U. S. DEPARTMENT OF THE INTERIOR
U. S. GEOLOGICAL SURVEY

TECTONIC CONTROLS ON MAGMATISM AND GEOTHERMAL RESOURCES IN THE GEYSERS-CLEAR LAKE REGION, CALIFORNIA: INTEGRATION OF NEW GEOLOGIC, EARTHQUAKE TOMOGRAPHY, SEISMICITY, GRAVITY, AND MAGNETOTELLURIC DATA

William D. Stanley[1], Harley M. Benz[1], Mark A. Walters[2], and Brian D. Rodriguez[1]

USGS Open-File Report 97-95

Prepared in cooperation with U. S. Department of Energy
Idaho Operations Office

[1]U. S. Geological Survey, Box 25046, Denver, Colorado 80225

[2]1573 Manzanita Ave., Santa Rosa, CA 95404

List of Illustrations

TECTONIC CONTROLS ON MAGMATISM AND GEOTHERMAL RESOURCES IN THE GEYSERS-CLEAR LAKE REGION, CALIFORNIA: INTEGRATION OF NEW GEOLOGIC, EARTHQUAKE TOMOGRAPHY, SEISMICITY, GRAVITY, AND MAGNETOTELLURIC DATA

William D. Stanley[1], Harley M. Benz[1], Mark A. Walters[2], and Brian D. Rodriguez[1]

Abstract

Several lines of geologic, geochemical, and geophysical evidence suggest that a northeast-trending zone of extension has provided tectonic control over magmatism and geothermal resources in The Geysers-Clear Lake region of northern California. To investigate magmatism and geothermal systems of The Geysers-Clear Lake region, we developed a new 3D seismic velocity model using finite-difference tomography based upon 3358 local earthquakes of >1.5 M. The new tomographic images resolve the velocity structure of the crust in the region to depths of approximately 13 km. The most significant velocity contrasts in The Geysers-Clear Lake region occur in the steam production area where high velocities are associated with a Quaternary granitic pluton, and in the Mt. Hannah region where low velocities occur in a 5-7 km thick section of Mesozoic argillites. New 3D gravity models have been developed in the area of the tomographic imaging and these models demonstrate that all density contrasts can be accounted for in the upper 5-7 km of the crust; large and deeper magma bodies are not required to fit the gravity data using reasonable density contrasts. Two-dimensional magnetotelluric models of data from an east-west profile indicate high-resistivities are associated with the granitic pluton in the steam production area and low resistivities in the section of Mesozoic argillites. No indication of mid-crustal magma bodies is present in the magnetotelluric data or seismic tomography. However, based upon heat flow and geologic evidence, small Recent magma bodies are thought to underlie the Northwest Geysers, Sulphur Bank Mine and perhaps other areas such as Ely Flat south of Mt. Konocti and Wilbur Springs. All of the new geophysical models and seismicity patterns indicate that a northeast-trending extensional zone within a transpressive environment is a controlling factor in the geophysical signatures. North-northeast and northeast-trending faults, fractures, lineaments and mineralized veins of Quaternary age are common in The Geysers - Clear Lake region. These are apparently the result of extension within a northeast-trending zone between two active northwest-trending faults parallel to the San Andreas system, the Maacama and Bartlett Springs faults. Analysis of seismicity patterns, temperature, heat flow, geochemical, and production data for The Geysers area indicates that extension within this northeast-trending zone may control many of the active processes that are important in understanding the geothermal system, its extent, and future exploration strategies.

[1] U. S. Geological Survey, MS966, Denver Federal Center, Denver, CO 80225, email:dals@bach.cr.usgs.gov. [2] 1573 Manzanita Ave., Santa Rosa, CA 95404, email:mwalters@sonic.net.

INTRODUCTION

The Geysers-Clear Lake area of northern California (Fig. 1) is one of the few regions of the world where dry steam is used to produce electric power. The geothermal resource of The Geysers-Clear Lake region encompasses an area of over 700 km^2. The developed steam reserves are the largest such development in the world and are defined by more than 600 drilled wells and an installed electrical producing capacity in 1989 of 2043 MW. However, an accelerated rate of steam pressure decline beginning in late 1984 signaled a reduction in production capability and several power plants have been decommissioned since 1989. The Geysers produced about 1230 megawatts of electrical power in July 1996 from about 420 wells. Despite, the production declines, The Geysers remains the largest producer of geothermal power in the world and exceeds the total output of any single country outside the United States. Many new data have become publicly available as the participating companies in the region attempt to evaluate the actual dynamics and geologic setting of the geothermal resource. The U.S. Geological Survey (USGS) conducted extensive geological, geophysical, and other studies in the region during the 1970's that were summarized in USGS Professional Paper 1141 (McLaughlin and Donnelly-Nolan, 1981). A publication by the Geothermal Resources Council (Stone, 1992) summarizes much of the current information available from the geothermal production area.

As research continued from the 1970's to the 1990's in The Geysers-Clear Lake region, details of subsurface geology were obtained from drilling. The ability to locate the steam reservoir in fracture systems within the production area has improved, but the total region of geothermal reserves is relatively confined, and anticipated possible new production has not been developed in the broader part of the Clear Lake volcanic field to the east. One fundamental question has been the subject of much research--where is the location of the heat source for the geothermal area? Parts of the Clear Lake volcanic field are younger than 1 m.y. in age and there is widespread evidence for high subsurface temperatures over the region (Walters and Combs, 1992), so it is quite evident that there is either one broad, or several smaller, "heat sources" in the area. Many early geophysical-geological interpretations involved a large magma chamber at depths starting at 7 km, but there was little published evidence for intrusive activity until subsurface information was released (Schriener and Suemnicht, 1980; Thompson, 1992; Hulen and Walters, 1994) about a concealed, Quaternary granitic pluton in The Geysers production area locally known as "the felsite" (Figs. 2,3). The age of the intrusion was determined at 0.9 Ma-2.4 Ma by Schreiner and Suemnicht (1980) and more recently at 1.32 Ma by Dalrymple (1992) and 0.57 Ma by Pulka (1991), which makes the pluton too old to be directly responsible for heat in the production area. The pluton is a composite body composed of rhyolite porphyry, granite, and granodiorite (Hulen and Nielson, 1993; Nielson and Hulen, 1996). Younger magma bodies, not yet sampled and dated, may have been emplaced close to, or within the "felsite" of the steam production area. Such unsampled intrusions are assumed to be the source of heat for the present geothermal system.

In the Clear Lake volcanic field (Figs. 2,3), measured temperatures in deep exploration wells have been as high as 326• C at depths of less than 3.5 km (Walters and Combs, 1992). Extrapolation of measured temperatures and fluid inclusion data suggests a temperature of close to 400° C at a depth of 3.7 km in the Wilson No. 1 well (Fournier, 1991) near Mt. Hannah (Figs. 2, 3). In the Borax Lake area (Figs. 2,3), temperatures >200°C have been measured in wells at depths of

2 km (Goff and Decker, 1983; Beall, 1985). Several geophysical anomalies seem to be centered over the Mount Hannah area (Fig. 2) and a residual Bouguer gravity low of about -30 mgal amplitude was interpreted by Isherwood (1975) to be caused by a spherical magma chamber centered at 13.5 km depth. Stanley and Blakely (1995) presented an updated review of the constraints provided by drilling, geophysical, geochemical, and geological data on heat sources. This review preferred a magmatic model that involves a lower-crustal magma chamber and discrete, isolated upper-crustal plutons located along tectonic features. The geophysical interpretations indicated that a large magma chamber in the upper and mid-crust is not required or supported by the geophysical data.

Stanley and Rodriguez (1995) outlined a revised tectonic model based upon the premise that features of extension and magma injection in the region could be related to details of Gorda Plate motion. In this paper we present evidence to support our view that the effects of a northeast-trending zone of extension explain many of the enigmatic aspects of thermal, geologic, and geophysical data from the region. This zone of extension can be mapped from The Geysers production area across the south end of Clear Lake and is related to transpressive stress which aligns extensional features along the direction of maximum compression. However, primary magma injection in this zone of extension probably has its roots in details of plate interactions in the interval 1-2 Ma when the Gorda-North America-Pacific plate triple junction passed through the area.

GEOLOGICAL AND GEOPHYSICAL SETTING

The Geysers-Clear Lake region is in the northern California Coast Ranges (Fig. 1) between the San Andreas fault system and the Coast Range thrust (Bailey et al., 1964). The Coast Range thrust fault separates accrectionary wedge rocks of the Franciscan assemblage from the Great Valley Sequence, both of Jurassic and Cretaceous age (Fig. 1). The Franciscan assemblage consists of melange units and less disturbed sedimentary, metasedimentary, and metavolcanic rocks that were scraped off the subducting plate in Jurassic to Cretaceous time. The Great Valley Sequence is interpreted to represent arc-trench gap or forearc basin deposits that were derived from the Klamath and Sierran magmatic-arc terranes (Dickinson, 1970; Ingersoll et al., 1977). The Great Valley sequence consists largely of sandstones and shales, underlain by the Coast Range ophiolite (McLaughlin and Pessagno, 1978).

At the scale of The Geysers-Clear Lake region, McLaughlin and Ohlin (1984) described tectonostratigraphic subterranes of the Franciscan assemblage and the lower part of the Great Valley Sequence. These terranes are bounded by segments of the northwest-trending San Andreas fault system that include the Maacama, Healdsburg, and Bartlett Springs fault zones (Figs. 1,2,3). The Collayomi fault zone (Figs. 2,3) occurs primarily in ophiolitic serpentinites that separate central Franciscan assemblage units from Great Valley Sequence and eastern Franciscan assemblage terrane of the Mt. Hannah and Clear Lake region. The Collayomi fault zone is not seismically active.

The rocks of the Clear Lake volcanic field are primarily Pleistocene and 2 m.y., or less, in age (Donnelly-Nolan and Hearn, 1981). The nearest similar volcanic rocks are Pliocene age in the Sonoma volcanic field just southwest of The Geysers-Clear Lake area (Fig. 1). No other young volcanic rocks are found north of the Clear Lake area in the Coast Ranges. The nearest Quaternary volcanic centers are at Sutter Buttes and in the Lassen Peak region (Fig. 1). The eruptive rocks of the Clear Lake volcanic field range from basalt to rhyolite, although ash flows like those in the Sonoma volcanic field are absent (Hearn et al., 1981). Age dates and the geomorphic preservation of volcanic vents indicates that the most recent volcanism in the Clear Lake volcanics appears to be migrating to the northeast, related to a zone of crustal extension analogous to that suggested by

McLaughlin (1981).

The Coast Range volcanic rocks are interpreted to have developed by crustal heating above a window in the junction between the three plates of the Mendocino triple junction (Lachenbruch and Sass, 1980; Jachens and Griscom, 1983; Graham et al., 1984; Furlong et al., 1989). This "slab window" migrated northward because of north-directed, dextral slip on the San Andreas fault system (Fig. 1). Movement of the Mendocino triple junction (MTJ) is widely believed to be the cause of northward migrating, late Tertiary and Quaternary volcanism in the California Coast Ranges (Dickinson and Snyder, 1979; Donnelly-Nolan et al., 1981).

Several geophysical anomalies are centered near the Mt. Hannah area (Fig. 2). A residual Bouguer gravity low of about -30 mgal amplitude was interpreted by Isherwood (1975) to be caused by a magma chamber whose top is at 7 km depth. Earlier models of the geophysical data attributed gravity and teleseismic delay-time anomalies (Isherwood, 1981; Iyer et al., 1981; Oppenheimer and Herkenhoff, 1981) strictly to mid-crustal properties without the effects of upper-crustal inhomogeneities that are now better understood. Using magnetotelluric data as a constraint on gravity models, Stanley and Blakely (1995) interpreted that the minimum depth to a large magma chamber in the Mt. Hannah region is closer to 15 km than 7 km as originally preferred by Isherwood (1975). They inferred that the gravity and electrical anomalies, as well as teleseismic P-wave delays, are largely attributable to rock property and physical state variations in the upper 7 km and not to "magma" at greater depths.

Stimac et al. (1992) used petrologic and other data to interpret that a mafic magma chamber developed in the lower to middle crust by dike injection of basaltic magma as a result of upwelling of hot asthenosphere. Continued episodic injection of mafic magma into the crust led to an established silicic magma network (Fig. 4) and that sustained production of mixed dacites over a relatively long interval (2 Ma). They infer that peripheral volcanic features like rhyolite flows that occur northeast of Clear Lake can be explained by northeast-stepping basaltic dike injection at depth. A 3D cartoon of our concept of magma injection in the region is shown in Fig. 4. We envision that the "slab window" was a narrow shutter that followed the southern edge of the Gorda Plate. The thermal effect of this slab window in the study area is inferred to have been focused in the Clear Lake Volcanic field, leading to the volcanism and assisting in modifying the crust so that other tectonic features were easily formed during the most recent volcanic phases.

Hearn et al. (1981) documented geologic evidence for extension in the Clear Lake area and Oppenheimer (1986) demonstrated active extension in The Geysers production area from earthquake focal mechanisms. Oppenheimer (1986) postulated that the entire region between the Maacama-Healdsburg and Bartlett Springs fault systems (Fig. 1) may be undergoing extension. Eberhart-Phillips (1988) found that most earthquakes east of The Geysers production area occur in a northeast-trending zone extending from The Geysers to the southern end of Clear Lake, and noted that this zone was not correlated with any known geologic structure. The northeast-trending seismicity noted by Eberhart-Phillips (1988) is not related to geothermal development and includes very recent events such as a M5 earthquake and aftershocks in 1996 near the city of Clear Lake. Stanley and Rodriguez (1995) concluded that much of the magmatic activity was concentrated along active northwest strike-slip zones and northeast-trending transtensional features. Transtension develops along the direction of maximum compression in a transpressive environment, and results in normal faults, joints, and fractures which may facilitate magma injection and vein ore deposits.

Published geologic maps are almost completely focused on the northwest-trending set of faults, geologic contacts, and topography that dominates the surrounding Coast Ranges. Recent geologic mapping and remote sensing analysis indicate that north-northeast and northeast faults occur in substantial numbers, often represent the youngest active faults, and play a key role in tectonics and geothermal resource controls. The Caldwell Pines, Adobe Creek Canyon, and Wight Way faults (Fig. 3) all appear to be significant northeast-trending faults associated with an extensional environment. Rich and Steele (1974) identified a system of north-northeast, discontinuous linears confined to the central core of the Coast Ranges in The Geysers region which are easily seen on ERTS (Earth Resources Technology Satellite) imagery; one set being coincident with the northwestern boundary of our extensional zone as jointly constrained by all of the various types of data. Rich and Steele further speculate that these are the youngest system of geologic features in the Coast Ranges except for the San Andreas Fault.

Detailed formation contact mapping in the northwestern part of The Geysers shows that young north-northeast and northeast-trending faults offset major lithologic units (Nielson et al., 1991) and older northwest-trending Quaternary faults (Walters et al., 1996). The Caldwell Pines Fault (Fig. 3) is an important northeast-trending fault in the Northwest Geysers steam reservoir which isolates a reservoir compartment that has not been extensively vented or diluted with meteoric waters. Within this reservoir compartment ^{3}He with R/RA values exceeding 8 (Truesdell, et al., 1995) are inferred to be related to young magma injection.

SEISMICITY PATTERNS, HEAT FLOW DATA AND VOLCANIC VENTS

Seismicity patterns in northern California are shown in Fig. 5. Most of the present crustal slip in northern California is related to transform motion of the Mendocino triple junction. Key regional faults other than the San Andreas fault appear to be currently transmitting this motion, including the Maacama, Healdsburg, Bartlett Springs, and Green Valley fault zones. Intense seismicity related to steam production is localized in The Geysers production area (Eberhart-Phillips and Oppenheimer, 1984).

As first noted by Eberhart-Phillips (1988) a zone of earthquakes can be traced along a northeast azimuth from The Geysers production area across the southern end of Clear Lake (Fig. 5). More details of the seismicity patterns in The Geysers-Clear Lake locale are shown in Fig. 6, along with heat flow data from Walters et al. (1995). Earthquakes in the northeast-trending zone of seismicity through the Clear Lake area are further concentrated along the northwest-trending Konocti Harbor fault on the southwest side of the south end of Clear Lake. Castillo and Ellsworth (1993) found that some deep earthquakes just west of Clear Lake were low-frequency in character and suggested that this might be indicative of magmatic processes at work. Ludwin et al. (1982) noted an interesting phenomena of "sympathetic" clusters of earthquakes at The Geysers and the southern arm of Clear Lake in which events appear to be correlated in time between the two regions, possibly reflecting the effects of concordant stress within the NE-trending extensional zone.

Walters and Combs (1992) describe results of heat flow measurements from 1971 to 1984 in 67 selected bore holes over The Geysers-Clear Lake region. The data in the report by Walters and Combs (1992) has been updated in Fig. 6 with the addition of data from an unpublished data base supplied by one of us (MAW) containing 644 holes and additional data from deep (>1.8 km) exploratory wells in the Northwest Geysers (California Div. of Oil, Gas, and Geothermal Resources open file records). Elongation of the heat-flow and temperature gradient contours to the northeast is inferred to be due to increased thermal input from small intrusive bodies in the southern Clear

Lake area. Information on thermal anomalies in the region has recently been expanded using detailed, terrain-corrected thermal gradient data (Walters, 1995). These new data indicate that the regional heat anomaly is probably composed of several thermal anomalies. These thermal anomalies include a northwest aligned feature in The Geysers production area which is truncated sharply in the Northwest Geysers and a set of anomalies aligned along a NE azimuth across the Mount Hannah area, the Sulphur Bank Mine-Borax Lake area and Wilbur Springs (Fig. 3). The thermal anomaly inside The Geysers steam production area directly reflects the depth and thickness of the caprock in the production area convective system. The temperature gradient data are used by the operating companies to estimate the depth to steam for deep exploratory wells.

Both heat flow and temperature gradient data indicate a northeast-trending boundary to the thermal anomaly which corresponds to the northern side of the extensional zone that we interpret from other types of data. The northern boundary of the extensional zone extends from Big Sulphur Creek in the production area (Fig. 3) to Mount Konocti along a steep gradient in heat flow values (Walters, 1995 and Young et al., 1983) and coincides with a NE-trending fault in Adobe Creek Canyon (Fig. 3). The northern boundary of the heat flow anomaly correlates with the steep gradients on the gravity data (Fig. 2), suggesting a lithologic cause. We study this northwestern boundary of the extensional zone in detail with our 3D gravity model in a later section.

High temperatures (>300• C) have been measured at depths of slightly over 3 km in the Audrey A-1 well in the Sulphur Bank Mine area (Fig. 3), which may indicate a local heat source in the Sulphur Bank Mine-Borax Lake area. A rather narrow zone of heat input may occur along the postulated northeast-trending zone of extension defined by the seismicity lineament, the concentration of basaltic vents in southern Clear Lake area (Fig. 6), and the northeast stretching of the 4 HFU contour. Between the Clear Lake Volcanic field and Sulphur Bank Mine, there is a boron concentration anomaly in Clear Lake (Lallatin, 1975); thermal anomalies in the bottom of the Clear Lake which align with the volcanic vents (Martin, 1976); and thermal springs which issue at the shoreline of Clear Lake (Sims and Rymer, 1976). These observations suggest the possibility of upflow from a hydrothermal system or local intrusions along these lineaments. All known high temperature wells (260 to 360 • C) in the region between the Northwest Geysers and Sulphur Bank Mine occur within the northeast-trending extensional zone and some are shown in Fig. 3. We hypothesize that the overall heat flow anomaly may be related to a number of small, high level plutons located along both northwest and northeast tectonic features.

Hearn et al. (1981) compiled and dated the sources of volcanic rocks in the Clear Lake field. The youngest basaltic vents in Fig. 6 appear to be located on well-defined dikes or tectonic features. Nearly all of the young vents are located within the proposed extensional zone. It is also evident from age dating that volcanism has been migrating to the northeast (Donnelly, 1977) within the inferred broad extensional zone over the last 1 Ma. The oldest vents in the Clear Lake field are located primarily along northwest-trending, strike-slip faults (Hearn et al., 1981). These may predate the formation of the extensional zone along which younger volcanism migrated to the northeast.

QUATERNARY MINERAL DEPOSITS

The literature for every mining district within, and in proximity to, the northeast-trending extensional zone make reference to subsurface transpressional features such as dilation veins and dikes which strike north-south or north-northeast. The mining districts include the well-known mercury deposit at Sulphur Bank Mine, the mercury deposits in the Mayacmas Mining District which is in and adjacent to The Geysers, and the mercury and gold deposit deposits in the Sulphur Creek

Mining District around Wilbur Springs (Fig. 3).

Northeast-trending features dominate the geological, geochemical, and geophysical data for the Sulphur Bank Mine - Borax Lake area (Fig. 3), related to magmatism and associated mineral deposition (Ciancanelli, 1976; Johnson, 1979). At least three northeast-trending faults dominate the Quaternary surface geology (Ciancanelli, 1970; Ciancanelli, 1976; Hodges,1966; McNitt, 1968; Rymer, 1978; and Vantine, 1970). The most prominent of these three northeast-trending faults is a minimum of 12 km long and is named the "Pomo Fault" (Fig. 3) by Ciancanelli (1970) and later re-named the "Cross Spring Fault" (Hearn et al., 1988). The Pomo Fault juxtaposes the Pliocene-Quaternary Cache Formation with Mesozoic Franciscan Assemblage. Quaternary volcanic vents and thermal springs emerge along the Pomo fault, although it not currently seismically active.

Two miles west of the Pomo Fault, there is a series of north to northeast-trending volcanic vents, thermal anomalies, and faults. These are designated by Ciancanelli as the "Cinder Cone linear". At the Sulphur Bank Mine (Fig. 3), a 0.045 Ma basalt is cut by several faults that strike N50-65• E with vertical displacement of less than 20 feet, and there are slickensided grooves showing nearly horizontal movement. (Ross, 1940). According to Everhart (1946; referenced by Rytuba et al., 1996) high grade ore bodies occur where northwest-trending faults are intersected by younger NE-trending structures. Seeps and fumaroles at Sulphur Bank Mine vent along a prominent N20• E to N40• E oriented normal fault zone. The present active deposition of mercury, the composition of gas from springs, conductive heat flow values exceeding 8 HFU, and volcanic flows dated at less than 0.05 Ma all indicate a Recent intrusion at Sulfur Bank Mine (Goff and others, 1993; Goff and Janik, 1994). Exploration studies between Sulphur Bank Mine and the Cinder Cone linear show that areally extensive soil gas (CO_2, CH_4 and H_2) and soil mercury anomalies are roughly oriented N35• E (Johnson, 1979).

Mercury deposits of the Mayacmas Mining District (Fig. 3) form a halo around the western and southern flanks of The Geysers production area (Bailey, 1946; Yates and Hilbert, 1946; Hulen and Walters, 1994). Ross (1940) recognized the difference in the faulting and folding style between Sulphur Bank Mine, which is within the NE-trending extensional zone, and the Mayacmas District at the southern end of The Geysers. He reported two sets of principal normal faults in the Mayacmas District which offset the Sonoma volcanics; a N60• W set downthrown on the south side, and a second conjugate set which trends north to N15• E with slickensides that pitch southward at angles of as much as 45• , indicating that the movement has a relatively large horizontal component. These faults are not clearly exposed except in mine workings.

EARTHQUAKE TOMOGRAPHY

Research on seismic velocities and structures in The Geysers-Clear Lake region has involved numerous controlled-source refraction/wide-angle reflection surveys and local earthquake and teleseismic tomography studies. Majer and McEvilly (1979) and Warren (1981) interpreted seismic refraction data from explosions recorded by the Northern California seismic network and 13 closely-spaced portable seismometers. They found velocities of less than 5 km/s for the upper 5 km of the crust, velocities greater than 5.5 km/s in the production zone, and slower velocities along the western edge of the Great Valley. Eberhart-Phillips (1986) studied the three-dimensional P-wave velocity structure in The Geysers-Clear Lake region using simultaneous inversion of local earthquake and controlled-source refraction arrival-times for velocity and hypocentral parameters. This study found velocities of 5.0-5.8 km/s in the upper 3 km of the crust beneath The Geysers production area, below which velocities increased to greater than 6.0 km/s. Eberhart-Phillips (1986) also found evidence for low-velocities (<5.0 km/s) in the Mount Hannah area at depths extending to >4 km.

Using teleseismic P-wave delays, Iyer et al. (1981) postulated a 15-25% velocity reduction beneath the Mt. Hannah region that extended from approximately 4 to 20 km depth. Using an alternative teleseismic modeling technique, Oppenheimer and Herkenhoff (1981) refined the previous model by identifying 10% and 20% P-velocity lows beneath The Geysers and Mt. Hannah, respectively. The most recent study of the deep velocity structures in The Geysers-Clear Lake area was done as part of a regional study of northern California by Benz et al. (1992) using teleseismic P-wave delay times. Like previous teleseismic studies in northern California, coarse parameterization of the velocity model resulted in limited crustal resolution. Benz et al. (1992) found velocity anomalies ranging from +9 % (fast) to -10.5 % (slow) in the crust over northern California. Their inversion model indicated -10.5 % lower velocities in the Clear Lake region in the depth range 0-15 km, and 7.3 % higher velocities over parts of the Clear Lake and Sonoma volcanic fields associated with volcanic rocks older than 1 Ma. The teleseismic low-velocity anomaly mapped by Benz et al. (1992) in the Clear Lake block agrees generally with the results of Iyer et al. (1981) and Oppenheimer and Herkenhoff (1981).

Recently, Julian et al. (1996) described a detailed V_p and V_s 3D tomographic study of The Geysers area. Centered on the production area, their model extended over a 20x20 km area and a maximum depth of 4 km. Their study, which primarily focused on the significance of V_p/V_s ratios, found a -9% V_p/V_s ratio anomaly centered in the production area at depths of about 2 km below the surface. They relate this anomaly to vapor domination of pore spaces in the reservoir area. Their inversion results also show a high V_p anomaly in the area of the felsite intrusion, but extending to the southwest toward the Mercuryville fault, and low velocities east of the Collayomi fault.

Benz et al. (1996) recently developed a high resolution local earthquake tomography technique that we used in this study. Travel times are calculated using finite differences and the 3-D velocity structure is determined using a large matrix solver (LSQR) with smoothing constraints. P_g first-arrival times (original time of source + travel time between source and receiver) are calculated using the technique of Podvin and Lecomte (1991), which estimates the travel-time wave-front (isochron) by solving the Eikonal equation across a finite-difference grid of rectangular, constant velocity cells. Standard formulations of the arrival time tomography problem require knowledge of the ray length within each cell sampled by a source-receiver pair, which is not explicitly known from finite-difference computations. Therefore, rays are found by backtracking along the perpendicular to the wave front (the steepest path) from source to receiver (Hole, 1992). Finite-difference travel-time calculations and ray-tracing are robust for the computation of direct, diffracted and refracted waves in complex velocity structures and extreme topography. This method is particularly well suited for application to The Geysers-Clear Lake region because of rugged topography and large velocity variations previously identified (Julian et al., 1996; Eberhart-Phillips, 1986). The velocity structure in The Geysers-Clear Lake region was parameterized using 2x2x1 km velocity cells, which covers an area 124x172 km centered roughly on The Geysers production area (Fig. 5). The grid outline shown in Fig. 5 encompasses 86 cells along strike of the active fault zones (N30°W) and 62 cells normal to strike (N60°E). The model extends to depths of 20 km below sea-level, but the majority of earthquakes occur above 10-km-depth. Within this area, 80,368 arrival-times from 3,358 earthquakes recorded at 85 stations are used in the inversion. Only P_g arrival-times recorded for epicentral distances less than 90 km are used, therefore, only the upper 12 km of the crust is well illuminated. The largest concentration of stations and earthquakes occurs within The Geysers production area, therefore, this portion of the model has the best resolution.

Results from the 3D tomographic inversion of The Geysers-Clear Lake area are shown in Figs. 7, 8, and 9. Four horizontal velocity slices from the tomographic inversion are indicated in Fig. 7 for depths of 0 to 1 km, 1 to 2 km, 2 to 3 km, and 3 to 4 km below mean sea level (msl). The first slice (0 to -1 km msl) is limited in data coverage except in The Geysers production area and Mt. Hannah regions where both topography is elevated and seismometers provide good coverage. The slice from -2 to -3 km msl broadens the coverage and, combined with the 0 to -1 km msl slice, provides good indications of geologic causes for the velocity anomalies. In these two slices, a velocity high with values ranging from 5.75 to 6.25 km/s occurs between the Mercuryville and Collayomi faults and in the southern half of The Geysers production area. This velocity high approximately matches the known extent (Fig. 3) of the granitic pluton in the production area, but broadens with depth. The presence of the granitic pluton has only been inferred in the Northwest Geysers by the presence of biotite-rich metagraywacke hornfels deep in the drilled portion of the reservoir (Hulen and Walters, 1994). In an earlier tomographic study using a smaller earthquake data base, Eberhart-Phillips (1986) noted a velocity high in the southeastern part of the steam production area and its possible relationship to a large intrusive body inferred by Thomas (1981) based on well logs.

In the -2 to -3 km msl slice, there is an indication that the velocity high of >5.75 km/s extends from the Northwest Geysers production area to the northeast across the Mt. Hannah region. In the final slice (-3 to -4 km msl) this northeast extension evolves to a deep high velocity center near Mt. Hannah. Details of the velocity high (Fig. 7c) that we interpret to be associated with the granitic pluton of the production area are shown in the detailed view of Fig. 8, with thermal data superimposed. Note the correlation between the northeast-trending temperature gradient contours and the high velocity anomaly. The northeast extension of the velocity high toward Mt. Hannah is also on strike with a major gradient in total noncondensible gas in the steam produced (Hulen and Nielson, 1996; Gunderson, 1991) and with a change in the depth to the top of the steam reservoir (Williamson, 1990). The latter anomalies in steam depth and noncondensible gas may also be related to control by the northeast-trending extensional zone.

Another high velocity anomaly is shown in the three deeper slices in Fig. 7, especially at -3 to -4 km msl, just northwest of Clear Lake. This anomaly is also an area of high gravity values (Fig. 2), suggesting these gravity and velocity highs are related to mafic metavolcanic and ophiolitic rocks within the Franciscan assemblage. A similar set of gravity and velocity highs occurs in the south-central part of the area indicated in Figs. 2 and 7, possibly also related to mafic metavolcanic ("greenstone") and ophiolitic rocks. A well-defined velocity low (4.0 to 5.25 km/s) between the Collayomi fault and Clear Lake, centered roughly on Mt. Hannah corresponds to the gravity and resistivity low (Fig. 2) that Stanley and Blakely (1995) interpret to be caused by a 5-7 km thick section of Mesozoic argillites. This velocity low is split in two on the -2 to -3 km msl slice by a northeast extension of the velocity high in The Geysers production area. Higher temperatures, larger percentages of noncondensible gases, along with high oxygen and other isotope values in the Northwest Geysers reflect younger magmatic activity. These geochemical data and the northeast extension of the high velocities associated with the production area granitic pluton are inferred to be related to the northeast migration of magmatism in the post 1 Ma time frame.

A trend of separate high velocity anomalies (Figure 7) extends to east of the Bartlett Springs fault; some of these discrete anomalies may be related to isolated intrusive bodies. An isolated velocity high east-southeast of The Geysers (at about row 26, column 42, on Fig. 7c) is in an area of gravity highs and probably is related to mafic ophiolitic rocks of the Coast Ranges thrust in the upper 10 km.

At successively greater depths, discrete velocity anomalies cannot be isolated except for the velocity highs northwest of Clear Lake and in the south-central part of the model. This is most conveniently illustrated in the vertical model slices of Fig. 9. At depths below about 9 km from the model top (or 7 km below sea level) a relatively high degree of uniformity is reached with velocities generally in the range from 5.75 to 6.0 km/s. The granitic pluton in the production area is interpreted to be cause of shallowing of velocities >5.75 km/s between the Mercuryville and Collayomi fault zones on the row 38 and row 33 slices. Low-velocities of the Mesozoic argillite section near Mt. Hannah are best expressed in the row 38 slice.

It is important to note that there are no low-velocity features which might represent extensive magma zones in the upper 13 km of the crust. Tomographic models that incorporate a broader region than that addressed in this paper extend the velocity models to depths of over 20 km. In these broader models (also based upon northern California regional earthquakes) there also is no apparent evidence for low-velocity magma zones. The latter models are beyond the scope of the present paper and will be discussed in a subsequent report that will incorporate teleseismic responses of the crustal structure derived from local earthquakes. The relative low-velocity regions that appear on the row 33 and row 48 slices extending down to depths of about 7 km below SL are presumably related to background Franciscan assemblage with low metamorphic grade and without significant mafic components. Such units contrast with sections in the axial part of the study area composed of higher velocity Franciscan assemblage (with high metamorphic grade and mafic content) and the granitic intrusions. Most of the higher velocity Franciscan components trend northwest, reflecting the original accretionary grain of the Franciscan assemblage and the strike of the San Andreas fault system. We infer that the original part of the composite granitic pluton in the steam production area was injected along this northwest tectonic grain, possibly as a large dike (Hulen and Nielson, 1996), and subsequent magmatism stepped to the northeast across this grain, controlled by the younger northeast-trending extensional zone.

GRAVITY MODELS

Stanley and Blakely (1995) reviewed past gravity modeling in The Geysers-Clear Lake region and provided an updated model which utilized recent information from deep exploratory wells such as the deep geothermal well, Wilson No. 1, in the Mt. Hannah area (Fig. 2,3). New information on densities for the granitic pluton were also incorporated into the model. The granitic pluton and the Mesozoic argillite sequence section in the Mt. Hannah region were both shown to be low density bodies that contributed greatly to the 25 mgal gravity low over the region. In contrast to earlier models such as those by Isherwood (1975) which incorporated a large magma chamber in the upper and mid-crust, the model of Stanley and Blakely (1995) used a much smaller, tabular, low-density magma zone at depths greater than 15 km. This deeper body honored constraints provided by MT modeling in the region and petrologic data of Stimac et al. (1992) which suggested that primary magma chambers are probably in the lower crust.

The model of Stanley and Blakely (1995) was a 2.5D (a two-dimensional model with limited strike length) model of a single profile that passed through the steam production area, near Mt. Hannah, and southern Clear Lake (Fig 2). For purposes of the present paper we developed a full 3D model of the gravity data for the study area. A forward modeling program was used to fit the residual isostatic gravity data. Isostatic gravity data assume an Airy compensation model for topography that removes some of the regional effects due to deepest crustal and mantle signatures like the plate boundary near the study area. However, it was still necessary to remove a linear trend surface to correct for non-isostatically compensated crustal thickening. The 3D prism model, observed isostatic residual, and calculated gravity values are shown in Fig. 10. The model is restricted to vertically sided prisms, so in some instances stacked thin prisms were used to simulate dipping body sides. Not all of the small areal extent anomalies were modeled, and we concentrated on the main features of the gravity field. The model demonstrates that the important gravity anomalies in the Mt. Hannah and Geysers region can be simulated with bodies that extend to a maximum of 7 km depth, as suggested by the tight gradients. These gradients are especially evident along the northwestern side of the Mt. Hannah gravity low where they correspond to gradients in the heat flow anomaly (Fig. 6).

Nineteen prisms with a maximum depth of 7 km were used in constructing the model and these bodies are numbered in Figure 10. The vertical extent of key bodies is indicated along profile AA' in the cross-section below the plan view in Fig. 10(a). The Mt. Hannah low and part of its extension into the production area were modeled with a large prism (body no. 6) of -0.07 gm/cc density contrast (assuming background densities of 2.7 gm/cc in the Franciscan Assemblage). An additional contrast of -0.1 gm/cc (body no. 1) was incorporated in the area of the thick section of Mesozoic argillites previously modeled by Stanley and Blakely (1995). A small, shallow additional prism of -0.07 contrast (body no. 3) was located directly near Mt. Hannah to explain the bullseye part of the gravity low, which is related to thick Clear Lake Volcanics on Mt. Hannah.

The granitic pluton in the production area was modeled with a -0.07 contrast (body no. 2) to the background density (2.7 gm/cc) and to a depth of 4.5 km. We infer that the granitic intrusion has densities of less than 2.6 gm/cc (but velocities of 5.75-6.25 km/s) and intruded metagraywacke and greenstone with densities of about 2.7 and 2.8 g/cc, respectively (Blakely and Stanley, 1995). Stewart and Peselnick (1977) found P-velocities for dry Franciscan metamorphic rocks of 5.2 to 5.8 km/s for pressures equivalent to the upper 5 km. Birch (1961) measured P-velocities of 5.84-6.35 km/s in laboratory granitic rocks, thus the tomographic velocities are very reasonable for the rocks involved. The dichotomy of higher velocity and lower density in the granitic pluton than in surrounding Franciscan assemblage rocks may be explained by distinctions between fracture density/velocity and grain density/velocity. The metasedimentary and metavolcanic rocks of the Franciscan assemblage have high grain densities that may affect the gravity values more than the fracture content. The unconnected high grain densities do not affect the seismic velocities quite so dramatically. In addition, intense fracturing in the upper parts of the pluton and intruded rocks may not be sampled well in the tomographic model, but highly influence the gravity data.

The extension of the broad low (-5 contour SE of The Geysers) and bounding gradients were modeled with body no. 6. The narrow "thumb" with sharp horizontal gradients that extends from the Mt. Hannah low into the northern part of Clear Lake (see Fig. 2 also) was modeled with a small prism (body no. 5) with contrast -0.14 gm/cc. Bodies 7 and 9 with negative contrasts and bodies 4, 8, 13, and 18 with positive contrasts were added to complete a simulation of the gravity signatures of the region. The strong northeast trending gradients on the northwest side of the Mt. Hannah and production area gravity lows require large, shallow density contrasts.

Bodies 1 and 6 correspond to a negative density contrast between Mesozoic argillites and Franciscan Assemblage metasedimentary and metavolcanic rocks. Body 5 is assumed to be a thick section of Tertiary and Quaternary sedimentary and volcanic rocks in a small graben near Clear Lake.

The narrow, negative body no. 19 that trends in a northeast direction was required to sharpen northeast-trending gradients. We interpret that this body represents a density contrast between low-density Tertiary and Quaternary sedimentary rocks on the northwest and higher-density Clear lake Volcanic and Mesozoic melange units to the southeast of the Wight Way fault (Fig. 3). The positive density contrasts of bodies 4 and 18 correspond to the velocity high just northwest of Clear Lake and may be related to high-metamorphic grade schists or mafic components such as greenstone in the Franciscan assemblage..

The model illustrates that no density contrasts below a depth of 7 km are required to fit the gravity field in The Geysers-Clear Lake area. In fact, the narrow gradients evident around the Mt. Hannah low require that most of the density contrast be in the upper several, as demonstrated in ideal body analysis by Blakely and Stanley (1995). We do not interpret this result to mean that there are no small intrusions or magma bodies not mapped by other data, rather that the signature of such features may be swamped by the known density contrasts of the complex upper crustal geology. In addition, we assume that there is a primary lower-crustal magma chamber, but in the form of a deep crustal layer with vertical mafic-silicic zonation that would make the gravity signature difficult to recognize below the strong horizontal gradients caused by upper crustal density contrasts.

MAGNETOTELLURIC MODELS

Stanley and Blakely (1995) reviewed past electrical and electromagnetic geophysical research in The Geysers-Clear Lake region, including the direct-current (DC) mapping study that outlined the thick section of partially drilled Mesozoic argillite whose density contrast dominates the Mt. Hannah gravity low. They compiled a geoelectrical cross-section through the region utilizing a combination of DC mapping and sounding data, time-domain electromagnetic soundings, and magnetotelluric soundings. The magnetotelluric data are inconsistent with the existence of a large magma chamber under the Mt. Hannah region above a depth of 15 km. Two new magnetotelluric profiles have been completed across the region as part of a broad crustal study. One of the profiles is indicated (AA') in Fig. 3, extending from the coast into the western part of the Great Valley.

The MT data from profile AA' was modeled using the 2D inversion algorithm of Smith and Booker (1991) and the results are shown in Fig. 11. The model confirms earlier geoelectrical results reviewed in Stanley and Blakely (1995) that the central Franciscan Assemblage in The Geysers-Clear Lake area has resistivities of about 40-100 ohm-m. Some less-metamorphosed, western Franciscan assemblage sandstone and shale near the coast have resistivities in the 10-20 ohm-m range as do meteorically flushed metagraywacke-argillite and serpentinite-rich melange units directly below the Clear Lake Volcanic Field, Borax Lake, and Sulphur Bank Mine. Mesozoic argillites, and Tertiary and Quaternary sedimentary rocks have lower resistivities of 2-20 ohm. Conductive units of up to 4 km thick west of The Geysers include both younger, western Franciscan assemblage (Tertiary-Cretaceous) and Tertiary-Quaternary basin sediments. Deeper resistivities of 40-100 ohm-m represent the typical Franciscan assemblage basement that can include altered mafic crust.

The granitic pluton in The Geysers area is the cause of higher resistivities at depths of 3-10 km. The upper, fractured part of the Quaternary granitic pluton is indistinguishable from the moderately resistive Mesozoic Franciscan assemblage. This electrical determination is based largely on the results of two MT soundings, but agrees with the seismic tomography model as shown in Fig. 9(c,d) where high velocities (>5.75 km/s) extend to within 2-3 km of the surface. The 5 km thick section of Mesozoic argillites in the Mt. Hannah area has resistivities of 2-5 ohm-m as previously interpreted by Stanley and Blakely (1995). he upper 3-4 km of the argillite section were penetrated in the Wilson No. 1 and Neasham No. 1 geothermal wells. On the east end of the profile, the model indicates a >10 km thick conductive section inferred to be lower Cretaceous Great Valley Sequence between the Bartlett Springs fault and Coast Range thrust. A section of Great Valley Sequence between these two structures fits with the interpretation of Phipps and Unruh (1992) in their model of crustal wedging beneath imbricate roof-thrusts. One of the seismic reflection profiles that Phipps and Unruh (1992) utilized in their interpretation was located parallel to our MT profile AA' and approximately 17 km to the south. The projected location of the seismic profile (Ramirez, 1992) is indicated on the MT model of Fig. 11 and data coverage was from just west of the Coast Range thrust to a point approximately 26 km to the east. Lower Cretaceous Great Valley Sequence rocks were interpreted by Ramirez (1992) to extend to a two-way travel time of 4 seconds, or approximately 10-12 km depth. West of the Coast Range thrust, basement deepens to greater than 13-15 km depth (two-way times of >5 seconds). This is in relatively good agreement with the MT model, although the interpreted depths are somewhat larger on the MT interpretation. The MT data have relatively poor resolution on the depth to the bottom of the conductive section above seismic basement due to its large thickness and possible poor contrast with the altered mafic rocks in the basement, but the general picture is in agreement with geological models and seismic reflection interpretations.

PLATE TECTONICS AND EXTENSIONAL ZONE

Because Quaternary volcanism in the California Coast Ranges is believed to be related to passage of the Mendocino triple junction, it is important to know more about its paleo-geometry. Several pieces of evidence may be used to map the past and present positions of the Gorda Plate, the plate just north of the MTJ. As in other plate motion studies, the most useful information about past positions of the Gorda Plate comes from analysis of offshore magnetic anomalies (stripes). Riddihough (1980) has studied motions of the Gorda Plate and the entire Juan de Fuca system (Riddihough, 1984) using such analyses. Riddihough (1980) found significant variations in spreading rates and directions in time and space along the Gorda Ridge. He interpreted from magnetic anomaly analysis that the Gorda Plate had strong oblique convergence in the interval 4.5 Ma to 2.5 Ma, but ceased underthrusting of the overlying America Plate at about 2 Ma and starting moving in a northerly relative direction. Smith and Knapp (1979) interpreted that the Gorda Plate is currently shearing along approximately northerly vertical strike-slip fractures and not underthrusting the North American plate. In a later paper Riddihough (1984) interpreted that the southern part of the Gorda Plate developed a clockwise rotation from 3 to 1 Ma. Furthermore, he found evidence for an increase in absolute motion at 0.5 Ma that he interpreted to be related to welding with the Pacific plate. Atwater and Molnar (1973) estimated the average rate of motion between the Pacific and North American plates at about 5.5 cm/yr for the last 4-6 Ma and Riddihough interpreted a rate of 5.6 cm/yr for the last 1 Ma.

Using back projections of motions of the Gorda plate, we infer that the Sonoma Volcanics (5.3 Ma to 2.9) developed during a period of major changes in triple junction velocity, with a slowing of overall Pacific/America/Juan de Fuca (and Gorda) plate motions (Riddihough, 1984). Clockwise rotation of the Gorda Plate is interpreted by Riddihough (1984) to have occurred between 3 Ma and 0.5 Ma. This rotation and slowing down of overall plate motion may have focused volcanism in the Clear Lake and Sonoma Volcanic fields. If the Gorda Plate became locked to North America subsequent to this rotation and slowing down, then the geometry of the slab window changed radically during this interval. This change in slab window geometry probably caused a thermal transient which was superimposed on the broad, tracking thermal input due to the northward moving slab window. The narrow geometry we infer for the slab window in Fig. 4 could partially explain the northeast migration of youngest volcanism in the Clear Lake Volcanic field. Conditioning of the crust by the superimposed thermal transient could explain a number of anomalous features within our interpreted northeast-trending zone of extension.

Liu and Furlong (1992) have computed numerical models of magma production in a presumed slab window caused by passage of the MTJ. Their models place several constraints on timing of volcanism related to a slab window in the California Coast Ranges. From flow modeling of upwelling asthenosphere they postulate that a 4-5 km-thick layer of basaltic magma may be produced and thermally induced crustal anatexsis occurs mainly in the deep crust (>20 km), as also suggested by Stimac et al. (1992) and Stanley and Blakely (1994). Their numerical models show that incremental magma production following passage of the MTJ should have peaked at about 0.4 Ma post-passage, but continued at lower levels for another 1 Ma. Magma production rates were assumed to be proportional to MTJ migration rate, taken to be 5 cm/yr in their models. Liu and Furlong (1992) note that there is generally a larger than expected interval between passage of the MTJ and Cenozoic volcanism in the Coast Ranges. They interpret that this interval may reflect the time required for crustal melt extraction and transportation. High-viscosity, silicic melt requires longer extraction times. The transportation factor depends upon development of tensional features to allow both low-viscosity mafic and viscous silicic melts to reach the surface. Thus, secondary development of tensional zones in the lee of the MTJ passage may be the most significant factor in the timing of surface volcanism. These factors all combined in the Clear Lake volcanic field and are concentrated in the inferred northeast-trending extensional zone.

ADDITIONAL EVIDENCE FOR A NORTHEAST-TRENDING EXTENSIONAL ZONE

Oppenheimer (1986) demonstrated from earthquake data that The Geysers production area is under active extension, and focal mechanisms have P-axes aligned predominately NE. Stark (1991) demonstrated a direct link between fluid injection in wells in the northern Geysers and induced seismicity. He noted that the induced seismicity tends to spread downward and laterally from the injection wells. He interpreted this effect to be caused by injected fluids flowing as a liquid, driven by hydraulic pressure or by gravity. He also found that where earthquake clusters extended far from the injection wells, the isotopic signature of produced steam indicates that it was produced from flashed injectate. This implies a hot, low-pressure reservoir with numerous deep fractures that allow injectate to spread downward and laterally from injection wells and then be converted to steam in producing wells. We have made a new plot that incorporates seismicity data from 1980-1996 and its correlation with producing wells (Fig. 12). There is a sharp, linear boundary near the northern edge of The Geysers production area that appears to be unrelated to density of geothermal wells. A similar, but less distinct boundary of intense seismicity occurs near the southern boundary of our interpreted extensional zone. The effects of injection in the SE Geysers on induced seismicity appears to be quite different from that in the NW and Central Geysers. Greensfelder (1993) and Enedy et al. (1993) noted that, although large volumes have been injected in study wells in the SE Geysers, the correlation of injection with seismicity is not nearly as clear as in the NW Geysers and that hypocenters are rarely deeper than the bottom of the injection interval. This suggests a much lower degree of deep fracturing than in the NW and Central Geysers within our interpreted extensional zone.

There is a dramatic increase in the amount of total noncondensible gas (NCG) in Geysers production area steam across the projection of the northeast-trending high-velocity toward Mt. Hannah. NCG values increase from less than 2000 ppm to over 10000 ppm in a very short distance across the zone noted by the dashed line in Fig. 8 ("NCG gradient"). In the center of the SE Geysers over the shallowest part of the felsite, total NCG values are only 500-1000 ppm. In the Northwest Geysers production area, values reach > 50,000 ppm. According to Beall and Box (1993), most of the NCG in the produced steam is CO_2. Minor amounts of H_2, CH_4, N_2, NH_3, and H_2S occur. Beall and Box (1993) demonstrate that there has been a dramatic increase in CO_2 production in the production area with by far the highest NCG values occurring in the NW Geysers. They interpret that the NCG originates from a very low pressure reservoir allowing degassing of deep Franciscan basement rocks. We infer that this degassing may be enhanced within the extensional zone that encompasses the NW and Central Geysers and related to increased heating by the younger intrusions that we interpret to occur in a northeast direction. The NCG gradient (Fig. 8) is coincident with a discontinuity in the top of the steam reservoir, with the steam production zone being deeper to the northwest and widening to the northeast and southwest, possibly due to increased fracture permeability in a northeast direction. To the north of the NCG gradient, oxygen-18 values in steam increase from about -6 to over +2 percent permil standard mean ocean water (SMOW).

Study of water phase tracers injected into production area wells (Box and Beall, 1989; Beall et al., 1989) indicate that the injection fluids move downward to the impermeable granitic pluton where they generally followed the intrusion fall line. However, vapor phase injection tracers, which were unburdened by gravity, tended to move rapidly in a northeast direction along the dominant fracture direction (pers. comm., D. Faulder, Idaho National Engineering Laboratory, 1996). A tracer test in the Southeast Geysers, known as the C-11 test, is interpreted to show that enhanced steam permeability occurs along fractures striking N20-30°E (Beall et al., 1993). Although the major structures, including faults and the granitic pluton, strike northwest, Beall and Box (1991) demonstrated that fracture permeability is enhanced in north-northeast directions as a consequence of east-west dilation of high-angle fractures. The high-angle fractures are apparently related to breaking of Franciscan Assemblage rocks along original weak zones and the younger dilation is due to the orientation of maximum compressive stress in a northeast direction. Drilling in parts of the Northwest Geysers production area has been found to be most successful along a zone of enhanced transmissibility associated with a northeast-trending fault zone.

SUMMARY OF EVIDENCE FOR A NORTHEAST EXTENSIONAL ZONE

In summary, the boundaries we infer on a northeast-trending extensional zone are defined by the following lines of evidence:

(1) As noted by Eberhart-Phillips (1988), there is a distinct zone of northeast trending seismicity from The Geysers production area that crosses the southern arm of Clear Lake (Fig. 5 and 6);

(2) More intense and downward propagating induced seismicity occurs in the Northwest and Central Geysers within the inferred northeast-trending extensional zone (Fig. 12). The boundary for this seismicity on the northwest is very linear and not related to a particular sequence of wells, possibly related to a northeast-trending fracture system.

(3) Narrow, north and northeast linear zones of late Pleistocene to Recent volcanic vents and surficial thermal manifestations (Fig. 6 and 8);

(4) Northeast-trending boundaries of the rectangular Mt. Hannah gravity low(Fig. 2 and 10);

(5) Steep gradients and northeast extension of heat flow and temperature gradient contours(Fig. 6 and 8);

(6) Electrical resistivity lows centered at Mt. Hannah and Borax Lake and high temperatures in both these locations;

(7) Extension of a high velocity anomaly associated with the production area pluton northeast to Mt. Hannah and other, possibly isolated high-velocity features extending further along this azimuth;

(8) Steep gradients for total noncondensible gas values with much higher values in the NW Geysers. A positive shift in oxygen isotope values also occurs within our interpreted extensional zone. ^{3}He anomalies indicative of magmatic processes also occur in the northeast-trending extensional zone. In addition, vapor phase tracer tests show rapid movement in a northeast direction.

(9) A sharp change in the top of steam depth across a northeast axis occurs near Cobb Mountain;

(10) Northeast-trending faults in the Northwest Geysers production area, such as the Caldwell Pines fault, indicate offsets of the obviously older northwest trending fault system. Vein azimuths and other ore deposit information show the influence of the northeast-trending extensional zone.

The available data suggest that this northeast-trending extensional zone has played a fundamental role in induced and natural seismicity, northeast stepping magmatism, heat flow, geologic parameters that affect gravity and electrical data, and in reservoir production and geochemical factors. Although the original tectonic grain was northwest from accretionary processes and the dominant strike-slip is northwest oriented, Recent extension has occurred in the direction of maximum horizontal compression, controlling many of the magmatic and tectonic features that are important to geothermal development.

SUMMARY AND DISCUSSION OF EXPLORATION STRATEGY

The productive Geysers steam reservoir evolved for a variety of geologic reasons. Multiple pulses of silicic intrusive activity during the Pleistocene occurred originally along a northwest-trending extensional feature near the corner of the Gorda plate in a large slab of brittle metagraywacke. Intrusive activity then continued without significant interruption along a right-stepping, northeast zone into the Mt. Hannah region. After this major episode, intrusions, mineral deposition and volcanism became more intermittent but continued into the Recent era and migrated to the northeast across the southern arm of Clear Lake and possibly as far as Wilbur Springs. The original large granitic intrusion ("felsite") in the production area caused a fracture and metamorphic halo in the brittle metagreywacke and other rocks of the Franciscan assemblage. Natural recharge into the geothermal reservoir was allowed by nearby thick, permeable volcanic flows like those on Cobb Mountain that are directly in contact with the fractured Franciscan assemblage rocks (Truesdell et al., 1993) and vent areas such as the Little Geysers (Walters et al., 1992).

There are indications of three or more Recent intrusions in the NE-trending extensional zone: (1) in the Northwest Geysers between Caldwell Pines and Tyler Valley (Fig. 3); (2) in the Clear Lake Volcanic Field in the areas of Mount Hannah and Thurston Creek; (3) a small one near Sulphur Bank Mine, and possibly one at Wilbur Springs. Most warm springs within the Clear Lake Volcanic field are within the proposed boundaries of the NE- trending extensional zone and a majority of the local mineral deposits are within this zone.

There have been approximately 10 geothermal exploration wells drilled in the area of Thurston Creek, Mount Hannah and Sulphur Bank Mine but commercially viable production capability has not been demonstrated due to insufficient permeability in the upper 3 km penetrated by these wells. For this reason, the southern Clear Lake area has been discussed as a hot, dry rock (HDR) exploration target (Stimac, et al., 1992; Goff et al., 1993; Burns and Potter, 1993). Goff et al. (1993) conclude that high temperatures with little fluids occur in most wells drilled in the Clear Lake region and that HDR technologies have the best chance for commercial success in the region. However, HDR potential may also be limited because of the known thick, argillite-rich melange sections at reservoir depths of 2 to 3 km.

In the Mt. Hannah region, thick ductile argillite sections of Mesozoic tectonic melange do not support vertical fracture systems coincident with the high temperatures in the drilled portion of the northeast-trending extensional zone. Sections of argillite-rich melange are cap rocks to the reservoir in The Geysers reservoir due to their low permeability and do not produce steam except in very rare instances. However, mixed in with the argillic melange may be isolated bodies of sandstone, fractured greenstone or other units that could have locally enhanced permeabilities and serve as productive reservoirs. The favorable situation for low-pressure which permits steam production in The Geysers area developed because of the extensive brittle fracturing, venting and high temperatures which rapidly boil off connate waters to produce single-phase steam as the primary fracture-filling fluid. One of the goals for future exploration in the high-temperature region near the southern part of Clear Lake should be to evaluate seismicity patterns, geological, geochemical, and geophysical data in order to locate brittle parts of the Franciscan assemblage that have been fractured to create zones of vertical and horizontal permeability. We are of the opinion that there are large areas where not enough drilling has been done to rule out the southern Clear Lake region as a potential high-temperature reservoir resource. Environmental problems may be a more severe hindrance to development of a resource here (Walters et al., 1992; Burns and Potter, 1993; Goff et al., 1993).

We have interpreted that there is no large, upper crustal or midcrustal magma body, although there is concentrated heat flow within the NE-trending extensional zone from 4 to 12 HFU, and inferred that intrusive bodies within the zone are small and somewhat localized. The evidence for such small features are indicated in surface alteration and hot springs. Chalk Mountain (Fig. 3), where small local Recent intrusions are in evidence, is one example. However, shallow temperature gradient and heat flow data are NOT indicative of a high-temperature (240° C) geothermal reservoir within 3 or 4 km of the surface at Chalk Mountain. Consequently, it is necessary to have adequate temperature and heat values prior to an attempt to drill into a high-temperature reservoir. The high-temperature wells drilled to date within the NE-trending extensional zone (Fig. 3) are suggestive of young, localized intrusions into less fractured rocks than at The Geysers.

Relatively undrilled areas with exploration potential include the Northwest Geysers near the current production area. The Northwest Geysers has the fewest environmental problems because of its remote location and large land holdings. Here, there is metagraywacke known at potential reservoir depth. A dacite plug dated at 0.8 Ma (Donnelly, 1977) 5 km northwest of the production area in Tyler Valley (Fig. 3), together with the indications of Recent magmatism and 260• C temperatures in the Bud Taylor #3 well (Hulen and Moore, 1995), are evidence of multiple intrusive phases in the last 1 Ma. Although the temperatures in Bud Taylor #3 are sufficient to support a steam reservoir, the temperature gradients in this well indicate conductive heat flow and the metagraywacke appears to be unmineralized and isotopically unexchanged (Hulen and Moore, 1995). These results are indicative that a convective hydrothermal system is missing at Bud Taylor #3. Location of a nearby intrusive heat center where fracturing of the brittle metagraywacke occurs represents the challenge for future exploration in The Geysers region.

The combination of a variety of geophysical methods has allowed us to refine the heat source model of the region primarily de-emphasizing the concept of a single large magma chamber and by definition of the influence of a northeast-trending extensional zone. Detailed geologic, geochemical, temperature, and drilling data support the importance of this extensional zone. We have also outlined the parts of the extensional zone that appear to be most promising for future exploration, but much remains to be done to refine our model of heat source development. High resolution electrical, magnetic, and gravity studies, seismic reflection and active tomographic imaging, additional geochemical and microtectonic studies, and new heat flow measurements would all be useful in locating the centers of small, hot, intrusive bodies and permeable zones needed for future exploratory drilling targets..

ACKNOWLEDGMENTS

The work of MAW is supported by the U.S. Department of Energy, Assistant Secretary for Energy Efficiency and Renewable Energy through Lockheed Idaho Technologies Company subcontract C96-176014 and DOE Idaho Operations Office contracts DE-AC07-96ID13223. Funding for the USGS co-authors was provided by the Geothermal Research Program of the USGS.

REFERENCES

Atwater, T., and Molnar, P., 1973, Relative motion of the Pacific and North American plates deduced from sea floor spreading in the Atlantic, Indian, and South Pacific Oceans: in Kovach, R. L., and Nur, A., eds., Proceedings of the conference on tectonic problems of the San Andreas fault system, Stanford University, Publications in the Geological Sciences, v. 13, 136-148.

Bailey, E.H., 1946, Quicksilver Deposits of the Western Mayacmas District, Sonoma County, CA, California Bureau of Mines, Report 42 of the State Mineralogist, pp.200-230.

Bailey, E. H., W. P. Irwin. and D. L. Jones, 1964, Franciscan and related rocks and their significance in the geology of western California: California Division of Mines and Geology Bulletin 183, 177p.

Beall, J. J., 1985, Exploration of a high temperature, fault localized, nonmeteoric geothermal system at The Sulphur Bank Mine, California: Transactions of the Geothermal Resources Council, 9, 395-401.

Beall, J.J., Enedy, S., and Box, W.T., 1989, Recovery of Injected Condensate as Steam in the South Geysers Field, Geothermal Resources Council Transactions, v.13, pp.351-358.

Beall, J. J., and Box, W. T., Jr., 1991, The nature of steam-bearing fractures in the south Geysers reservoir: Geothermal Resources Council, Monograph on The Geysers Geothermal Field, Special Report No. 17, 69-75.

Beall, J.J., and Box, W.T., Jr., 1993, The future of noncondensible gas in the southeast Geysers steamfield: Geothermal Resources Transactions, 17, 221-225.

Benz, H. M., G. Zandt, and D. H. Oppenheimer, 1992, Lithospheric structure of northern California from teleseismic images of the upper mantle: Journal of Geophysical Research, 97, B4, 4791-4807.

Benz, H. M., Chouet, B. A., Dawson, P. B., Lahr, J. C., Page, R. A., and Hole, J. A., 1996, Three-dimensional P and S wave velocity structure of Redoubt volcano, Alaska: Journal of Geophysical Research, 101, B4, 81111-8128.

Blakely, R. J., and Stanley, W. D., 1995, The Geysers magma chamber, California: constraints from gravity data, density measurements and well information: Geothermal Resources Transactions, 17, 227-234.

Bufe, C. G., S. M. Marks, F. W. Lester, R. S. Ludwin, and M. C. Stickney, 1981, Seismicity of The Geysers-Clear Lake region: in U. S. Geological Survey Professional Paper 1141, Research in The Geysers-Clear Lake Geothermal Area, Northern California, p. 129-138.

Burns, K. L., and Potter, R. M., 1993, Potential geothermal development near the city of Clearlake, California: Geothermal Resources Council Transactions, 17, 317-323.

Castillo, D. L., and Ellsworth, W. L., 1993, Seismotectonics of the San Andreas fault system between Point Arena and Cape Mendocino in northern California: implications for the development and evolution of a young transform: Journal of Geophysical Research, 98, 6543-6560.

Ciancanelli, E.V., 1970, Geologic Map of the Mount Konocti Prospect, Geothermal Resources International, 1 map sheet.

Ciancanelli, E.V., 1976, Geology of the Barceloux Lease, Lake County, CA, unpublished report for Phillips Petroleum Company, in: Johnson, S.D., Feb. 15, 1979, Borax Lake 7-1 Well Summary, Borax Lake Prospect, Lake County, CA, 19p. + maps and figures.

Dalrymple, G. B., 1992, Preliminary report on 40Ar/39Ar incremental heating experiments on feldspar samples from the felsite unit, Geysers geothermal field, California: U.S. Geological Survey Open-File Report 92-407, 15 p.

Dickinson, W. R., 1970, Clastic sedimentary sequence deposited in shelf, slope, and trough settings between magmatic arcs and associated trenches: Pacific Geology, v. 3, p. 15-30.

Dickinson, W. R. and W. S. Snyder, 1979, Geometry of triple junctions related to the San Andreas transform: Journal of Geophysical Research. v. 84, 561-572.

Donnelly, J.M., 1977, Geochronology and Evolution of the Clear Lake Volcanic Field, Ph.D. Dissertation, Univ. of Calif., Berkeley, 48p.

Donnelly-Nolan, Julie M. and B. Carter Hearn, Jr., 1981, Geochronology and evolution of the Clear Lake volcanics: in U. S. Geological Survey Professional Paper 1141, Research in The Geysers-Clear Lake Geothermal Area, Northern California, p. 47-60.

Eberhart-Phillips, Donna, and Oppenheimer, D. H., 1984, Induced seismicity in The Geysers geothermal area, California: Journal of Geophysical Research, 89, 1191-1207.

Eberhart-Phillips, Donna, 1986, Three-dimensional velocity structure in northern California Coast Ranges from inversion of local earthquake arrival time: Bulletin of the Seismological Society of America, 76, no. 4, 1025-1052.

Eberhart-Phillips, Donna, 1988, Seismicity in the Clear Lake area, California, 1975-1983: in Geological Society of America Special Paper 214, ed. John D. Sims, p. 195-206.

Enedy, S. L., Smith, J. L., Yarter, R. E., Jones, S. M., and Cavote, P. E., 1993, Impact of injection on reservoir performance in the NCPA steam field at The Geysers: Stanford Geothermal Program Eighteenth Annual Workshop in Geothermal Reservoir Engineering, January 26-28, Stanford University, 125-134.

Fournier, R. O., 1991, The transition from hydrostatic to greater than hydrostatic fluid pressure in presently active continental hydrothermal systems in crystalline rock: Geophysical Research Letters, 18, 955-958.

Goff, F.E., Donnelly, J.M., Thompson, J.M., Hearn, B.C., Jr., 1977, Geothermal Prospecting in The Geysers-Clear Lake Area, Northern California, Geology, v.5, pp.509-515.

Goff, F., Decker, E. R., 1983, Candidate sites for future hot dry rock development in the United States: Journal of Volcanology and Geothermal Resources, 15, 187-221.

Goff, Fraser, Kennedy, B. M., Adams, A. I., Trujillo, P. E., and Counce, Dale, 1993, Hydrogeochemical evaluation of conventional and hot dry rock geothermal resource potential in the Clear Lake Region, California: Geothermal Resources Council Transactions, 17, 335-342.

Goff, F. and Janik, C.J., 1994, Gas Geochemistry and Guide for Geothermal Features in the Clear Lake Region, CA, in: Rytuba, J.J., ed., Active Geothermal Systems and Gold-Mercury Deposits in the Sonoma-Clear Lake Volcanic Fields, CA, Society of Economic Geologists, Guidebook Series, v.16, pp. 207-261.

Graham, S. A. , McCloy, C., Htzman, M., Ward, R., Turner, R., 1984, Basin evolution during change from convergent to transform continental margin in central California: American Association of Petroleum Geologists, 68, 233-249.

Greensfelder, R. W., 1993, New evidence of the causative relationship between well injection and microseismicity in The Geysers geothermal field: Geothermal Resources Council Transactions, 17, 243-247.

Gunderson, R. P., 1991, Distribution of oxygen isotopes and noncondensible gas in steam at The Geysers: Monograph on The Geysers Geothermal Field, Special Report No. 17, Geothermal Resources Council, 133-143, Davis, CA.

Hearn, B. Carter, Jr., J. M. Donnelly-Nolan, and F. E. Goff, 1981, The Clear Lake Volcanics: Tectonic setting and magma sources: in U. S. Geological Survey Professional Paper 1141, Research in The Geysers-Clear Lake Geothermal Area, Northern California, p. 25-46.

Hearn, B. Carter, Jr., R. J. McLaughlin, and J. M. Donnelly-Nolan, 1988, Tectonic framework of the Clear Lake basin, California: Geological Society of America Special Paper 214.

Hodges, C.A., 1966, Geomorphic History of Clear Lake, CA, Ph.D. Dissertation, Stanford University, CA, 171p.

Hole, J. A., 1992, Nonlinear high-resolution three-dimensional seismic travel time tomography: Journal of Geophysical Research, 97, 6553-6562.

Hulen, J. B. and D. L. Nielson, 1993, Interim report on geology of The Geysers felsite, northwestern California: Geothermal Resources Transactions, 17, 249-258.

Hulen, J.B. and Walters, M.A., 1994, The Geysers Felsite and Associated Geothermal Systems, Alteration, Mineralization, and Hydrocarbon Occurrences, in: Rytuba, J.J., ed., Active Geothermal Systems and Gold-Mercury Deposits in the Sonoma-Clear Lake Volcanic Fields, CA, Society of Economic Geologists, Guidebook Series, v.16, pp. 141-152.

Hulen, J.B. and Moore, J.N., 1995, Secondary Mineralogy and Oxygen-Isotope Geochemistry of Two Peripheral Steam-Exploration Boreholes at The Geysers Geothermal Field, Geothermal Resources Council Transactions, v.19, pp.451-456.

Hulen, J. B. and Nielson, D. L., 1996, The Geysers felsite: Geothermal Resources Council Transactions, 20, 295-306.

Ingersoll, R. V., E. I. Rich, and W. R. Dickinson, 1977, Field trip guide to the Great Valley sequence: Geological Society of America, Cordilleran Section, Annual Meeting, 73d, 72 p.

Isherwood, W. F., 1975, Gravity and magnetic studies of The Geysers-Clear Lake geothermal region, California:Second U. N. Symposium on Development and Use of Geothermal Resources, San Francisco, CA, Proceedings, v. 2, p. 1065-1073.

Iyer, H. M., Oppenheimer, D. H, Hitchcock, Tim, Roloff, J. N and Coakley, J. M (1981) Large teleseismic P-wave delays in The Geysers-Clear Lake geothermal area. in R. J. McLaughlin and J. M. Donnelly-Nolan (eds.), U. S. Geological Survey Professional Paper 1141, Research in The Geysers-Clear Lake Geothermal Area, Northern California, 97-116.

Jachens, R. C. and A. Griscom, 1983, Three-dimensional geometry of the Gorda plate beneath northern California: Journal of Geophysical Research, v. 88, p. 9375-9392.

Johnson, S.D., Feb.15, 1979, Borax Lake 7-1 Well Summary: Borax Lake Prospect, Lake County, CA, unpublished Phillips Petroleum Company report, 19p. + maps, tables and appendices.

Julian, B. R., Ross, A., Foulger, G. R., and Evans, J. R., 1996, Three-dimensional seismic image of a geothermal reservoir: The Geysers, California: Geophysical Research Letters, 23, 685-688.

Lachenbruch, A. H. and J. H. Sass, 1980, Heat flow and energetics of the San Andreas fault zone: Journal of Geophysical Research, 85, 6185-6222.

Lallatin, R.D., 1975, Clear Lake Water Quality Data, CA Dept. of Water Resources, Northern District, 319p.

Liu, Mian and K. P. Furlong, 1992, Cenozoic volcanism in the California Coast Ranges: numerical solutions: Journal of Geophysical Research, 97, 4941-4951.

Ludwin, R. S., Cagnetti, V., and Bufe, C. G., 1982, Comparison of seismicity in The Geysers geothermal area with the surrounding region: Bulletin of the Seismological Society of America, 72, 863-871.

Martin, R.C., 1976, Clear Lake Geothermal Gradient Survey, in: Geothermal Investigations of California Submerged Lands and Spherical Flow in Naturally Fractured Reservoirs, CA State Lands Commission, Part C, 12p. + 19 figures.

McLaughlin, R. J., and Pessagno, E. A., 1978, Significance of age relations above and below Upper Jurassic ophiolite in The Geysers-Clear Lake region, California: U.S. Geological Survey Journal of Research, 6, 715-726.

McLaughlin, R. J., 1981, Tectonic setting of pre-Tertiary rocks and its relation to geothermal resources in The Geysers-Clear Lake area: in U. S. Geological Survey Professional Paper 1141, Research in The Geysers-Clear Lake Geothermal Area, Northern California, p. 3-24.

McLaughlin, R. J., and Donnelly-Nolan, J. M., editors, 1981, Research in the Geysers-Clear Lake geothermal area: U.S. Geological Survey Professional Paper 1141.

McLaughlin, R. J., and H. N. Ohlin, 1984, Tectonostratigraphic framework of The Geysers-Clear Lake region, California: in Blake, M. C., Jr., ed., Franciscan Geology of Northern California, Pacific Section S.E.P.M., v. 43, p. 221-254.

McNitt, J.R., 1968, Geology of the Clearlake Oaks 15-Minute Quadrangle, Lake County, CA, CA Div. of Mines and Geology, open-file, 1 map sheet.

Nielson, D. L., Walters, M. A., and Hulen, J. B., 1991, Fracturing in the Northwest Geysers, Sonoma County, California: Geothermal Resources Council Transactions, 15, 27-31.

Nielsen, D. and Nash, G., 1996, unpublished ESRI-enhanced thematic mapping imagery with interpreted fault structure, presented at DOE Annual Review, Berkeley Marriott Hotel, April 9-11, 1996.

Oppenheimer, D. H. and Herkenhoff, K. E. (1981) Velocity-density properties of the lithosphere from three-dimensional modeling at The Geysers-Clear Lake region, California. Journal of Geophysical Research, 86, p. 6057-6065.

Oppenheimer, D. H., 1986, Extensional tectonics at The Geysers geothermal area, California: Jounral of Geophysical Research, 91, 11,463-11,476.

Phipps, S. P., and Unruh, J. R., 1992, Crustal-scale wedging beneath an imbricate roof-thrust system: geology of a transect across the western Sacramento Valley and northern Coast Ranges, California: Field Guide to the Tectonics of the Boundary Between the California Coast Ranges and the Great Valley of California, Pacific Section of the American Association of Petroleum Geologists, GB-70, 117-140.

Phillips Petroleum Company, September, 1979, Evaluation of the Geothermal Potential of GRI Leases East of Borax Lake, unpublished report, 14p.+ appendices and maps.

Podvin, P. and Lecomte, I., 1991, Finite difference computation of travel-time in very contrasted velocity models: a massively parallel approach and its associated tools: Geophysical Journal International, 105,271-284.

Pulka, F.S., 1991, Recent Intrusives at Ford Flat and Relationships to Faulting and the Geothermal Heat Source, Geysers Geothermal Field, CA, Geol. Soc. of America Abstracts with Program, v.23, no.2, p.90.

Ramirez, V. R., 1992, Geology and deep structure of the Rumsey Hills area, Sacramento Valley, California: Field Guide to the Tectonics of the Boundary Between the California Coast Ranges and the Great Valley of California, Pacific Section of the American Association of Petroleum Geologists, GB-70, 85-94.

Rich, E.I., 1971, Geologic Map of the Wilbur Springs Quadrangle, Colusa and Lake Counties, CA, USGS Misc. Geologic Investigations Map I-538, 1:48,000 map sheet.

Rich, E.I. and Steele, W.C., 1974, Speculations on Geologic Structures in Northern California as Detected from ERTS-1 Satellite Imagery, Geology, v.3, pp.165-169.

Riddihough, R. P., 1980, Gorda plate motions from magnetic anomaly analysis: Earth and Planetary Science Letters, 51, 163-170.

Riddihough, R. P., 1984, Recent Movements of the Juan de Fuca Plate System: Journal of Geophysical Research, 89, B8, 6980-6994.

Ross, C.P., 1940, Quicksilver Deposits of the Mayacmas and Sulphur Bank Districts, CA, USGS Bulletin 922-L, pp.327-353.

Rymer, M.J., 1978, Stratigraphy of the Cache Formation (Pliocene and Pleistocene) in Clear Lake Basin, Lake County CA, USGS Open-file Report 78-924, 102 p. + maps.

Rytuba, J.J., Donnelly-Nolan, J.M. and McLaughlin, R.J., 1994a, The Geysers Geothermal Area and Mercury Deposits in the Clear Lake Volcanic Field: Road Log, in: Rytuba, J.J., ed., Active Geothermal Systems and Gold-Mercury Deposits in the Sonoma-Clear Lake Volcanic Fields, CA, Society of Economic Geologists, Guidebook Series, v.16, pp.153-170.

Rytuba, J.J., Donnelly-Nolan, J.M. and McLaughlin, R.J., 1994b, Hot Springs and Deposits of Mercury and Gold in the Clear Lake Volcanic Field: Road Log, in: Rytuba, J.J., ed., Active Geothermal Systems and Gold-Mercury Deposits in the Sonoma-Clear Lake Volcanic Fields, CA, Society of Economic Geologists, Guidebook Series, v.16, pp.270-288.

Schriener, A., Jr. and Suemnicht, G. A., 1980, Subsurface intrusive rocks at The Geysers geothermal area, California: in Silberman, M. C. et al. (eds.), Proceedings of Symposium on Mineral Deposition in the Pacific Northwest, U.S., U.S. Geological Survey Open File Report 81-355, 294-303.

Sims, J.D. and Rymer, M.J., 1976, Map of Gaseous Springs and Associated Faults in Clear Lake, CA, Miscellaneous Field Studies Map MF-721.

Smith, J. T., and Booker, J. R., 1991, Rapid inversion of two and three-dimensional magnetotelluric data: Jour. Geophys. Res., 96, 3905-3922.

Smith, S. W. and J. Knapp, 1979, Seismic velocity structure, Humboldt Bay, California: in The San Andreas Fault in Northern California, Special Report, California Division of Mines and Geology.

Stanley, W. D. and R. J. Blakely, 1995, The Geysers-Clear Lake geothermal area, California-an updated geophysical perspective of heat sources: Geothermics, 24, no. 2, 187-211.

Stanley, W. D., and Rodriguez, B. D., 1995, A revised tectonic model for The Geysers-Clear Lake Geothermal Region, California:Proceedings of the World Geothermal Congress, International Geothermal Association, Florence, Italy, May, 1995, 1193-1198.

Stanley, W. D., Johnson, S. Y., Qamar, A. I., Weaver, C. S., and Williams, J. M., 1996, Tectonics and seismicity of the southern Washington Cascade Range: Bulletin of the Seismological Society of America, 86, No. 1A, 1-18.

Stark, M. A., 1991, Microearthquakes-a tool to track injected water in The Geysers reservoir: Geothermal Resources Council, Monograph on The Geysers Geothermal Field, Spec. Rept. 17, 111-117.

Stewart, R., and Peselnick, L., 1977, Velocities of compressional waves in dry Franciscan rocks to 8 Kbar and 300° C: Journal of Geophysical Research, 82, 2027-2039.

Stimac, James, Goff, Fraser and Hearn, Jr., B. Carter, 1992, Petrologic considerations for hot dry rock geothermal site selection in the Clear Lake region, California: (abs) Proceedings of the 1992 Annual Geothermal Resources Council Meeting, San Diego, CA, Oct. 4-7.

Thomas, R. P., 1981, Rservoir assessment of The Geysers geothermal field-subsurface geology: Report TR27, California Division of Oil and Gas, Sacramentor, CA, 9-20.

Thompson, R. C., 1992, Structural stratigraphy and intrusive rocks at The Geysers geothermal field: in Geothermal Resources Council Special Report No. 17, Monograph on The Geysers Geothermal Field, 59-64.

Thompson, J.M., 1994, Chemical and Isotopic Constituents in the Hot Springs along Sulphur Creek, Colusa County, CA, in: Rytuba, J.J., ed., Active Geothermal Systems and Gold-Mercury

Deposits in the Sonoma-Clear Lake Volcanic Fields, CA, Society of Economic Geologists, Guidebook Series, 16, 190-206.

Truesdell, Alfred, Walters, Mark, Kennedy, Mack, and Lippman, Marcelo, 1993, An integrated model for the origin of The Geysers geothermal field: Geothermal Resources Council Transactions, 17, 273-280.

Truesdell, A. H., Kennedy, B. M., Walters, M. A., and D'Armone, F., 1995, New evidence for a magmatic origin of some gases in The Geysers geothermal reservoir: Proceeedings of the Nineteenth Workshop on Geothermal Engineering, Stanford University, 297-301.

Vantine, J.V., Dec. 1970, Engineering Geology of the High Valley-Bear Valley Conveyance System, Memorandum Report of the CA Dept. of Water Resources Northern District, 27p.+ maps.

Walters, M.A., Haizlip, J.R., Sternfeld, J.N., Drenick, A.F. and Combs, J., 1991, A Vapor-Dominated High-Temperature Reservoir at The Geysers, CA, in: Stone, C., ed., Monograph on The Geysers Geothermal Field, Geothermal Resources Council, Special Report 17, pp.77-87.

Walters, M.A. and Combs, J., 1992, Heat Flow in The Geysers-Clear Lake Geothermal Area of Northern California, USA, in: Stone, C., ed., Monograph on The Geysers Geothermal Field, Geothermal Resources Council, Special Report 17, pp.43-53.

Walters, M.A., 1995, Generalized Heat Flow, The Geysers-Clear Lake Region, CA, unpublished map, LITCO contract #C95-175505.

Walters, M.A., Moore, J.N., Renner, J.L. and Nash, G.D., 1996, Oxygen Isotope Systematics and Reservoir Evolution of the Northwest Geysers, CA, Geothermal Resources Council Transactions, 20, 413-421.

Williamson, K.H., 1990, Development of a Reservoir Model for The Geysers Geothermal Field, in: Claudia Stone, ed., Monograph on The Geysers Geothermal Field, Geothermal Resources Council, Special Report No.17, pp.77-87.

Yates, R.G. and Hilbert, L.S., 1946, Quicksilver Deposits of the Eastern Mayacmas District, Lake and Napa Counties, CA, California Bureau of Mines, Report 42 of the State Mineralogist, pp.231-286 + plates.

Young, L. G., Kishi, E. H., Campion, L. F., 1983, Preliminary report on the low temperature geothermal resources of Big Valley, Lake Co., CA: California Division of Mines and Geology, Open File Report 83-30, Sacramento, 74 p. and 6 plates.

FIGURE CAPTIONS

Figure 1--Geologic index map of northern California Coast Ranges, with location of The Geysers geothermal area, Clear Lake volcanic field, Sonoma volcanic field, Sutter Buttes, and major strike-slip faults. Modified from McLaughlin (1981).

Figure 2-Geology of The Geysers-Clear Lake area with Bouguer gravity (left) and resistivity (right) anomalies superimposed. Gravity contours are in milligals and resistivity contours are ohm-m. Outline of granitic pluton "the Geysers felsite" at a depth of 5000 feet (1524 m) below sea level in the steam production area is shown by the cross-hatched pattern (from Thompson, 1992). KN=Mt. Konocti; MH=Mt. Hannah; N=Neasham No. 1 well; W=Wilson No. 1 well. Our proposed extensional zone is defined by the barred lines terminated with arrows that point along the boundaries of the zone.

Figure 3-Local index map for The Geysers-Clear Lake region. Important geothermal wells are: Wil=Wilson No. 1; Nea=Neasham No. 1; Jor=Jorgenson No. 1; and Aud=Audrey A-1; Bud=Bud Taylor No. 3. CPF=Caldwell Pines fault; CMF=Cobb Mountain fault; GR=Geysers Resort; BSC=Big Sulfur Creek fault zone. Adapted from Goff et al, 1993, Hulen and Nielson, 1993, and Walters et al., 1996. Gray line labelled AA' is a profile transect used in gravity, magnetic, and magnetotelluric modelling.

Figure 4-Schematic 3D model of magmatism in The Geysers-Clear Lake region adapted from similar cross-section of Stanley and Blakely (1995). Interpreted northeast-trending extensional zone indicated by dashed lines. A thick block of Mesozoic argillitic (mildly metamorphosed shale) rocks centered beneath Mt. Hannah that controls the gravity and electrical anomalies of Fig. 2 is also shown in the sketch, as is the approximate location of the granitic pluton in The Geysers production area. Wilbur Springs is a mineralized, volcanic/geothermal zone (Fig. 3) inferred to be associated with the tectonomagmatic zone extending from the Clear Lake area. Sutter Buttes is a 2-3 Ma volcanic center in the Great Valley.

Figure 5-Seismicity of northern California from USGS Northern California seismic network for period 1970-1996 using best located events with magnitudes >1.5. MA=Maacama fault, BS=Bartlett Springs fault, HD=Healdsburg fault, RC=Rodgers Creek fault, GV=Green Valley fault, SB=Sutter Butte. The rectangle encloses the events and model grid used in regional earthquake tomographic study of this paper. Rows and columns of the model grid are labelled on the rectangle and the four rows which were used for cross-section in Fig. 9 are indicated (33, 38, 43, and 48).

Figure 6-Heat flow, seismicity, and recent basaltic volcanic vents in the Geysers-Clear Lake region. Heat flow contours in heat flow units taken from Walters (1995). Seismicity taken from USGS Northern California seismic network for period 1970-1994 with magnitudes >1.5. Solid squares are the locations of basaltic and basaltic andesite volcanic vents from 0.3-.65 Ma and open squares are vents from 0.01-0.1 Ma (Hearn et al., 1981). Direction of maximum ($\bullet_1$) and least ($\bullet_3$) principal stresses from earthquake focal mechanisms as determined by Bufe et al. (1981) and Oppenheimer (1986) are shown by bold arrows. KHFZ=Konocti Harbor fault zone.

Figure 7-Horizontal velocity slices of finite-difference 3D inversion for study area for elevations above mean sea level of 0 to -1 km, -1 to -2 km, -2 to -3 km, and -3 to -4 km. The surface datum for the model is 2 km above msl. The depths represent values of 2 to 3, 3 to 4, 4 to 5,

and 5 to 6 km below the model datum.

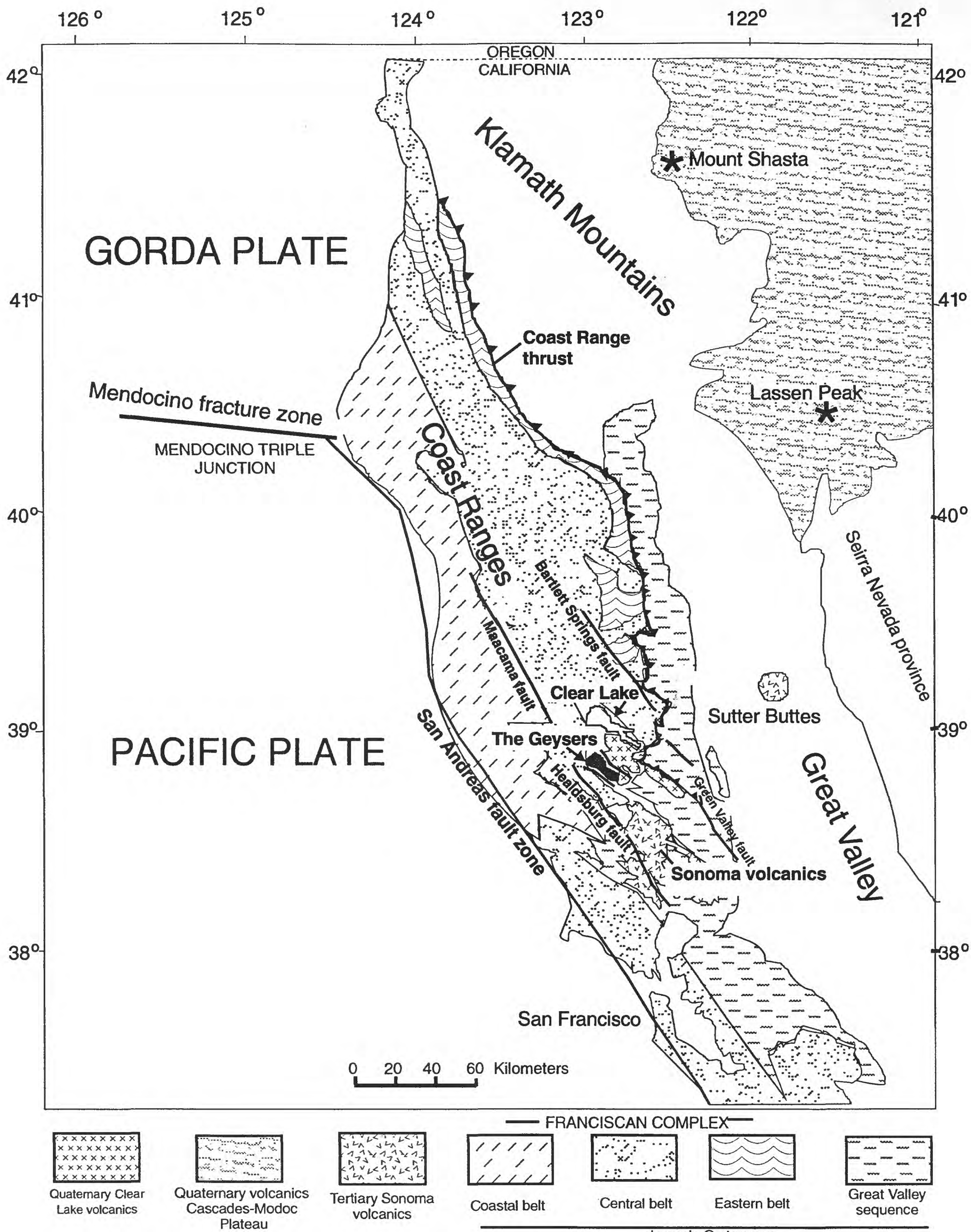
Figure 8-Details of horizontal velocity slice at -2 to -3 km below msl. The white space corresponds to velocities from 5.25 to 5.75 km/s where no closures occurred in the detailed area. Temperature gradient values from data base prepared for the USGS (Walters, 1995) are contoured in °C/km. Only selected contours are shown for clarity. Location of vertical model slices of Fig. 10 are shown as (a), (b), (c), and (d). The narrow box labelled "NCG gradient" represents the trend and location of gradients in noncondensible gases in produced steam discussed in text.

Figure 9-Vertical velocity slices of 3D tomographic model at rows (Fig. 5) 48 (a) , 43 (b), 38 (c), and 33 (d). MFZ=Mercuryville fault zone, DFZ=Collayomi fault zone. Topographic profiles along each of the slices is shown at a vertical exaggeration of 5:1.

Figure 10-(A) Three-dimensional gravity model and cross section along profile AA'; (B) calculated gravity field; and (C) observed isostatic residual gravity field. The white areas are assumed background density of 2.70 gm/cc and patterns represent contrasts with this background as indicated in the legend. The location of the interpreted northeast-trending extensional zone is shown by the barred lines on (c).

Figure 11-2D magnetotelluric model for profile AA' (Fig. 3) and its extensions. Patterns represent resistivity ranges in the model.

Figure 12-Seismicity in The Geysers steam production area with extent of granitic pluton ("felsite") drilled at elevations of 5000 feet (1524 m) below mean sea level (msl). The extent of the steam reservoir at elevations of 3000 below msl. Solid dots are producible wells. NWG= Northwest Geysers; GR=Geysers Resort; CG=Central Geysers; SEG= Southeast Geysers.



126°
125°
124°
123°
122°
121°
42°
41°
40°
39°
38°
OREGON
CALIFORNIA
Klamath Mountains
Mount Shasta
GORDA PLATE
Coast Range thrust
Lassen Peak
Mendocino fracture zone
MENDOCINO TRIPLE JUNCTION
Coast Ranges
Bartlett Springs fault
Seirra Nevada province
Maacama fault
Clear Lake
Sutter Buttes
PACIFIC PLATE
The Geysers
Healdsburg fault
Green Valley fault
Great Valley
San Andreas fault zone
Sonoma volcanics
San Francisco
0 20 40 60 Kilometers
FRANCISCAN COMPLEX
Quaternary Clear Lake volcanics
Quaternary volcanics Cascades-Modoc Plateau
Tertiary Sonoma volcanics
Coastal belt
Central belt
Eastern belt
Great Valley sequence
Jurassic-Cretaceous

Figure 1

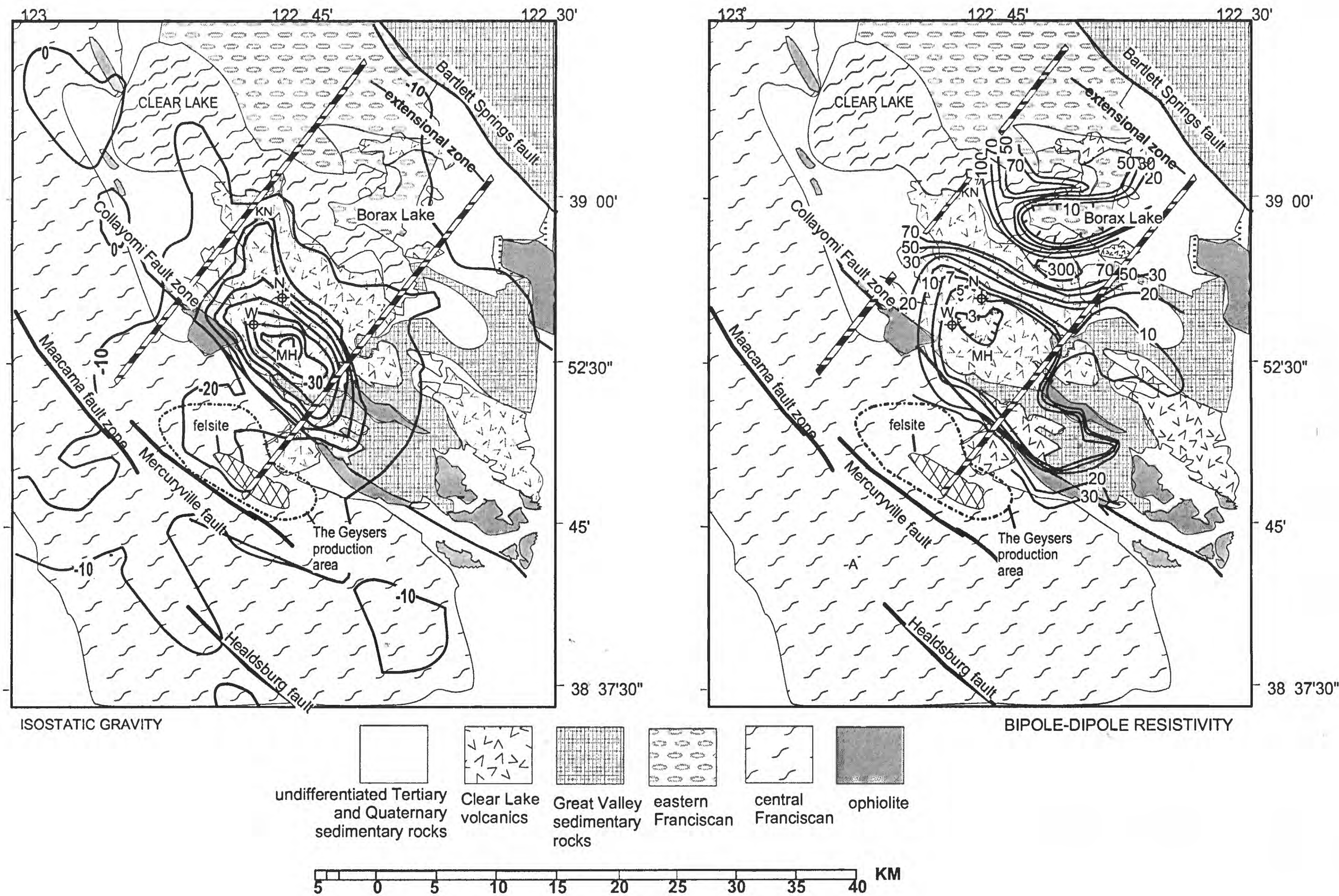
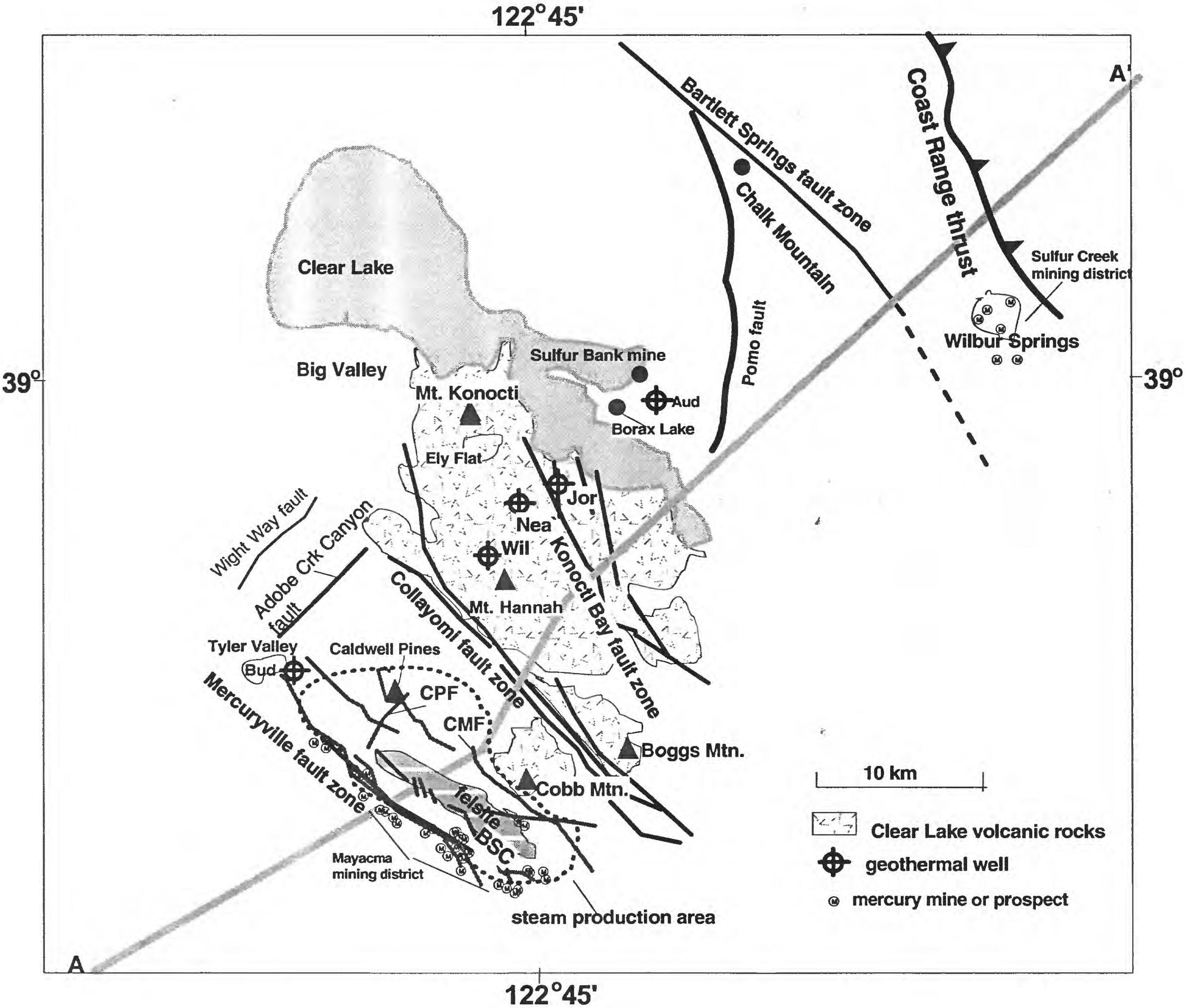

ISOSTATIC GRAVITY
BIPOLE-DIPOLE RESISTIVITY
123°
122° 45'
122° 30'
39° 00'
52'30"
45'
38° 37'30"
CLEAR LAKE
Borax Lake
Bartlett Springs fault
extensional zone
Collayomi Fault zone
Maacama fault zone
Mercuryville fault
Healdsburg fault
felsite
The Geysers production area
KN
N
W
MH
A
undifferentiated Tertiary and Quaternary sedimentary rocks
Clear Lake volcanics
Great Valley sedimentary rocks
eastern Franciscan
central Franciscan
ophiolite
KM

Figure 2



122°45'
A'
Bartlett Springs fault zone
Coast Range thrust
Chalk Mountain
Clear Lake
Sulfur Creek
mining district
Pomo fault
Wilbur Springs
Sulfur Bank mine
Big Valley
39°
39°
Mt. Konocti
Aud
Borax Lake
Ely Flat
Jor
Nea
Wight Way fault
Adobe Crk Canyon
fault
Wil
Konocti Bay fault zone
Collayomi fault zone
Mt. Hannah
Tyler Valley
Caldwell Pines
Bud
CPF
CMF
Mercuryville fault zone
Boggs Mtn.
10 km
Cobb Mtn.
felsite
BSC
Clear Lake volcanic rocks
geothermal well
mercury mine or prospect
Mayacma
mining district
steam production area
A
122°45'

Figure 3

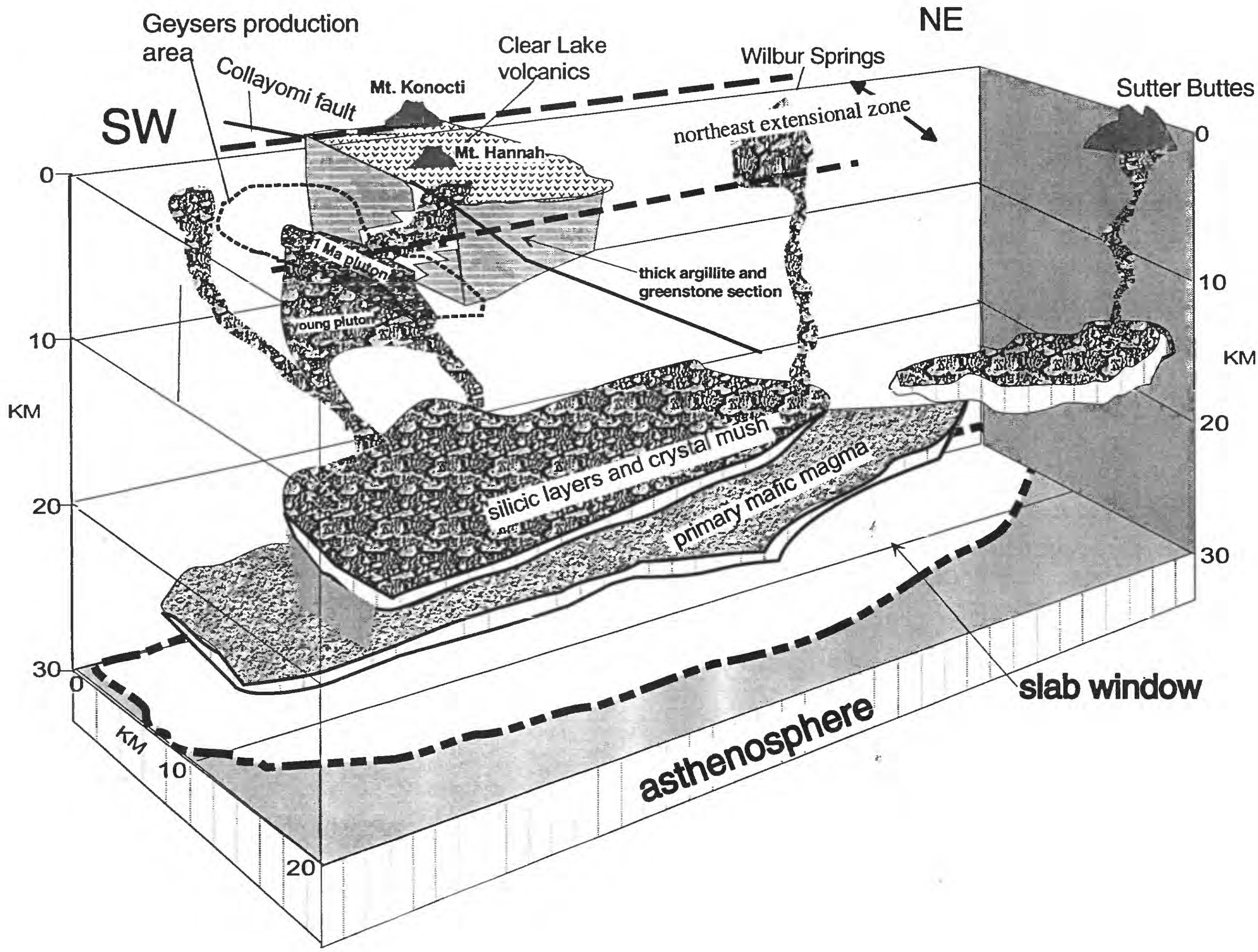

Geysers production area
Collayomi fault
Clear Lake volcanics
Mt. Konocti
Wilbur Springs
NE
SW
Sutter Buttes
northeast extensional zone
Mt. Hannah
1 Ma pluton
young pluton
thick argillite and greenstone section
silicic layers and crystal mush
primary mafic magma
slab window
asthenosphere
KM
0
10
20
30

Figure 4

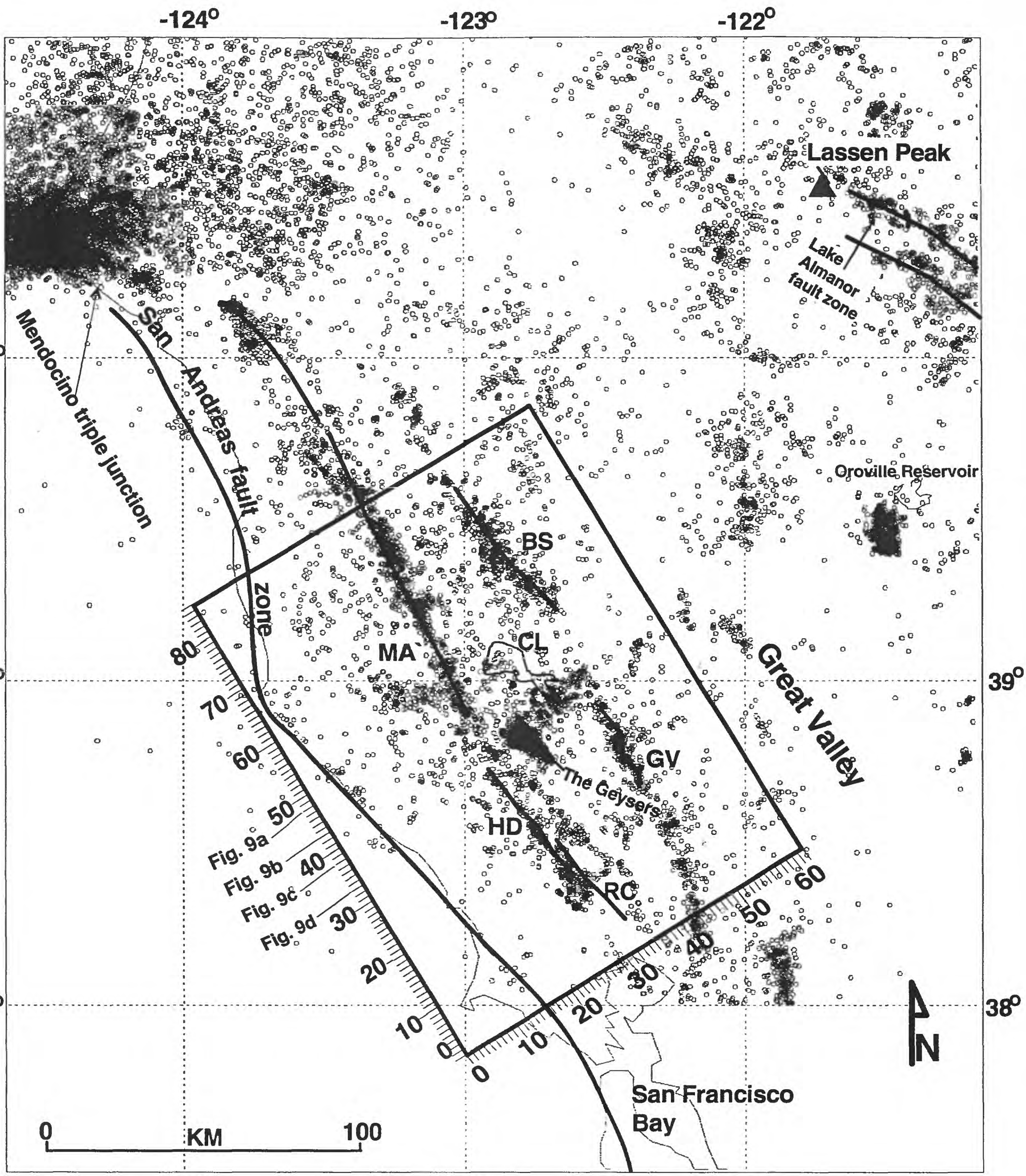
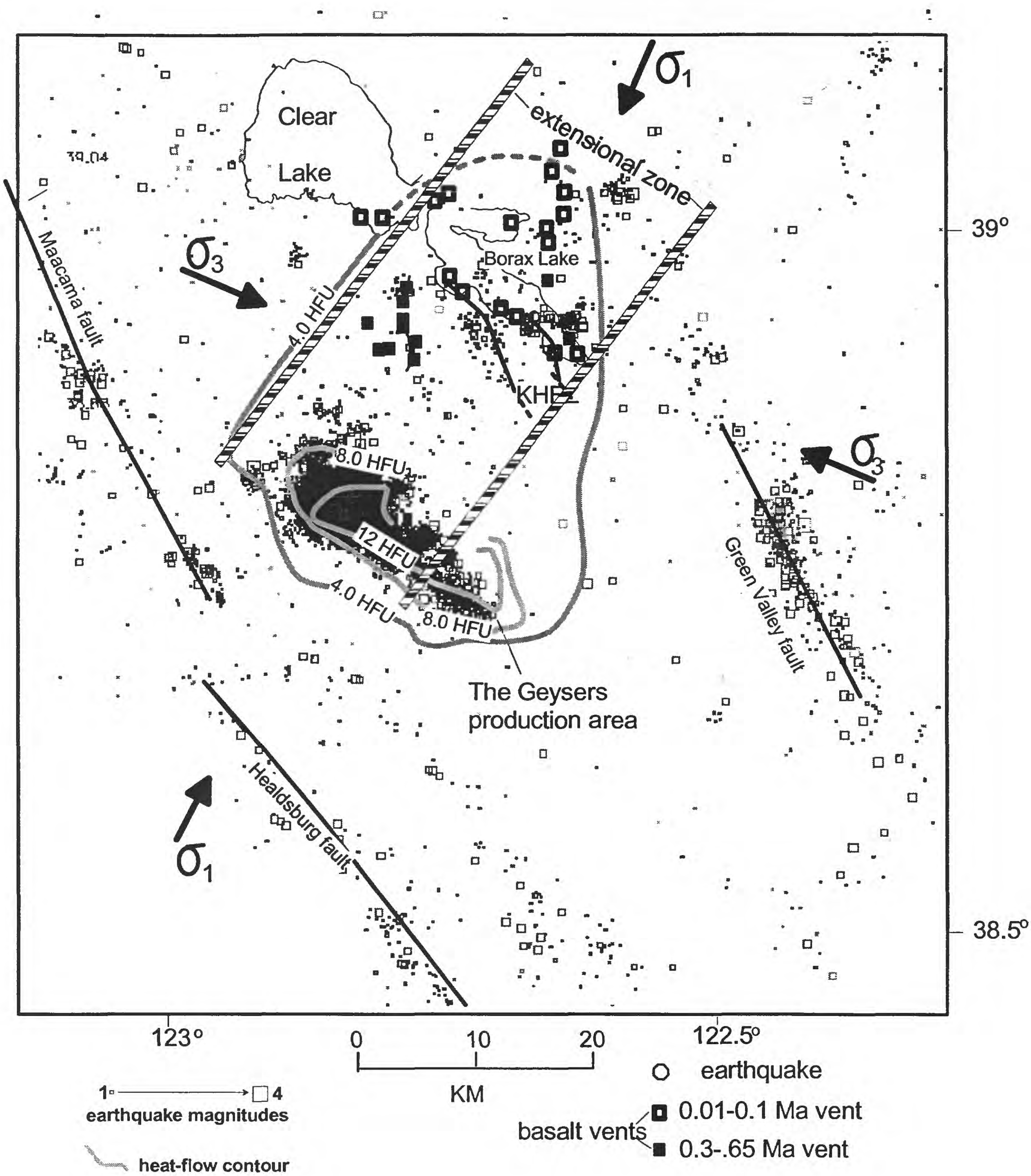
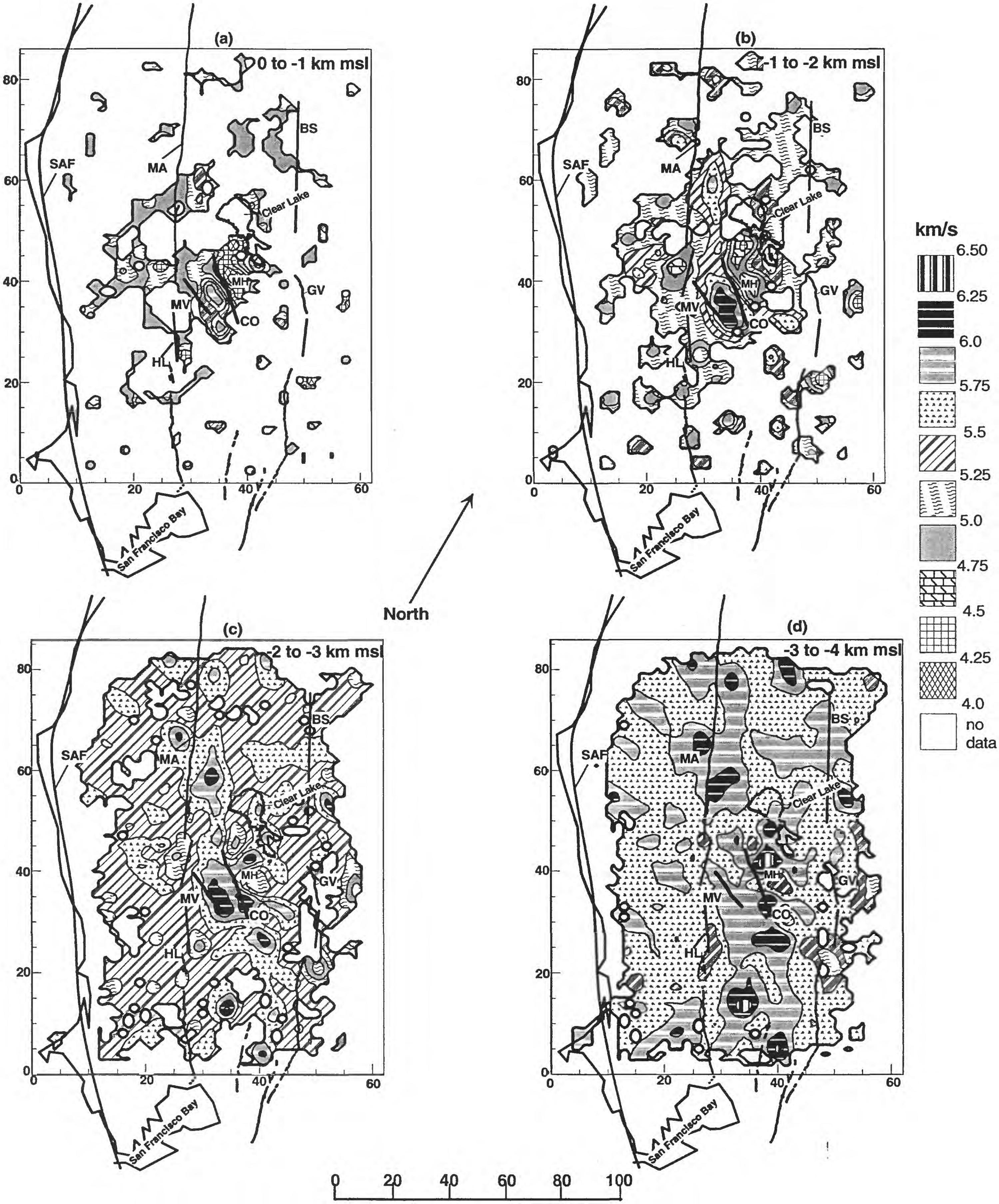

-124°
-123°
-122°
Lassen Peak
Lake Almanor fault zone
Mendocino triple junction
San Andreas fault zone
40°
39°
38°
Oroville Reservoir
BS
CL
MA`
GV
The Geysers
HD
RC
Great Valley
Fig. 9a
Fig. 9b
Fig. 9c
Fig. 9d
San Francisco Bay
0 KM 100
N

Figure 5



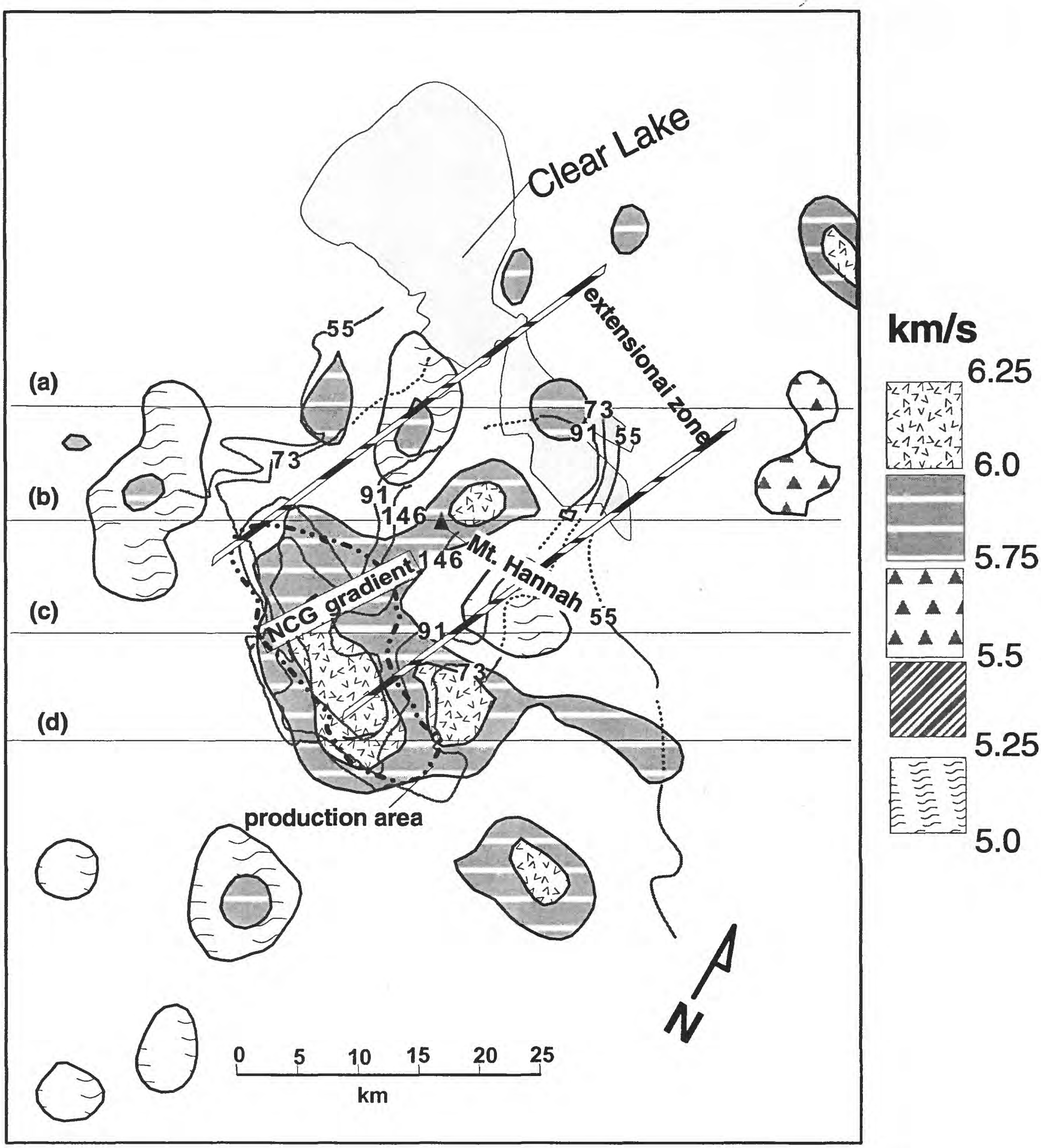
Clear
Lake
39.04
extensional zone
Borax Lake
KHEZ
4.0 HFU
8.0 HFU
12 HFU
4.0 HFU
8.0 HFU
The Geysers
production area
Maacama fault
Healdsburg fault
Green Valley fault
39°
38.5°
123°
122.5°
0
10
20
KM
1
4
earthquake magnitudes
heat-flow contour
earthquake
basalt vents
0.01-0.1 Ma vent
0.3-.65 Ma vent

Figure 6



(a)
0 to -1 km msl
(b)
-1 to -2 km msl
(c)
-2 to -3 km msl
(d)
-3 to -4 km msl
SAF
MA
BS
Clear Lake
MH
GV
MV
CO
HL
San Francisco Bay
North
km/s
6.50
6.25
6.0
5.75
5.5
5.25
5.0
4.75
4.5
4.25
4.0
no data
0
20
40
60
80
100
horizontal scale, kilometers

Figure 7



Clear Lake
extensional zone
(a)
(b)
(c)
(d)
55
73
91
146
Mt. Hannah
NCG gradient
production area
km/s
6.25
6.0
5.75
5.5
5.25
5.0
0 5 10 15 20 25
km
N

Figure 8

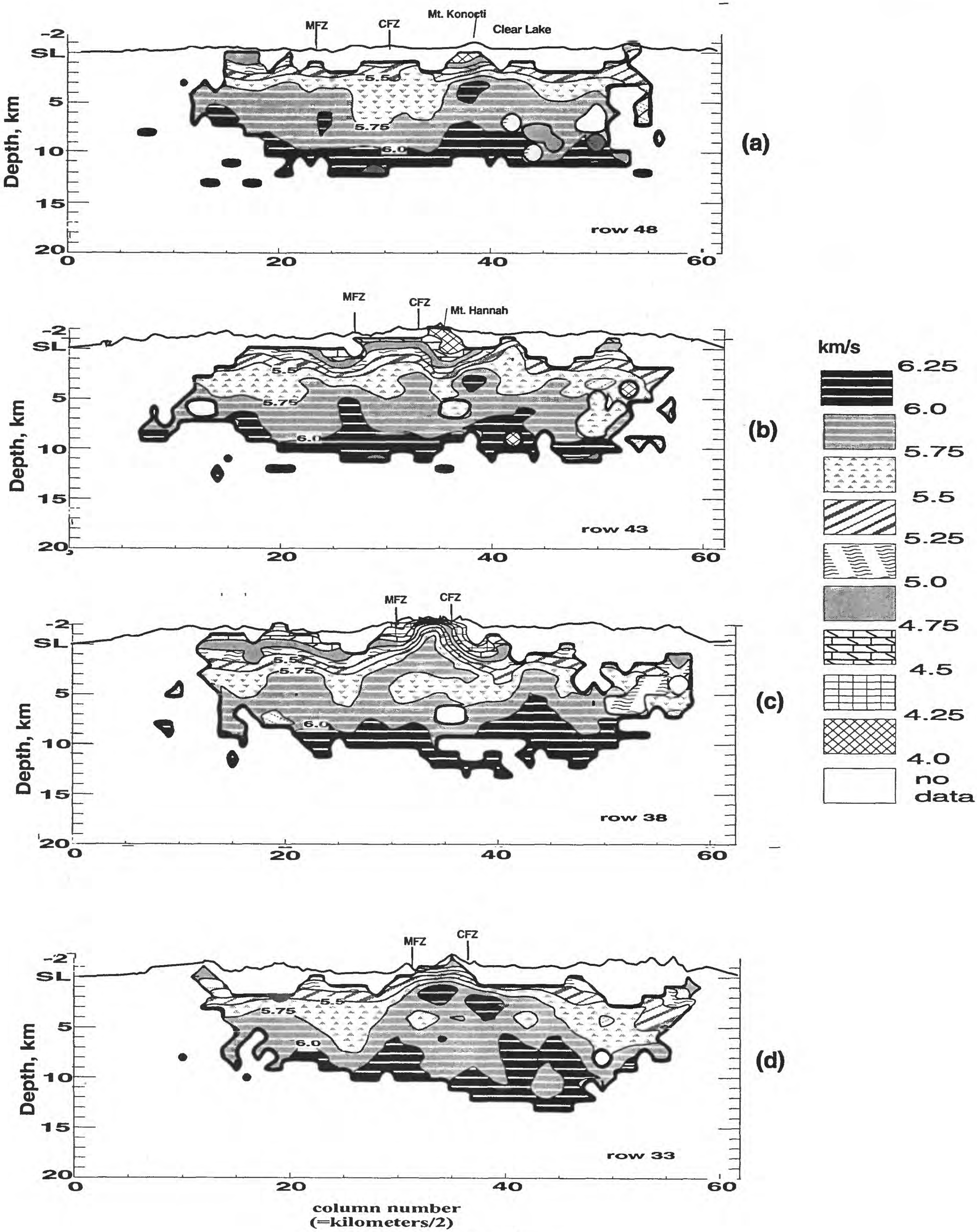

MFZ
CFZ
Mt. Konocti
Clear Lake
-2
SL
5
10
15
20
Depth, km
0
20
40
60
row 48
(a)
Mt. Hannah
row 43
(b)
row 38
(c)
row 33
(d)
5.5
5.75
6.0
column number
(=kilometers/2)
km/s
6.25
6.0
5.75
5.5
5.25
5.0
4.75
4.5
4.25
4.0
no data

Figure 9

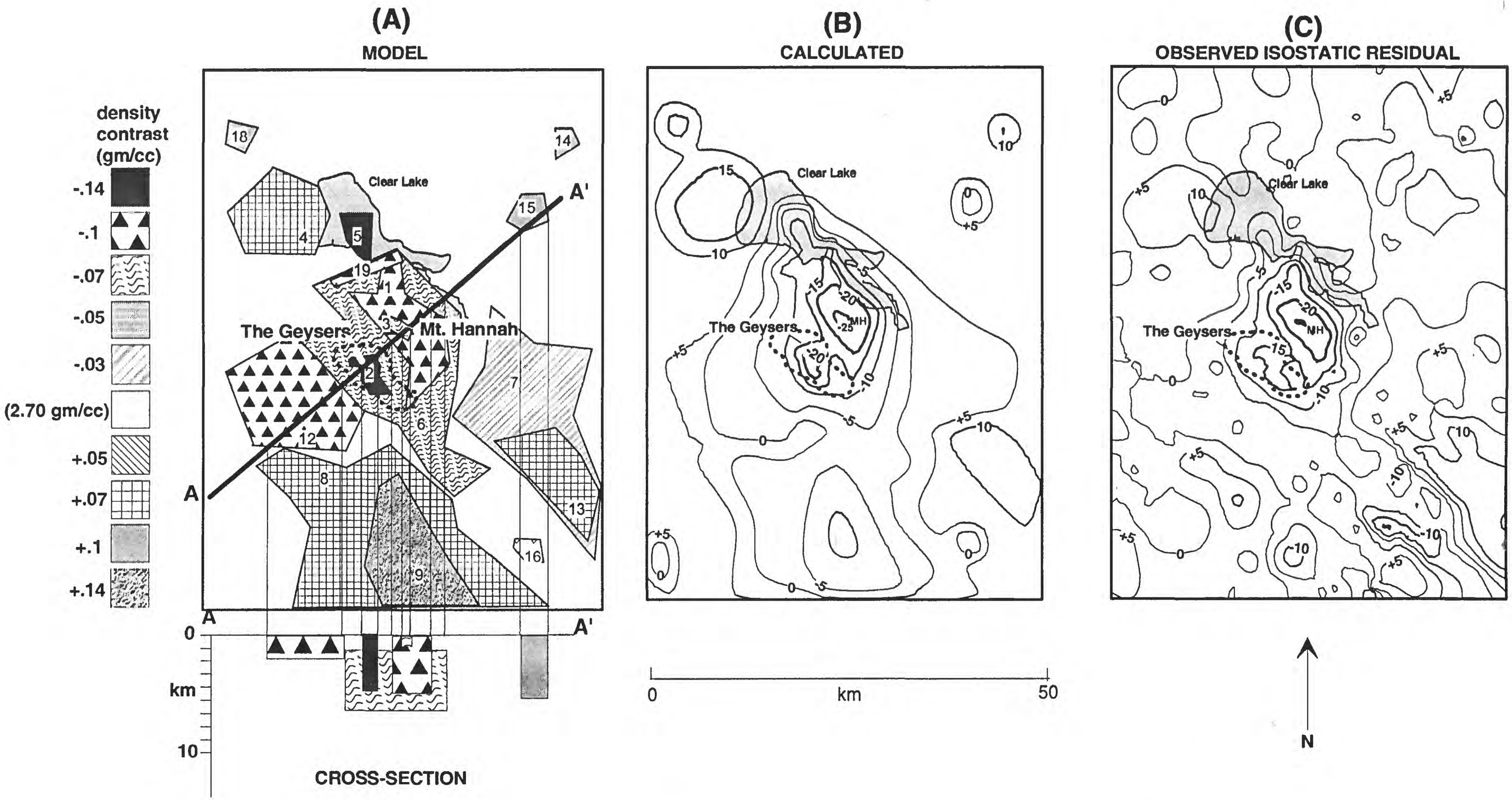
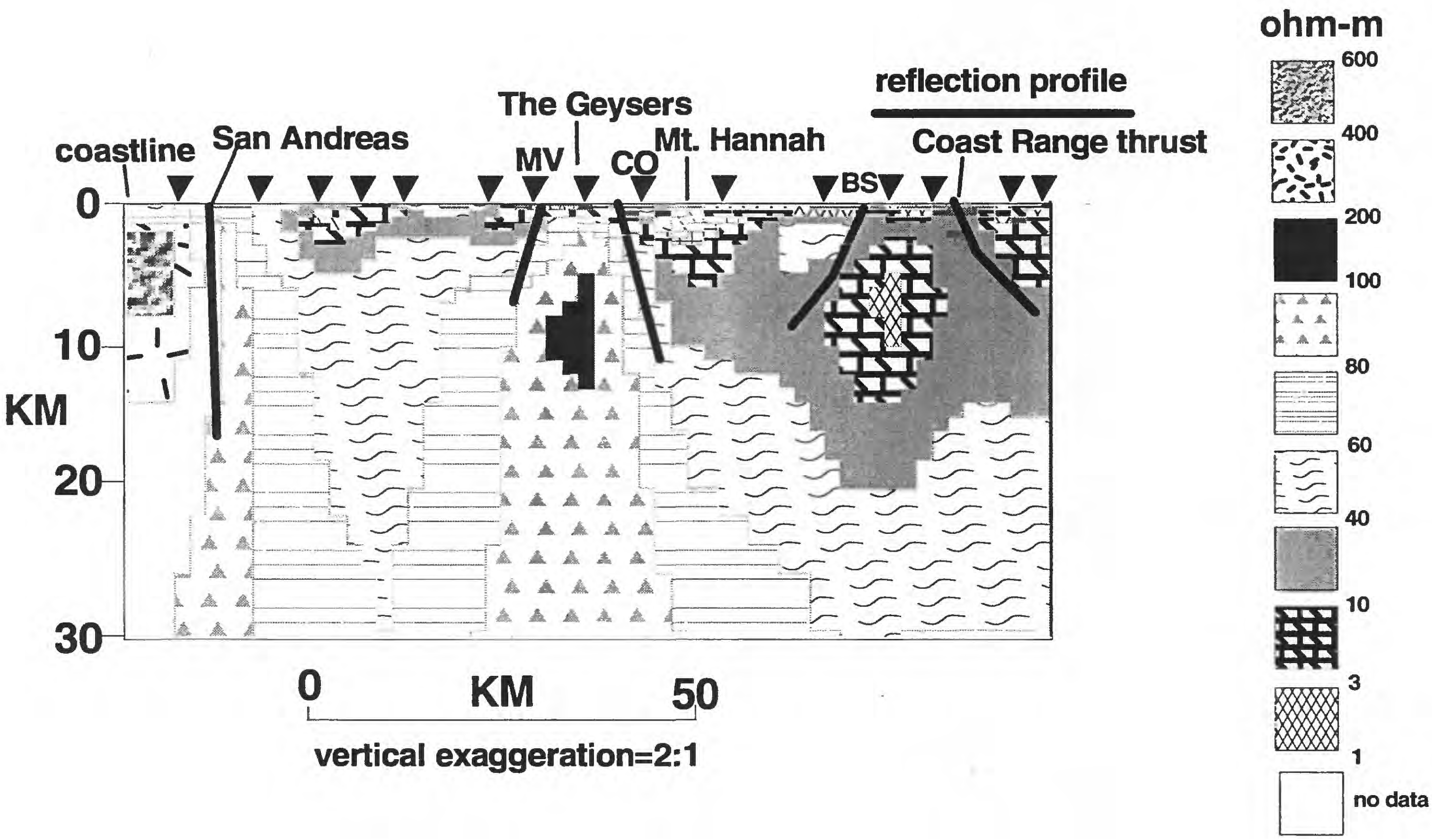

(A)
MODEL
density contrast (gm/cc)
-.14
-.1
-.07
-.05
-.03
(2.70 gm/cc)
+.05
+.07
+.1
+.14
Clear Lake
The Geysers
Mt. Hannah
A
A'
0
km
10
CROSS-SECTION
(B)
CALCULATED
Clear Lake
The Geysers
0
km
50
(C)
OBSERVED ISOSTATIC RESIDUAL
Clear Lake
The Geysers
N

Figure 10



reflection profile
The Geysers
coastline
San Andreas
MV
CO
Mt. Hannah
BS
Coast Range thrust
0
10
KM
20
30
0
KM
50
vertical exaggeration=2:1
ohm-m
600
400
200
100
80
60
40
10
3
1
no data

Figure 11

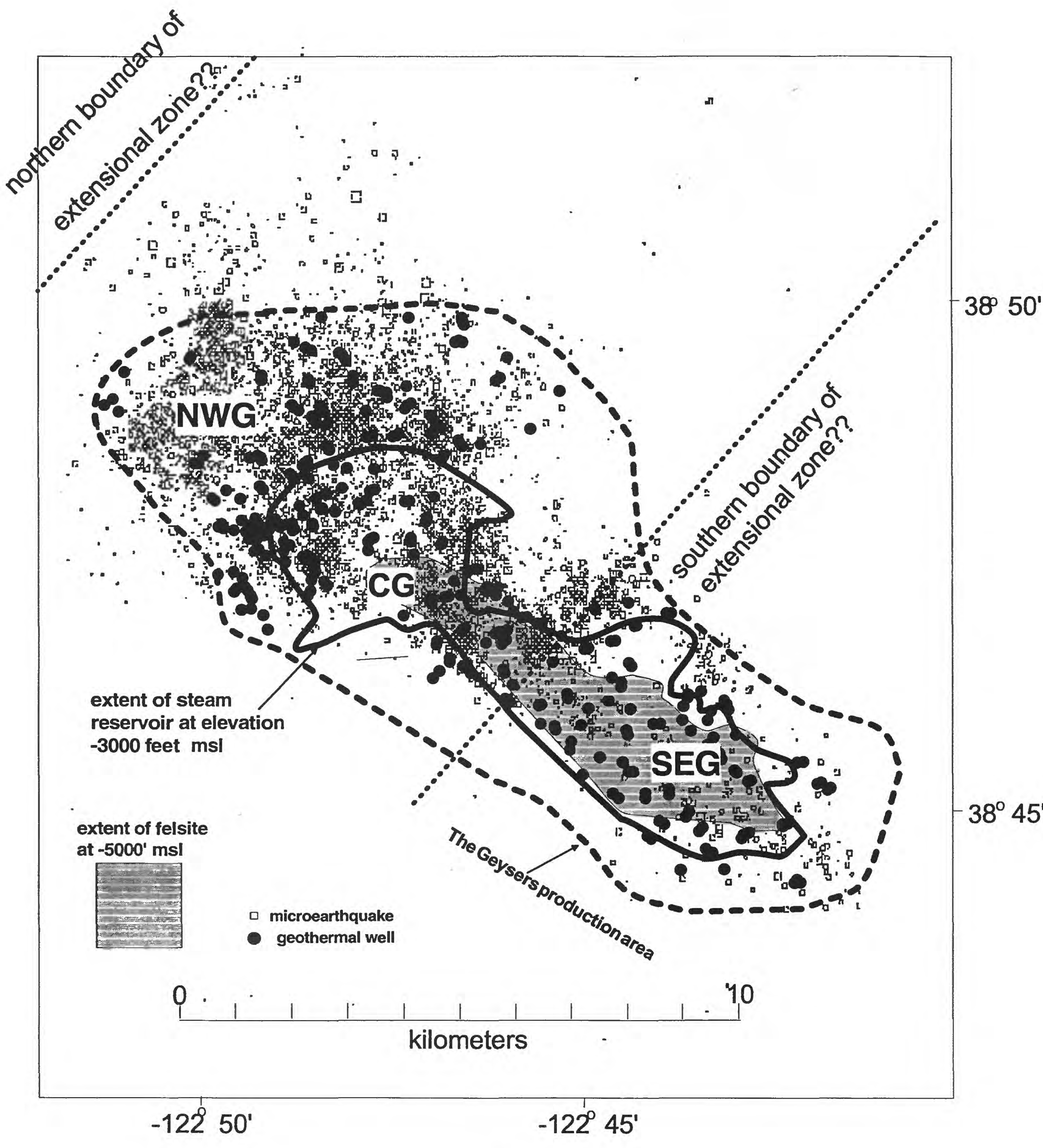

northern boundary of
extensional zone??
southern boundary of
extensional zone??
38° 50'
38° 45'
NWG
CG
SEG
extent of steam
reservoir at elevation
-3000 feet msl
extent of felsite
at -5000' msl
microearthquake
geothermal well
The Geysers production area
0
10
kilometers
-122° 50'
-122° 45'

Figure 12