bond.

19. The Bureau of Land Management reserves the right to close any area to operators in periods of fire danger or when irreparable damage to natural resources is imminent.

20. Contractor will be liable for assuring compliance with all terms and conditions of this *Notice* and all sections of his designated operator, agents, and employees.

21. Where continuation of the operation will result in irreparable damage to the land and other natural resources this *Notice* will be immediately canceled by the BLM.

22. **Special Stipulations:**

5 COA's attached.

Francis C. Monasterio	02/23/09		
(Signature of Applicant)	**(Date)**	**(Signature of Operator)**	**(Date)**

We hereby agree to the special stipulations added and made a part of this *Notice* to conduct exploration operations.

(Signature of Holder of Notice)	**(Date)**	**(Signature of Operator)**	**(Date)**

I hereby approve this *Notice* to conduct exploration operations.

[signature] Knutson	Stillwater Field Mgr.	6-7-2010
(Signature of BLM)	**(Title)**	

Title 18 U.S.C Section 1001, makes it a crime for any person knowingly and willfully to make to any department or agency of the United States any false, fictitious, or fraudulent statements or representations as to any matter within its jurisdiction.

(Continued on page 3)

CONDITIONS OF APPROVAL
NOTICE OF INTENT TO CONDUCT GEOTHERMAL RESOURCE EXPLORATION OPERATIONS

MAGMA ENERGY (US) CORP. SODA LAKE
CHURCHILL COUNTY, NEVADA

GEOTHERMAL LEASES NVN-086869 & NVN-86870
MDBM T20N, R28E; T21N, R28E; T20N, R29E

CATAGORICAL EXCLUSION, DOI-BLM-NV-C010-2009-0051-CX

A COPY OF THESE CONDITIONS OF APPROVAL MUST BE FURNISHED TO YOUR FIELD REPRESENTATIVE TO INSURE COMPLIANCE

1. Bureau of Reclamation will review all road or bridge crossings, piping or closure of any reclamation project feature, and review NEPA and Cultural clearances on an individual basis.

2. Vibrator trucks will maintain a minimum distance of 100 feet of any improvements either owned, permitted, leased, or otherwise authorized by the Bureau of Reclamation within the approved project area.

3. The Applicant will notify the Bureau of Reclamation (775-884-8354) two business days prior to the first time vibrator truck activity is scheduled to come within 500 feet of Emigrant Drain in order for the Bureau of Reclamation to monitor the drain for any impacts caused by the Operator's project.

4. The Applicant shall be liable for all damage to the property of the United States, its successors and assigns, resulting from the exploration, development, or operation of the works contemplated by this project, and shall further hold the United States, its successors and assigns, and its officers, agents, and employees, harmless from all claims of third parties for injury or damage sustained or in any way resulting from the exercise of the rights and privileges conferred by this project.

5. An archaeological monitor shall be present prior to the undertaking to flag for avoidance of the eligible under the NHPA guidelines cultural. To ensure the sites are avoided, an archaeological monitor will be on site during all activities related to the undertaking that occur within 30 meters (100 feet) of these historic properties. The monitor will remove flagging tape, stakes, and other site markings. The monitor shall also provide Reclamation and BLM with brief updates during the undertaking. As per the Discovery Plan, if previously unrecorded cultural resources are encountered during the undertaking, all action at the location of the discovery will cease within 100 meters/330 feet of the discovery, and the Reclamation and BLM would be notified. No surface disturbing activities will be allowed until the BLM Authorized Officer issues a Notice to Proceed (NTP) based upon the evaluation, mitigation, as necessary, and the acceptance of a summary description of the fieldwork performed for the discovery situation.

DAWSON
Dawson Geophysical Company

Magma Energy Corp
Soda Lake 3D Survey - South Part
Churchill County, Nevada
550' Receiver Lines and Tandem 770' Source Lines with 220' Receiver Group Intervals and 110' Source Group Intervals

Geometry – 28 lines by 46 stations

Date: March 8th, 2009

Dawson Geophysical

** Note: Sources could change due to playas and archeological sites.

Soda Lake 3D – South Part – Stats Page

Magma Energy Corp
Soda Lake 3D
Churchill Co, Nevada
RL 550 and Tandem SL 770 (South Part)

Designs by: Dawson Geophysical - Oklahoma City
March 8, 2010

STATISTICAL INFORMATION

DESIGN Total Sq. Mi.	DETECTOR STATISTICS LINE INT.	GROUP INT.	TOTAL PER SQ. MI.	Total Detector Lines	SOURCE STATISTICS LINE INT.	GROUP INT.	TOTAL PER SQ. MI.	AVG. SOURCE per SWATH	BIN SIZE TOTAL BINS	TRACE COUNT per SQ. MILE
RL550 SL770 (SP) 13.13	550 Feet	220 Feet	2,952 224.83	36	770 Feet 110 Ft Tandem	110 Feet	8,684 661.39	248.11	55' x 55' 118,801	7,643,468 582,137.70

FOLD ATTRIBUTES

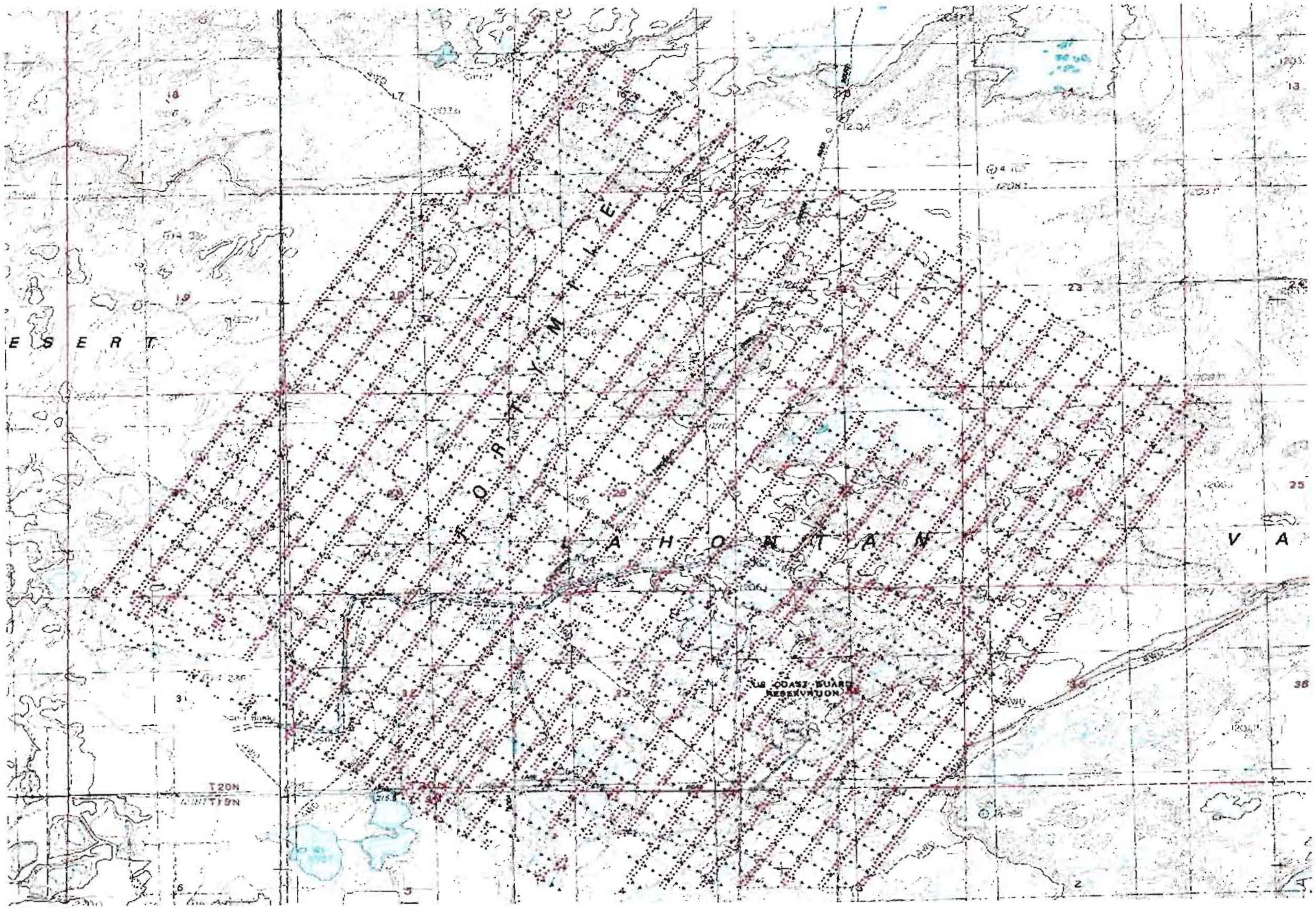
DESIGN	FOLD STATISTICS ALL OFFSETS SQ. Miles	0' - 1,000'	0' - 2,500'	0' - 4,000'	0' - 7,000'		OFFSET STATISTICS MAXIMUM	MINIMUM	CROSS LINE	INLINE
RL550 SL770 (SP)	84-98	1-4	10-15	27-34	68-82		9,181 Feet	29 Feet	7,645 Feet	5,005 Feet

	RECORDING GEOMETRY GEOMETRY Total Channels	# OF LINES X GEOMETRY	MIN Geometry Channels	MAX Geometry Channels
RL550 SL770 (SP)	28 x 46 1,282	36 36 x 46 =1,656	305 Channels	1,282 Channels

Note: The statistics shown in the Fold Statisics are preplot

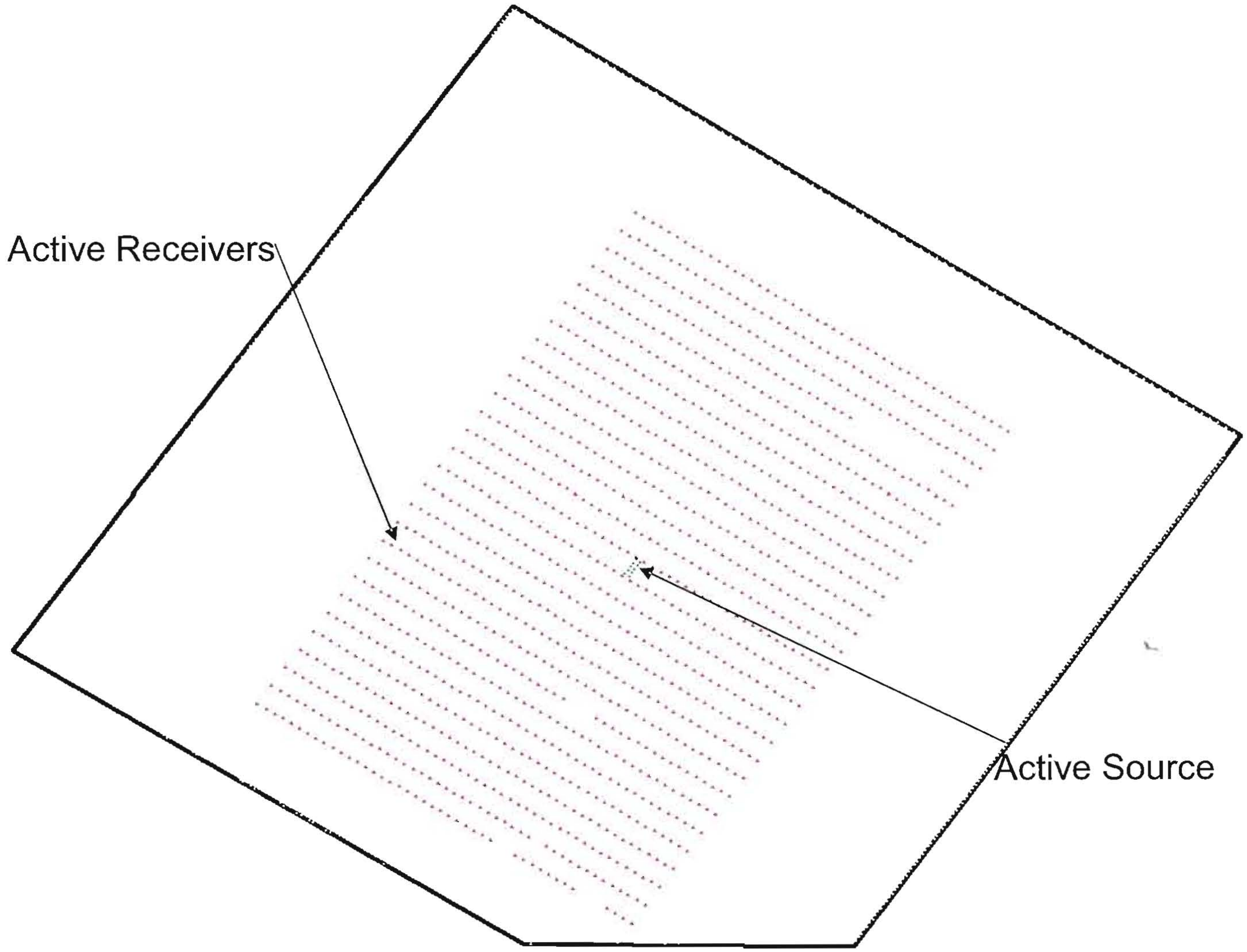
** Note: Sources could change due to playas and archeological sites.

Soda Lake 3D – South Part – Source (red) and Receiver (blue) Layout with Topo



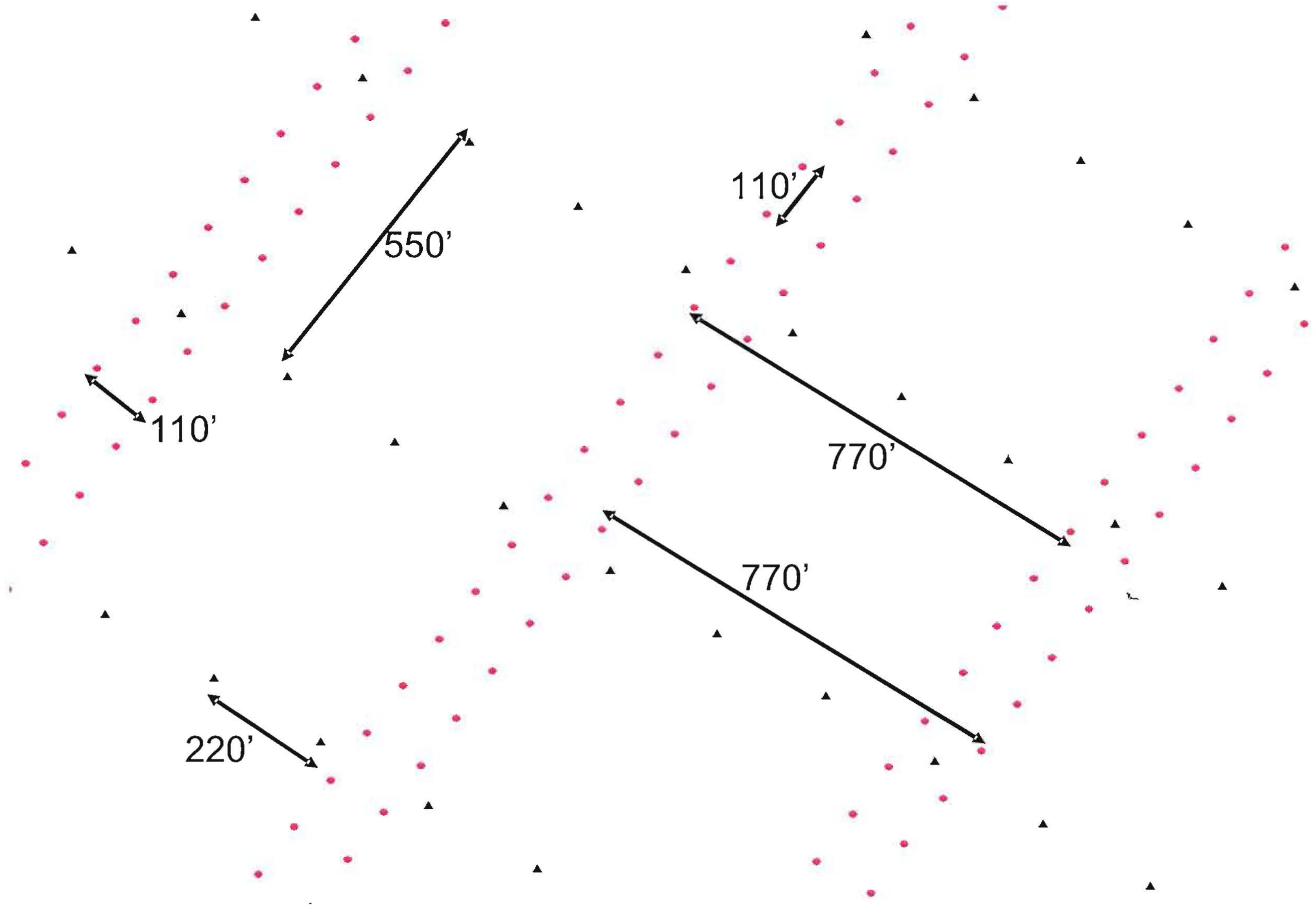
Dawson Geophysical Company

Soda Lake 3D – Geometry – 28 lines by 46 stations
Active Source (Green) – Active Receiver (Pink)



Dawson Geophysical Company

Soda Lake 3D – Source (red) and Receiver (blue) Layout – Zoomed In



Appendix 3 - Seismic Data Processing

A Request for Proposal for seismic data processing and interpretation services was sent to four geophysical contractors and consultants in March 2010. Proposals were received before April 20, 2010 and evaluated. Geokinetics, Houston, TX, was awarded the contract based on the combination of cost, turnaround and recommendations from qualified individuals.

P-Wave Processing

Geokinetics received the data from Dawson on July 9. A kick-off meeting was held on July 13 in Houston. Geokinetics was unable to decode a new SegD format revision, where the FFID could be a two-bit or four-bit number. Dawson replaced the field tapes in a SegY format, delaying the processing stream by 10 days. The basic processing flow is as follows:

1. Input of original data with original sampling & conversion to internal format
2. Geometry Merge/LMO-QC (Linear Move-out Application) for every shot every receiver line. QC/Shot-Receiver-Geometry and Geometry Merged Seismic Fold Maps (near, mid, far offset) QC
3. Trace Edit and High Amplitude & Spiky Noise Attenuation in any domain in sufficient number of passes
4. Field statics correction, Refraction Statics
5. Spherical Divergence Correction
6. Model Based Noise Attenuation (MBNA) to eliminate low-velocity surface noise
7. Designature to a minimum or zero-phase.
8. Surface consistent amplitude correction
9. Surface Consistent Deconvolution
10. CDP Sort
11. First Pass Stacking Velocity Analysis, 1/2 mile interval
12. First Pass Surface Consistent Residual Statics
13. Second Pass Stacking Velocity Analysis
14. Second Pass Surface Consistent Residual Statics
15. Archival of CDP gathers in SEGY format
16. Offset Binning and Regularization and Missing Trace Interpolation
17. Curved-Ray 3D Kirchhoff Pre-Stack Time Migration for Velocity Analysis
18. Pre-Stack Time Migration Velocity Analysis.
19. Curved-Ray 3D Kirchhoff Pre-Stack Time Migration (sufficient half-aperture, 75 degree migration dip and include P-wave VTI-anisotropy if significant)
20. PSTM Residual Velocity Analysis
21. Mute Analysis and Application (inner & outer mute)
22. Post-Stack Processing (Filter, Scaling, S/N enhancement including : inline & cross-line cascaded FXY-deconvolution)

The first significant result of the p-wave processing was a product of the refraction statics solution (Figure 3-1), the elevation of the shallow refractor and interpreted as the water table. In plan view, Big Soda Lake is in the lower left corner at an elevation of 3,990 ft. The areas in pink and red along the south end of the survey reflect the high water table from agricultural activity and proximity to the lake. The red to pink area in the center of the survey reflects the elevated water table from the buoyancy of hot water and possible influence from injection in the 87-29 area. Another high water table corresponds to a low-elevation playa, northeast of the plant and east of the green profile.

Two profiles from the refraction solution through the center of field show a fifty foot elevation change in the water table over the field (Figure 3-2). Above the water table (blue), the velocity of the near surface is color-coded. The increase in velocity across the crest of the field is attributed to silicification of the shallow sediments. On the Red Profile, the velocity increase at 8,475 ft correlates to the silicified sand dunes around the Steam Bath House.

Converted-wave (PS) Processing

At this writing, the converted-wave processing has not yielded any results. The basic geometry of the conversion of a down-going p-wave to an up-going shear-wave is shown from Thomsen, 1999 (Figure 3-3). The location of the conversion point is dependent on the p- and s-wave velocities (Vp/Vs ratio (γ, gamma)). The two profiles (Figure 3-2) are divided into three distinct shear-wave regimes, V_{s1} (sand dunes), V_{s1} (dry lake sediments), and V_{s3} (saturated lake sediments). In consolidated rocks, gamma ranges from 1.5 to 3.0. In unconsolidated sediments, the Vs/Vs ratio has been measured as high as 8 in one study (Asten & Boore, 2005). In the survey area, Vp/Vs ratios were higher than expected.

Processing PS data requires taking a number of "short-cuts" to get the data volume into an equivalent "brute" stack. Proper alignment of seismic events depends on 1) correct geometry, distance between source and receiver; 2) creating a seismic datum removing topographic effects; 3) a surface-consistent static solution for both source and receiver; 4) correcting for normal move-out, the time-delay a reflection exhibits due to offset and velocity of the material; and 5) removing or muting anything that degrades the signal.

As shown in Thomsen, in a standard p-wave survey, the midpoint, common-depth point (CDP) or common-mid point is a hypothetical reflection point based on reciprocity, the travel time from two surface locations will be the same, whether source or receiver, which makes the geometry a trivial solution. A PS survey relies on a down-going p-wave to generate an up-going shear-wave at an interface through a mode conversion. PS processing starts with the assumption that the final p-wave velocity field is optimal. The source static solution is derived from the p-wave survey. In a multiple-layered, continuously changing velocity field, the common-conversion point (CCP) is constantly changing location with depth. Since one does not have an optimal shear-wave velocity or receiver static solution, early processing is done through an asymptote conversion point (ACP) based on a gamma (γ_0) that begins to yield coherent reflections for velocity analysis (Vp/Vs ratio picking). Much like the p-wave survey, velocity analysis is performed before and after multiple iterations of residual statics. Instead of using constant velocity stacks or coherency from a guide function, PS velocity analysis uses the corresponding p-wave velocity and varies the gamma with time.

A typical gamma between 1.5 and 2.5 was verified below 4,000 ft by the 41B-33 dipole sonic. The initial estimate for the Soda Lake survey has a near surface gamma of 5, ± 0.2. The implication of a high near surface gamma is that the up-going shear-waves are near vertical, creating aliasing in pre-stack migration.

The impact of offset and the Vp/Vs ratio feeds back to the acquisition parameters (Figure 3-3). At Soda Lake, the surface geometry of 550' receiver line, 220 ft receiver interval and770' source line was established prior to consideration of the PS survey and could not be altered due to the cultural resource survey already in progress. In the upper-left hand of the image, the receiver line interval is represented by a series of vertical lines. The shaded area represents the mute that removes noise and NMO stretch.

With only the 1977 Chevron seismic data as a guide, it was not known where the "seismic basement" would be using modern 3D technology. Acquisition parameters are always a compromise of a variety of factors, available equipment, time in the field, etc. The PS survey failed to achieve the goal of an S1/S2 data cube due to a high Vp/Vs ratio leading to the up-going shear energy being under-sampled at the surface.

The PS processing flow is listed below and where the process failed:

1. Input of correlated original data with original sampling & conversion to internal format
2. Rotation to radial and transverse components and QC of vector fidelity.
3. Field statics correction (Utilize PP statics (field plus total residual statics PP) for the source-side and apply normal datum statics for receiver statics
4. Azimuthal anisotropy analysis via narrow angle azimuthal stacking of common receiver gathers.
5. If there is azimuthal anisotropy, data will be rotated to fast and slow shear wave directions (S1 and S2) and processed until anisotropic effects removed and rotated back to radial direction where transverse component can be dropped (pre-migration or post migration). In any case, S1 and S2 volumes will be processed through C-wave pre-stack time migration with their vector fidelity preserved. From this flow, a fracture orientation map and a relative fracture density map may be generated. If there is no azimuthal anisotropy is present, processing will be carried on with the radial component.
6. Trace Edit and High Amplitude & Spiky Noise Attenuation in any domain in sufficient number of passes
7. Spherical Divergence Correction using a C-wave RMS velocity function.
8. Model based Noise Attenuation (MBNA) if necessary.
9. Designature to a minimum phase using Clauder wavelet derived from the vibroseis sweep signal.
10. Surface consistent amplitude correction
11. Surface consistent deconvolution
12. ACP (asymptotic conversion point) binning using the available log or estimated single gamma (Vp/Vs).

    ** **ACP binning did not yield coherent reflectors. CCP binning could not resolve high Vp/Vs****
13. Vp/Vs ratio picking for receiver statics correction.
14. Common receiver gather stack static correction.
15. Vp/Vs ratio picking (second iteration)
16. Automatic receiver residual statics with a 3D structural term.
17. C-wave Kirchhoff pre-stack time migration of velocity lines for velocity analysis (ray-tracing based)
18. C-wave pre-stack time migration velocity analysis.
19. C-wave 3D Kirchhoff pre-stack time migration (ray-tracing based)
20. Post migration residual velocity analysis.
21. Mute Analysis and Application (inner & outer mute)
22. C-wave stack of the entire 3D volume and C-wave angle stacks (Near, Mid, Far)
23. Post-Stack Processing (Filter, Scaling, S/N enhancement)
24. Conversion of All C-wave stacks and CIP gathers to PP times.

Plan B

Given that the shear-wave energy was under-sampled at the surface and cannot produce an S1 and S2 volume, there are 36 receiver lines with an abundance of sources with wide azimuthal distribution. Figure 3-4 shows the PP and PS1 version of Inline 162. Tests are underway to determine optimal bin dimensions that collect enough traces to produce an image while not degrading the image from structural dip. In the inset, there is a 50ms time delay between S1 and S2. The next challenge will be to image shallow reflectors through a combination of bin dimensions and mute.

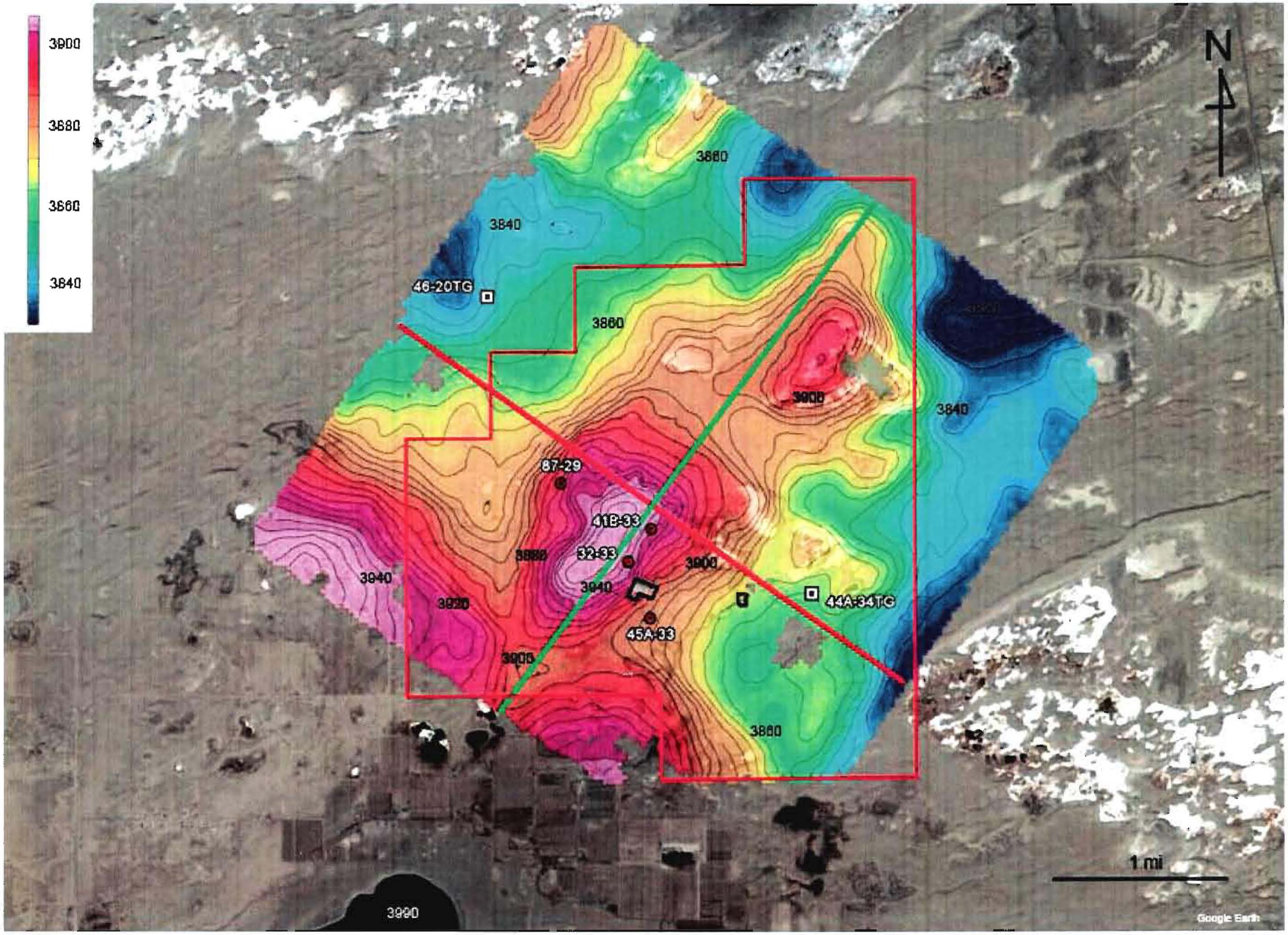


Figure 3-1: Elevation of Shallow Refractor. The first product from the reflection seismic survey is the elevation of the shallow refractor, the boundary between dry and saturated sediments, shows a raised areas corresponding to irrigation along the southern edge of the survey and the geothermal system. See Figure 3-2 for the two profiles (red and green).

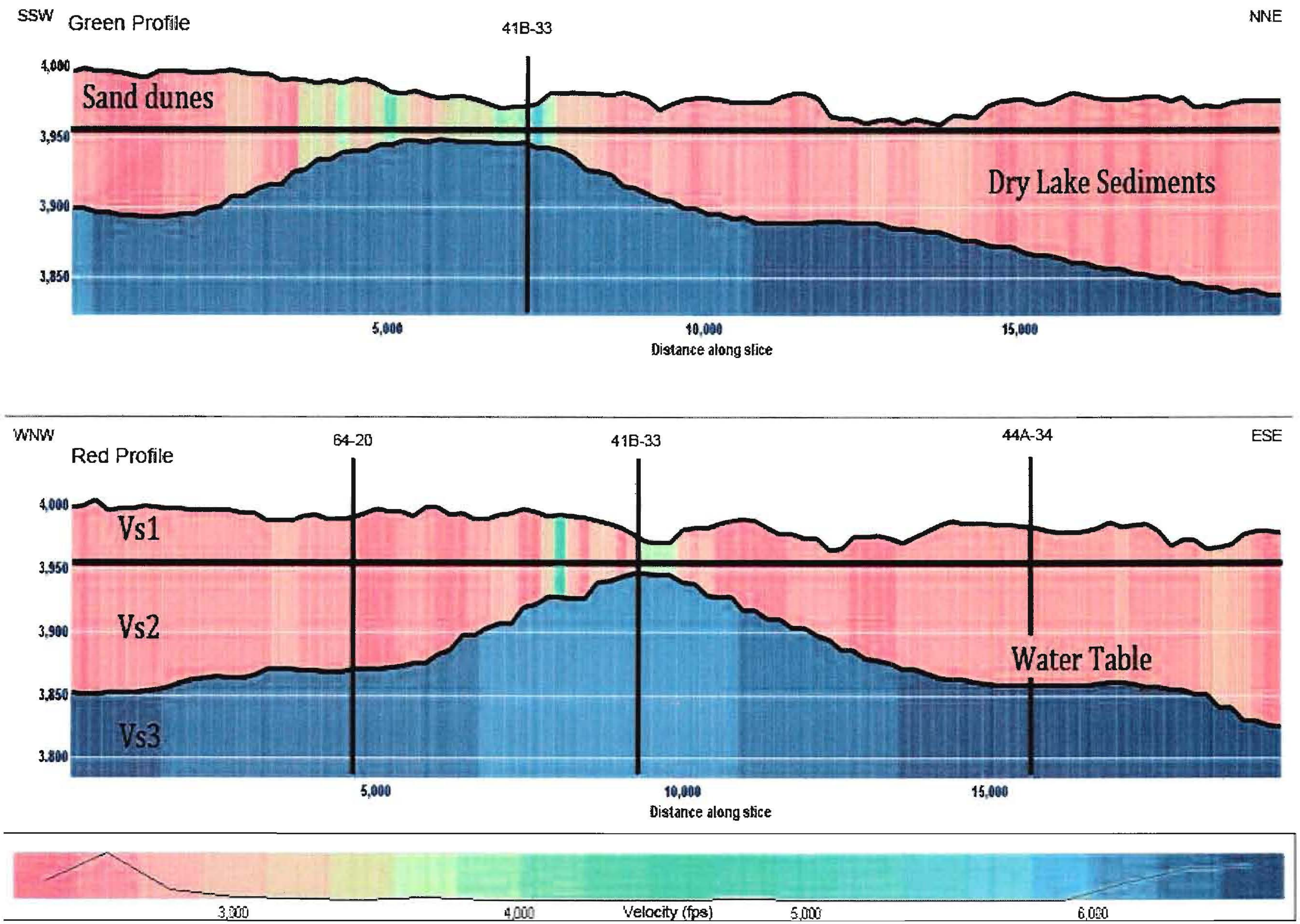


Figure 3-2: Elevation Profiles of Shallow Refractor. The top 1500 ft of sediments at Soda Lake consists of sand dunes (0-50 ft) and lake-bed sediments. The water table varies greatly due to the agricultural areas to the south and the geothermal system. Two profiles from the refraction solution show the water table has a 100 ft elevation difference across the survey and a velocity contrast between the dry and saturated sediments are >2:1.

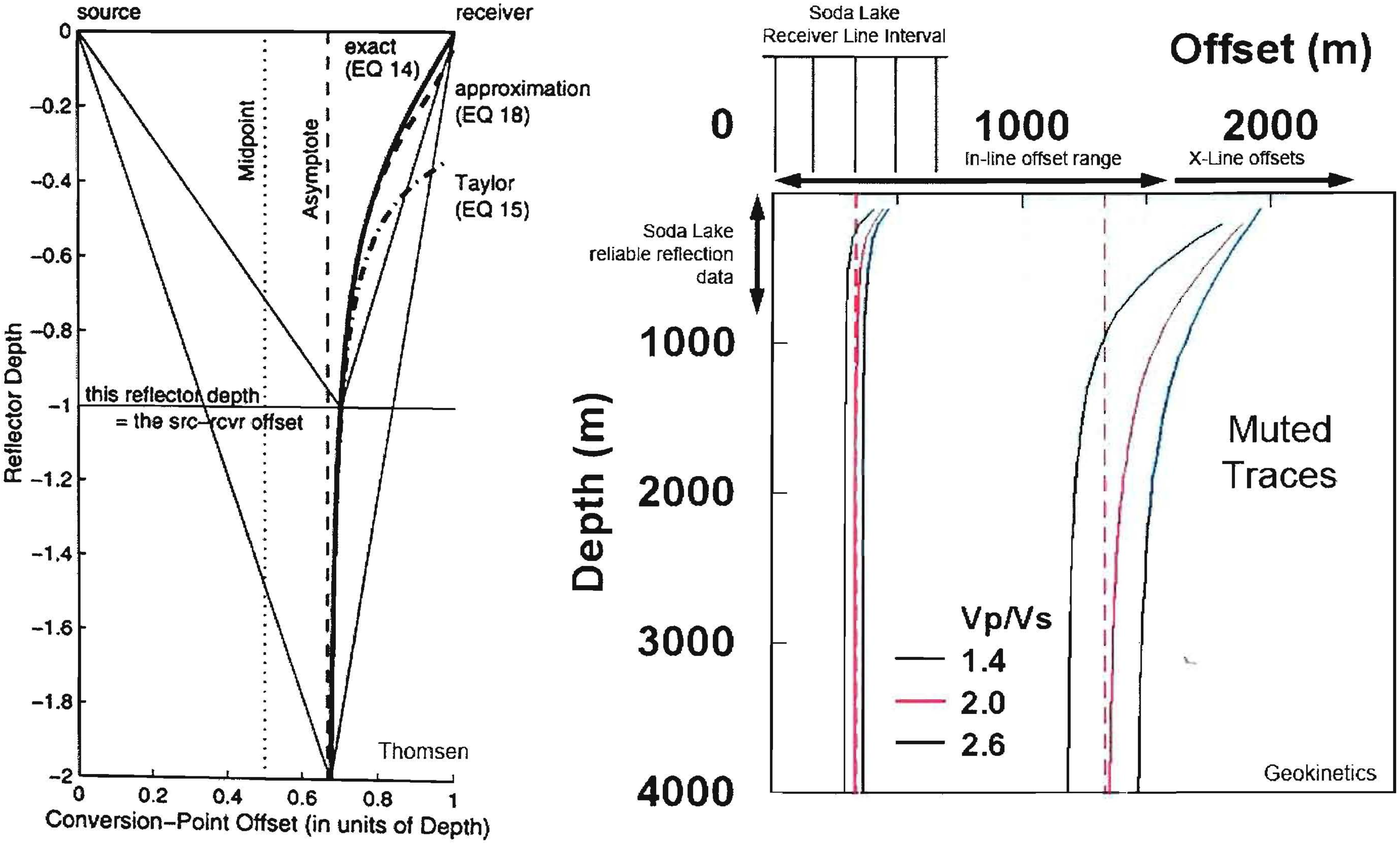


Figure 3-3: Factors Impacting Converted-Wave Survey Processing. Left: In this diagram, the reflector depth is equal to the source-receiver offset and Vp/Vs = 2.0. At Soda Lake, a Vp/Vs ~5 moves the conversion point closer to the receiver creating a nearly vertical ray path. Right: Receiver line spacing is represented by the five vertical lines above the origin of the graph. With reliable reflections in the upper 2000 ft and a high Vp/Vs, the shear-wave energy is under-sampled with 220' receivers and 550' receiver lines.

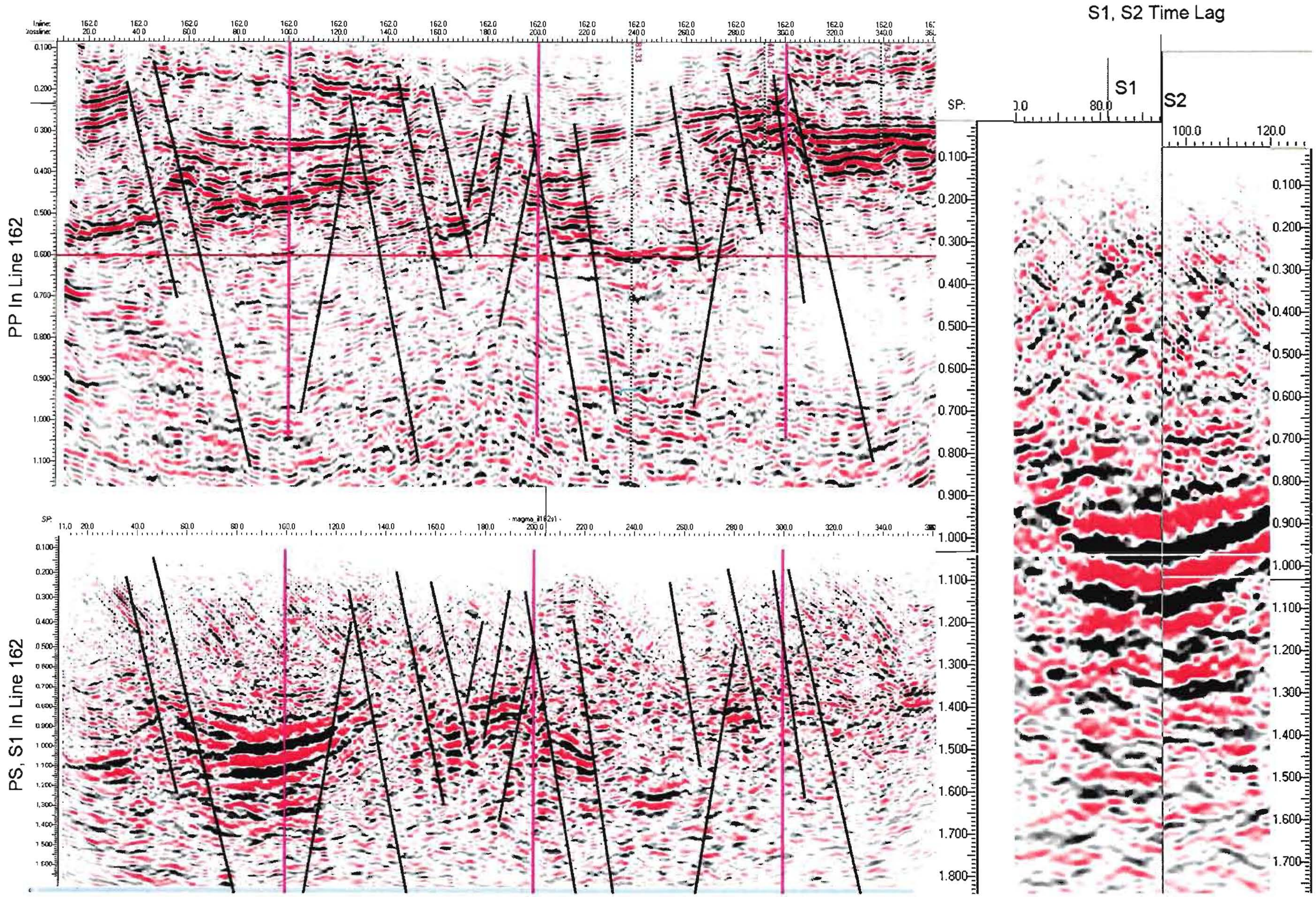


Figure: 3-4: Comparison of P-Wave and Converted-Wave Data. Left: Inline 162 is coincident with a line of receivers. Similar structural features can be identified in both profiles, however shallow data is nearly absent in the PS data. In the S1, S2 comparison (R), a time shift of ~50ms is in the data. Better shallow data is needed to "layer strip" the portion of time delay attributable to shallow horizons.