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GEOTHERMAL ENERGY RESOURCE ASSESSMENT ON MILITARY LANDS

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ABSTRACT

Innovative Technical Solutions, Inc. (ITSI) evaluated geothermal potential on selected military bases in the U.S. for the Department of Defense. Assessment activities included literature reviews, interviews with local specialists, geothermal field investigations at 3 installations, and development of conceptual geothermal occurrence models. Occurrence models integrate geothermal system characteristics with local structural/tectonic characteristics to identify potential geothermal targets. Spatial analyses of selected coverages using GIS were also performed for the ranges at Nellis AFB in order to identify possible geothermal targets.

NAF El Centro has "high" utility-grade geothermal potential and at least four other installations investigated warrant additional investigation. Twenty-one western U.S. installations have direct-use geothermal potential, with bases in Oregon, Nevada and California having the greatest potential.

INTRODUCTION

Eighteen selected military installations in the continental United States were assessed for utility-grade geothermal potential, and over 100 military facilities in Colorado, Utah, Wyoming, Arizona, Washington, Oregon, Idaho, Nevada, New Mexico, California, Alaska, and Hawaii were assessed for direct-use geothermal potential. This investigation was part of a larger renewable resource assessment being conducted by the Department of Defense (DoD) on selected military installations as part of the 2003 military construction appropriations process.

Data for the utility-grade and direct-use assessments were drawn largely from available literature and data gathered from local, state and federal officials. Reconnaissance field work supporting utility-grade assessments was performed at Naval Air Field El Centro (NAFEC), CA, Mountain Home AFB, ID, and White Sands Missile Range (WSMR), NM.

This article briefly highlights the methods and selected results of a broad geothermal potential investigation. It was excerpted and modified from a larger unpublished report provided to the government (ITSI, 2003).

METHODOLOGY

Utility-grade geothermal fluids are those with temperatures that can support electricity production. Based on previous analyses, DoD identified eighteen military installations for a utility-grade potential evaluation, three of which were to be the focus of specific field investigations.

Geothermal targets at each base were identified through a evaluation of published information plus internally developed occurrence models. Where targets were identified at each base, mapping, sampling, and self-potential geophysical surveys were conducted in these areas.

The last part of this project was to evaluate direct-use potential from military bases in Colorado, Utah, Wyoming, Arizona, Washington, New Mexico, Oregon, Idaho, Nevada, California, Alaska, and Hawaii. The ITSI team created a list of bases, adopted a direct-use evaluation criteria from the Geo-Heat Center (Boyd, 2002), then gathered relevant, publicly-available data to determine which of these bases might have low temperature geothermal resources.

UTILITY-GRADE GEOTHERMAL ASSESSMENT

The eighteen sites selected by DoD for utility-grade geothermal assessments are located in the Basin and Range, Snake River Plain, Pacific Cordillera and Rio Grande Rift tectonic provinces. The following describes geologic characteristics, results of field work and the geothermal potential assessment of two of the more intriguing installations: NAF El Centro in the Salton Trough of the Pacific Cordillera, California and Nellis AFB, in the Basin and Range of southern Nevada.

NAF El Centro

NAFEC is located in southeastern California directly south of the Salton Sea. The base includes a main site with an air field and six distinct bombing ranges including BR101, where Superstition Mountain is located.

The Salton Trough is in the Pacific Cordillera, a tectonic province that generally reflects deformation associated with transcurrent and convergent plate motion along the western continental margin of North America (Figure 1). In the Gulf of California, Mexico, the eastern boundary of the oceanic Pacific plate is a series of northwest-striking dextral faults that link short, active, NE-trending oceanic spreading centers. The system of alternating strike-slip faults and spreading ridges extends northward into California, and terminates in the Salton Trough. The Salton Trough is about 10-16 km deep, underlain by young (Pliocene) oceanic crust, and is a locus of Quaternary volcanic activity associated with continental rifting and nascent sea-floor spreading.

Several areas of very high heat flow in the Pacific Cordillera are associated with high rates of crustal extension and active volcanism. Rhyolitic volcanic centers at the southern end of the Salton Sea and rhyolitic flows present at depth within the Quaternary section (Hulen and Pulka, 2001) indicate that volcanism accompanied sedimentation and crustal spreading in the area.

The El Centro area is a site of significant crustal thinning and nascent sea-floor spreading. The step in the faults to the west into the San Jacinto system is considered to be a restraining bend with associated crustal shortening. This is consistent with the presence of basement granitic outcrops in the Superstition Mountain area to the NW of El Centro.

Neotectonic Activity

The El Centro area is located in one of the most seismically active areas of California. Two large earthquakes have occurred on the Imperial Fault in recent years: an M=7.1 in 1940 (Neumann, 1942) and an M=6.5 in 1979 (Hutton et al., 1991; Bausch and Brumbaugh, 1996). Seeber and Armbruster (1999) report that their preferred model for crustal deformation within this releasing bend, transtensional system is one where fault blocks rotate within an overall extensional regime, similar to interpretations for the Walker Lane belt by Oldow et al. (2001).

Heat Flow

The El Centro area lies within the Salton Trough heat flow area (Figure 2) (Blackwell et al., 1991) with heat flow values generally in excess of 100 mW/m^2, making it one of the hottest known geothermal areas in the world. Lachenbruch et al. (1985) determined that the crust in the area is very thin (~23 km), is underlain by high-temperature asthenosphere and that the heat flow is generated by rapid extension related to the opening of the Gulf of California and the creation of new oceanic crust in the region.

Temperature Gradients

Corrected temperature gradients generated from almost 40 wells within 100 miles of NAFEC range from 21 to 98°C/km. A well at Superstition Mountain straddles Bombing Range 101 of NAFEC and has a gradient of 64°C/km. This well is the only site in the area with a gradient above 50°C/km that is located outside a KGRA.

Incomplete California Department of Oil and Gas records and unpublished material (publicly presented to NAFEC and BLM by a private developer) identify a zone along the northeast flank of Superstition Mountain with a calculated temperature gradient exceeding 300ºC/km (17.5ºF/100 ft.).

Geothermal Resources

The Salton Trough contains three electricity-producing geothermal fields as well as six KGRAs (Figure 3). By far the most active area of production is the Salton Sea Geothermal Field at the southern end of the Salton Sea with a capacity in excess of 350 MW. California's two other producing geothermal fields in the Salton Trough - East Mesa and Heber - each generate around 100 MW of power. With over 770 MW production from Cerro Prieto (Mexico) in the southern Salton Trough and an additional 175 MW production increase anticipated for the Salton Sea Geothermal Field, total production in the Salton Trough will soon exceed 1200 MW.

Field Investigation: Superstition Mountain

The Superstition Mountain site is on the NW side of Navy BR 101 (Figure 3). Several factors make it prospective for geothermal resources:

- Regional features include high heat flow, surface geothermal manifestations (mudpots, CO_2 venting), young silicic volcanic rocks, geophysical anomalies (localized gravity highs associated with geothermal production at Heber and East Mesa geothermal fields), and active geothermal production.
- A pronounced Bouguer gravity high which may be due to high-density granites surrounded by

lower density alluvium or due to localized cementing of alluvium by hot, mineralizing fluids at depth.

- Superstition Mountain is speculated to have been "squeezed" within a left step in the San Jacinto-San Andreas Fault system. Young (i.e., active; not sealed) range-bounding faults in these regions are preferred fluid pathways.
- Temperature-gradient data from a 1970's and early 1980's reconnaissance program (Mike Wood, CA State Oil and Gas office, El Centro, personal communication, 2003; Eric Layman, Layman Energy Associates, personal communication, 2002) point to localized hot spots. A 300ºC/km (17.5ºF/100 ft.) temperature gradient straddles the Navy-BLM border on the NE side of Superstition Mountain.
- An apparent spatial correlation of a barren vegetative zone with sporadic calcite-veined float (paleo hot-springs?) exists along the NE flank of the mountain.

A self-potential survey at NAFEC was conducted during this project using a basic radial or "spoke" survey technique. 186 stations were recorded on 11 profiles along 11.2 line-km (37,000 line-ft) for an area of 3.71 km^2 (1.43 mi^2). Figure 4 shows contoured SP voltages for the Superstition Mountain survey, all referenced to an assumed datum of 0 millivolts (mV) at Base Station (B.S.) #1. B.S.#1 has a relative value of about –120 mV and the survey minimum is about –150 mV with respect to regional background.

Figure 4 illustrates a substantial SP anomaly with significant lateral extent, continuity, and amplitude. It occurs over Quaternary alluvium 300-600 m north of granite outcrops of Superstition Mountain. It is elongate sub-parallel to the topography, with a half-amplitude length of about 1800 m and a half-amplitude width of about 500 m. The considerable elongation of the anomaly suggests a SP source associated with covered faults and fractures and a possible covered fluid upflow zone near this location.

Summary

The combination of geothermal production in the region, active extension, a temperature gradient anomaly with a coincident SP anomaly, and possible hot-spring mineralization suggests NAFEC has high utility-grade geothermal potential. A prime target at NAFEC is immediately NE of Superstition Mountain.

<u>Nellis AFB</u>

Nellis Air Force Range (NAFR) occupies approximately 3.1 million acres in southern Nevada (Figure 5) surrounding the Nevada Test Site. Methods employed to assess potential utility-grade geothermal energy at NAFR included the construction of a GIS because data and access required to perform an evaluation of geothermal potential are limited. Results indicate that portions of NAFR appear prospective, but on-site investigations are recommended to fully assess these areas.

Geologic and Neotectonic Setting

NAFR is within the Basin and Range Province of southern Nevada at the junction between the Walker Lane Belt and the Basin and Range extensional province. GPS velocities and directions of motion indicate that the strain field changes in this region from the east-west extension typical of the Basin and Range to the northwest-southeast directed transtension characteristic of the Walker Lane belt.

NAFR has some areas of concentrated seismic activity (e.g. Stonewall Mountain region) but no well-defined, through-going linear alignments that may define discrete seismogenic faults. A problem with the application of such data for tectonic interpretations is that the NAFR area is not well covered by seismic stations and actual seismic activity in the area may be under-sampled at present.

The presence or absence of active faults in NAFR is not well documented. A study on the age and location of young structures by Dohrenwend et al. (1996) employed aerial photos and satellite imagery to develop a reconnaissance map of Quaternary and late Tertiary faults in Nevada. It may be inferred from these data that faults are present but relatively sparse. Dohrenwend et al. (1996) observed that this region appears devoid of late Quaternary fault scarps but noted that this observation may be due to limited imagery data.

Heat Flow

Although the majority of very high temperature geothermal reservoirs in the Basin and Range are concentrated in the northwestern portion of Nevada, the presence of warm springs and wells within the NAFR region indicates a potential for high-temperature resources in this area as well (Garside and Hess, 1994; Shevenell et al., 2000). Several areas of anomalous heat flow within the Basin and Range stand out among the average high values characteristic of this province including the Eureka Low (the green colored 50-60mW/m^2 region in central NV; Fig. 2) in the southern Great Basin and the Battle Mountain Heat Flow High to the northwest, regions of depressed and elevated heat flow, respectively, relative to background Basin and Range values (Blackwell et al., 1991; Sass et al., 1971).

Tingley et al. (1998) indicate that flow within thick Paleozoic carbonate aquifers in the Basin and Range typically connects basins with little or no surface outflow, and that individual groundwater flow paths may stretch for 150 km. Interbasin flow of meteoric fluids at deep levels in these aquifers is accompanied by an overall downward seepage that effectively blankets upwardly flowing heat from deeper levels in the crust (Tingley et al., 1998). As indicated by Garside and Schilling (1979), the generally low reported spring and well temperatures throughout the area occupied by the Eureka Low reflects the regional-scale influence of this hydrologic disturbance. However, several workers contend that heat flow values beneath the Eureka Low return to typical Basin and Range values of 80 to 100 mW/m^2 at depth (Sass and Lachenbruch, 1982).

Groundwater Geochemistry

Available groundwater data are limited to a portion of NAFR although data are more plentiful beyond the range boundaries. Geothermometry calculations generated from these wells yield calculated groundwater temperatures generally ranging from 30 to 105°C, with a rough correlation between the SiO_2-chalcedony and the Na-K-Na (Mg-corrected) geothermometers. Several broad geographic patterns in these temperatures are observed:

- Elevated temperatures (e.g., above about 70°C for both geothermometers) are present in the north-central and far northwestern portions of NAFR;
- Elevated temperatures appear to exist in the main base area;
- Generally low temperatures dominate in the eastern area of NAFR, and
- With the exception of the samples from the north-central parts of NAFR, higher-temperature geothermometry occurrences in NAFR are from areas outside the Eureka Low.

Elevated geothermometry temperatures are found across widely separated parts of NAFR but sample density is sparse; thus, specific statements assessing the relative potential for geothermal resources on NAFR based on geothermometry, or lack thereof, are not well constrained by available data.

Geothermal Resources

There is no utility-grade geothermal production at NAFR although there are direct-use areas to the east and west (e.g., Baileys Hot Spring near Beatty; Ash Springs near Alamo). According to Garside and Schilling (1979) and Tingley et al. (1998), NAFR is characterized by a relative lack of geothermal activity in comparison with adjacent areas throughout the state of Nevada. Regardless, several areas in and around NAFR and the adjacent Nevada Test Site show evidence of past and present geothermal activity.

Tingley et al. (1998) summarize data on known thermal springs on and within 5 km of NAFR property. Climax Seep, located east of the Belted Range to the north of Yucca Flat, has a reported temperature of 41.5°C, although Tingley et al. (1998) consider such temperatures for the area anomalous , unconfirmed, and thus suspect. Additionally, thermal springs present in Hot Creek Valley, the northward continuation of the Reveille Valley east of the Kawich Range, show surface discharge temperatures around 60 °C, with estimates of reservoir temperatures from silica geothermometry up to 110°C (Garside and Schilling, 1979). Major, range-bounding normal faults present along the western margin of this area and the Reveille Valley to the south exert primary control over the distribution of thermal springs and spring deposits in this area (Garside and Schilling, 1979). To the southwest, thermal fluids from numerous hot and warm springs in the Sarcobatus Flat-Beatty area west of Pahute Mesa and Yucca Mountain exhibit temperatures up to 42 °C, with the majority of spring temperatures between 25 and 40 °C (Garside and Schilling, 1979; Flynn et al., 1995; Tingley et al., 1998).

The results of deep drilling throughout NAFR and the adjacent Nevada Test Site allow additional inferences to be drawn about the thermal characteristics of areas without reported surface manifestation of geothermal activity. As reported by Sass and Lachenbruch (1982), the hottest wells in this area lie in the northwestern section of the Test Site, centered near Pahute Mesa and the adjacent Gold Flat. The deepest well evaluated in this location encountered temperatures over 120 °C at approximately 3,700 m depth, although such high temperatures may reflect areas of localized upwelling (Tingley et al., 1998), as adjacent wells at shallower depths show more moderate temperatures. Wells showing the hottest thermal gradients are also concentrated in this area, with the highest measured value of 50 °C/km in a well to 600 m depth in the Gold Flat area (Sass and Lachenbruch, 1982; Tingley et al., 1998).

Tingley et al. (1998) note that deep holes near Pahute Mesa showing estimated reservoir temperatures of over 90 °C at several kilometers may be representative of the thermal regime within deep carbonate aquifers beneath the area. Despite the presence of young silicic volcanic rocks and recent basalt flows within the NAFR and vicinity, there is general agreement that a non-volcanic heat source is the origin of thermal waters throughout the area (Flynn et al., 1995; Tingley et al., 1998).

Summary

NAFR was evaluated as having high geothermal potential based on the combination of warm wells, springs and apparent favorable structures all within a large, poorly explored area situated on the margins of some of the most prospective geothermal systems in the country. Additionally, geothermal occurrences throughout the Basin and Range share many similar features with NAFR:

- Range-bounding normal faults show (unmapped) evidence for recent displacement and relatively large structural throw;
- Active seismicity;
- Apparent strain field changes (e.g. at Stonewall Mountain);
- Gravity anomalies;
- Elevated groundwater temperatures (e.g., above about 70°C for both geothermometers) present in the north-central and far northwestern portions of NAFR;
- Deep well data indicating the presence of localized areas of upwelling of thermal fluids;
- Mineralization suggesting possible hydrothermal activity including opal, silicification and calcareous deposits.

The above features have either been described or can be inferred from geologic data for NAFR. It is clear that faults of large throw are present, although they are poorly documented in the literature. Deep, fault-bounded basins are present in the area. Although the largest gravity anomaly is the Timber Mountain Caldera, many other areas show isostatic anomalies exceeding 15 milligals (mgal) indicating that significant basin fill or areas of low density rocks are present. Finally, there are some geothermal features and some local utilizations of warm waters.

At least three sites within NAFR warrant further investigation because they are within a tectonically active region displaying features compatible with known geothermal occurrences, and because there are no geothermal investigations appear to have ever been performed at these sites: (1) Stonewall Mountain, at the western edge of NAFR, is bounded to the north by what appears to be a releasing bend in a strike-slip fault. It is adjacent to the Walker Lane belt and just east of a cluster of thermal wells, one with a temperature gradient exceeding 100°C/km. (2) The Kawich and Reveille Valleys are bounded by northerly-trending Quaternary faults along trend with Hot Creek Valley (the northward continuation of the Reveille Valley), which is characterized by springs with surface discharge temperatures around 60 °C, with estimates of reservoir temperatures from silica geothermometry up to 110 °C (see Garside and Schilling, 1979). (3) The Groom Range and Groom Lake are characterized by steep, linear range fronts and active playas that may be at a releasing step or some other structure which localizes crustal strain and geothermal resources.

DIRECT-USE ASSESSMENT

There are currently about 1,000 single-user, direct-use installations and 18 district heating systems operating in the United States. For this study, it was assumed that space heating and cooling are the primary applications for moderate-temperature (>48°C) geothermal fluids on military bases.

Thirty-five military sites (culled from over 100 installations in Colorado, New Mexico, Utah, Idaho, Washington, Oregon, Nevada, Arizona, California, Alaska and Hawaii) were assessed for direct-use potential. Available literature was reviewed to identify wells within 5 miles of each installation with temperature gradients >~20°C/km. Sites were then assessed using a method modified after the GeoHeat Center (Boyd, 2002), and grouped into categories based on water temperatures, depth to water, and distance of wells from military buildings.

Twenty-one of the bases reviewed were determined to have direct-use potential, the top 11 of which are listed in Table 1. The most promising of these bases include Kingsley Air National Guard Base, Oregon, Fallon NAS, Nevada, Sierra Army Depot, California, Hawthorne Army Ammunition Depot, Nevada, Fort Bliss, Texas, and Luke AFB, Arizona. All have structures within 5 miles of wells with measured temperatures in excess of 93°C at depths of less than 1,000 meters.

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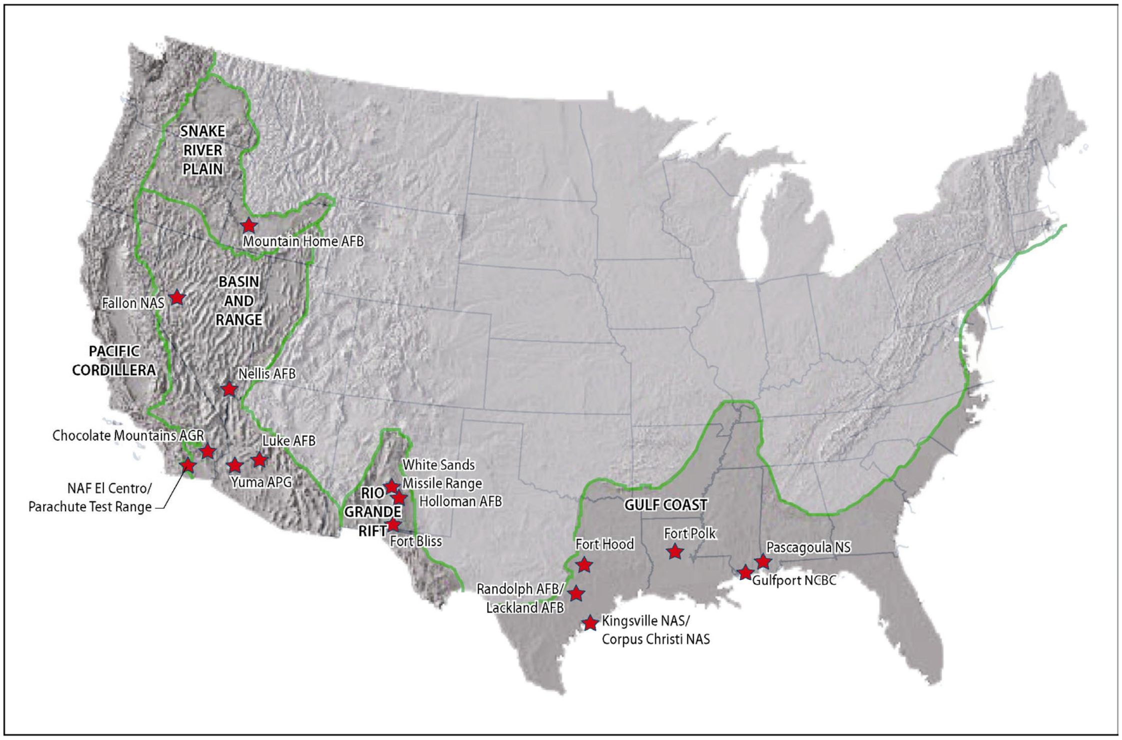

Figure 1. Military installations considered for utility-grade assessment and their tectonic provinces.

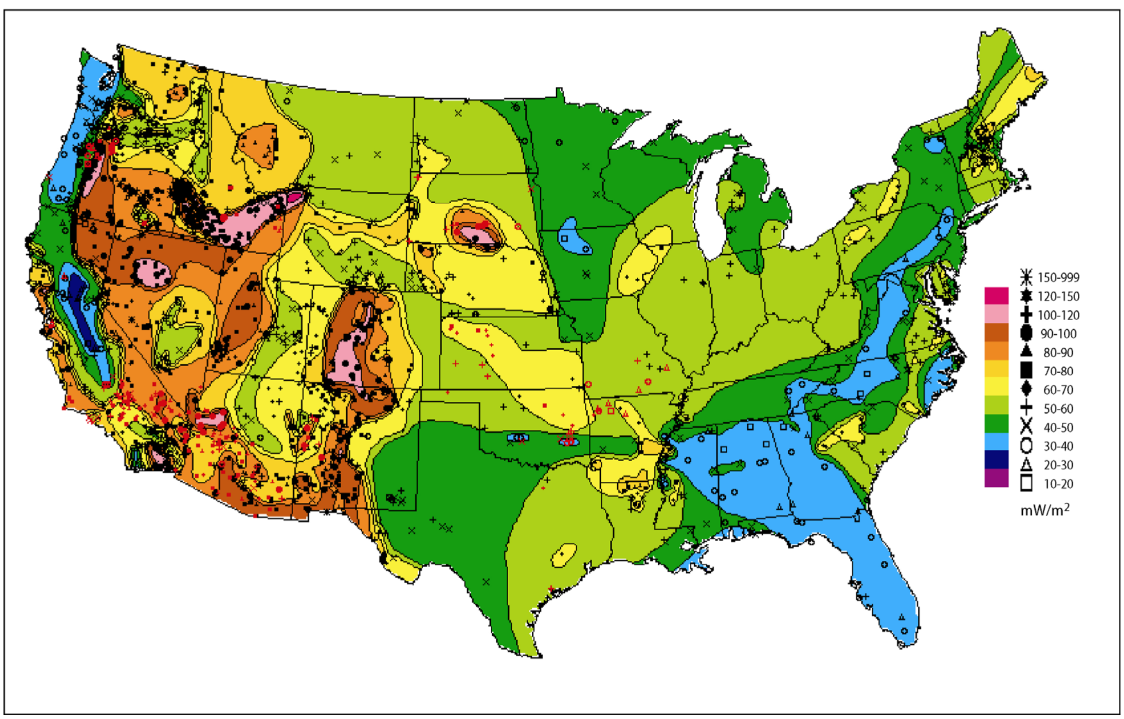

Figure 2. Heat flow map of U.S. Heat flow boundaries generally mimic tectonic province boundaries.

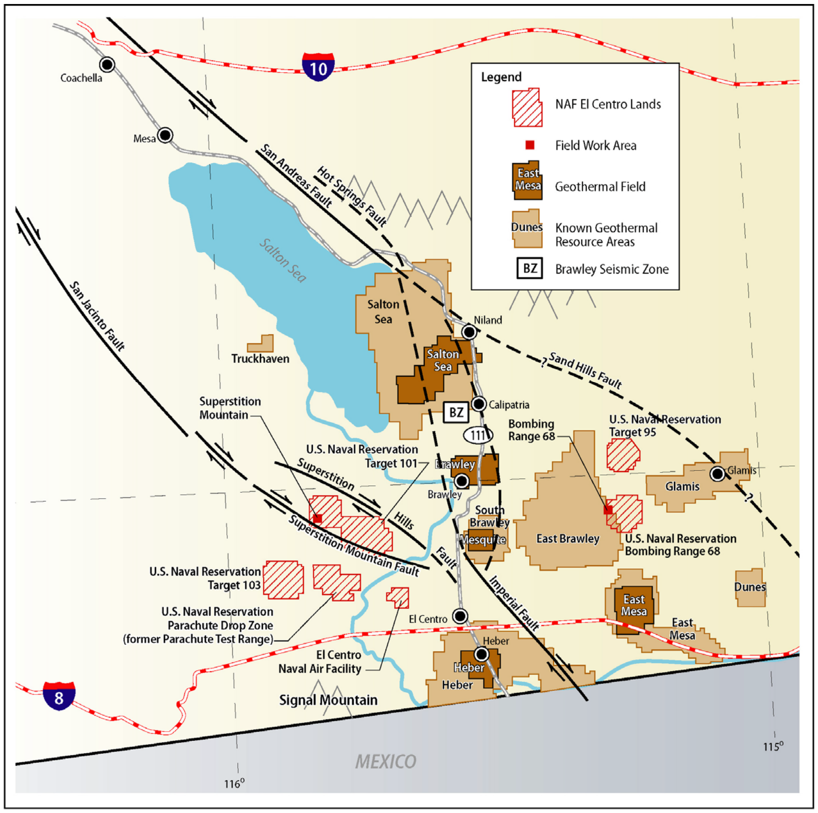

Figure 3. NAFEC region with Superstition Mountain target, geothermal producers, KGRAs and important structures.

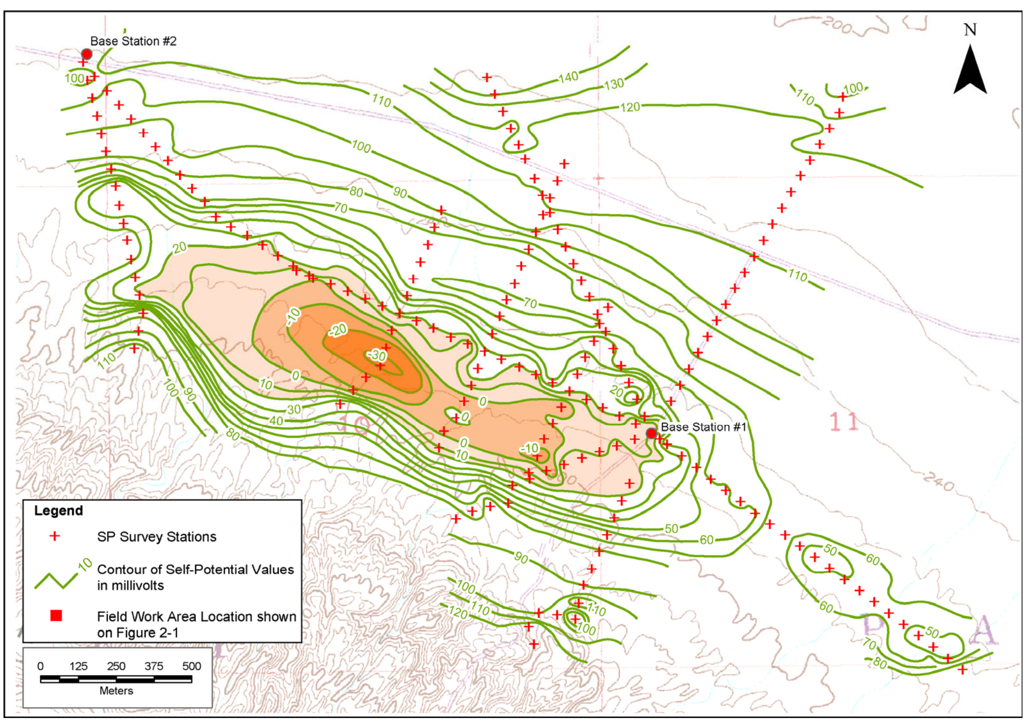

Figure 4 -120 mgal SP anomaly along NE flank of Superstition Mountain, NAFEC.

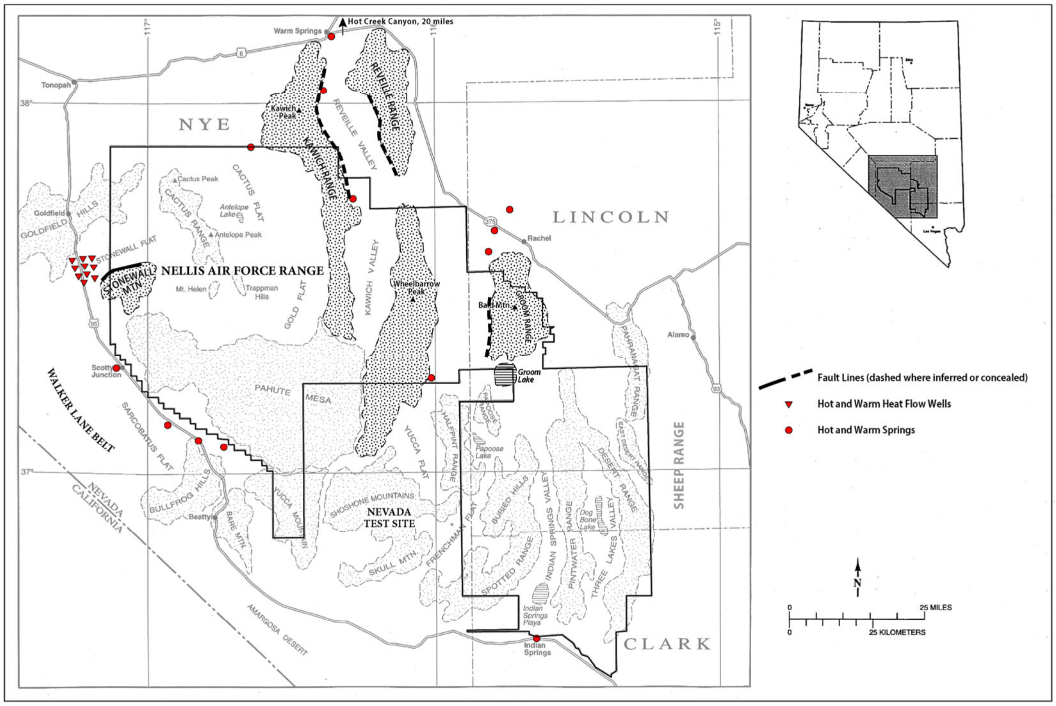

Figure 5. *NAFR location map with approximate boundaries, young faults, hot springs and hot wells (modified after Tingley et al., 1998).*

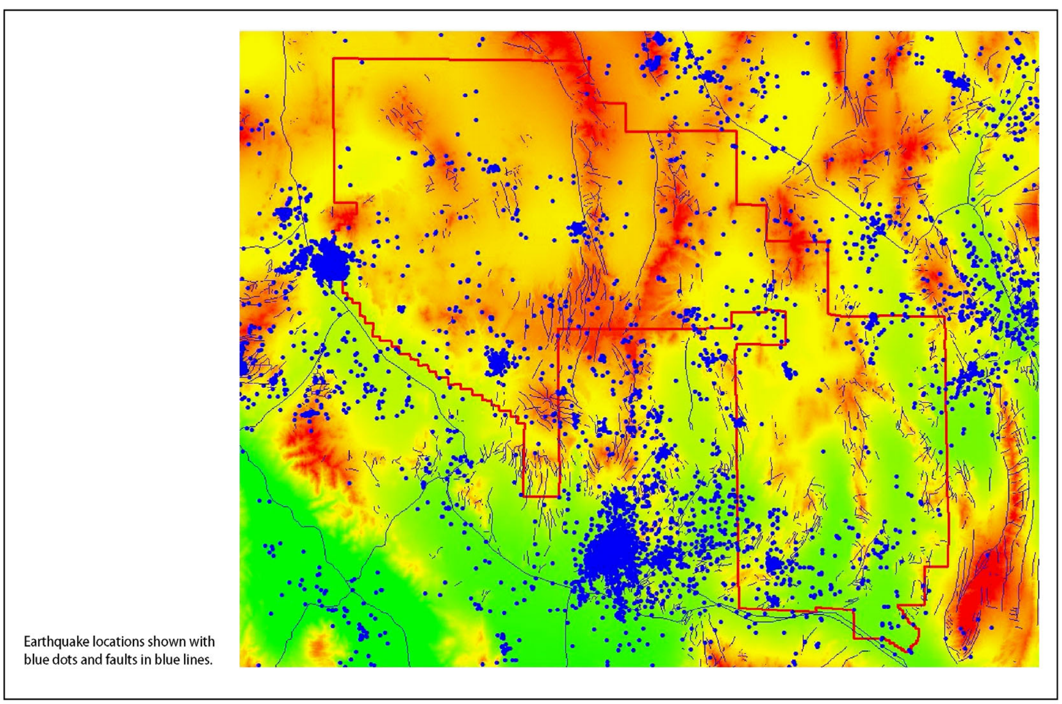

Figure 6. *Digital elevation model (green low and red high elevations) with earthquake locations and faults, NAFR.*

Table 1. Prioritized List of Military Installations with Geothermal Direct-Use Potential

Rank	Military Facility	Well Temperatures or Gradients and Distances from Buildings
1	Kingsley Field Air National Guard Base, OR (Air Force)	5 mi S of the Klamath Falls district heating system, with > 300 wells with temperatures above 160°F; highest measured T within 5 miles is the Kent well (306°F). Two Air Force wells about 2 mi S have gradients over 4°F/100 ft at less than 500 ft.
2	Naval Air Station Fallon, NV	FOH-3 measured 376°F at 6,952 feet. Numerous wells in and around the base have gradients above 4.5°F/100 ft.
3	Sierra Army Depot, CA	Well MP21-HLI, with a gradient of 4.3°F/100 ft, is within boundary of the base, about 5 mi W of the Depot Storage Facilities. Amedee No. 2, 4 mi from Amedee Airfield (Nevada ANG) recorded 225°F. Base is partially closed.
4	Hawthorne Army Ammunition Depot, NV	Three wells (El Capitan, HAW-GC, and HHT-1) with temperatures > 180°F at 1,000 ft or less are within 5 mi of the main cluster of base buildings.
5	Camp Williams, UT (Army)	Nine wells with temperatures > 120°F are clustered near the State Prison about 3.5 mi N of the main cantonment area. Five have Ts > 150°F at less than 500 feet.
6	Gowen Field Air National Guard Base, ID (Air Force)	Twelve wells within 5 mi of the ANG Base (including Boise Geothermal No. 4 at 175°F) have Ts >160°F.
7	Fort Bliss, NM/TX (Army)	MG-16, appx 4 mi SE of McGregor Range Camp recorded 173°F at 1,500 feet. Two others (MG-14 and N-9) with Ts > 160°F at 1,000 feet or less are within 2 mi of the camp.
8	Fort Huachuca, AZ (Army)	Geo-Heat Center database lists 5 wells >135°F within 5 mi of the Main Post. Highest T is 154°F appx 4.5 mi SW.
9	Twenty-nine Palms Marine Corps Air/Ground Combat Center, CA (Navy)	Three wells with temperatures from 127°F to 152°F are within about 5 mi of the Main Base. TNP6, 2 mi W of the Airfield, reported 153°F.
10	Luke Air Force Base, AZ	Within 5 mi of buildings at Luke AFB, 4 wells report Ts from 120 to 133°F at depths ranging from 1,043 to 2,320 feet. a well S of McMicken reported 184°F at 705 feet.
11	Davis-Monthan Air Force Base, AZ	Well PM-15, just outside the SW boundary of base (on the opposite side of the airstrip appx 2 mi from the main building cluster), has a temperature >120°F at 2,500 feet.