A Revised Tectonic Model for The Geysers-Clear Lake Geothermal Region, California

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ABSTRACT

A new program of study in The Geysers-Clear Lake geothermal region by the U.S. Geological Survey is directed toward a better understanding of the nature of heat sources in the area. Geophysical models based on gravity, earthquake tomography, seismicity and electrical geophysical data have been utilized to place new constraints on the location of possible magma bodies. In contrast to past models of a large, single magma chamber in The Geysers-Clear Lake region that generated the Clear Lake volcanic field, our model portrays a system of upper crustal plutons generated from a middle to lower crustal mafic melt zone. This mafic melt zone may be related to heating in a "slab window" resulting from passage of the Mendocino triple junction. Injection of deep crustal magmas into the upper crust appears to have been controlled by northwest-trending strike slip faults and northeast-trending, extensional, stepover features between the northwest-trending faults, The most prominent of these extensional zones trends northeast from The Geysers Production area, through the Mt. Hannah area, and across the southern end of Clear Lake. It may be related to a combination of factors including: (1) interior block deformation between two key northwest trending strike-slip faults; (2) preserved extensional features from an unstable triple junction; (3) heating effects due to mafic underplating

INTRODUCTION

The Geysers-Clear Lake area of northern California (Figs. 1,2) is one of the few regions of the world where dry steam is used to produce electric power, The steam-electrical production at The Geysers is the largest in the world (1200 megawatts) and the production area encompasses an area of over 700 square kilometers defined by more than 450 drilled wells. A decline in steam pressures over the past few years has resulted in a decrease in production capability in the steam field. The Geysers-Clear Lake geothermal area encompasses the dry-steam production area in The Geysers field and a poorly-defined, high-temperature, water-dominated system in the area between The Geysers and Clear Lake (Fig. 1) which has not been fully explored. In addition to reservoir temperatures of about 250°C in The Geysers production area, deep wells have encountered temperatures of as much as 300°C at depths of less than 4 km (Fournier, 1991) in the Mt. Hannah area (Fig. 2). Both systems have been extensively studied with geophysical techniques, drilling, and geological mapping in the past 20 years. Stanley and Blakely (1994) have reevaluated geophysical data for the area and point out that earlier view of a single magma chamber occurring at a depth of about 7 km beneath the Quaternary Clear Lake volcanic field is probably too simplistic. Their recent analysis favored a middle to lower crustal magma chamber with small, upper crustal plutons and injection of melt along area faults and zones of extension. In this paper we take a broader view of northern California tectonics in order to better understand the generation of Quaternary volcanic features in the northern California Coast Ranges.

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 of Bailey et al. (1964). The Coast Range thrust fault separates rocks of the Franciscan accretionary wedge from the Great Valley Sequence, both of Jurassic and Cretaceous age (Fig. 1). The Franciscan Complex is divided between melange and less disturbed sedimentary and metasedimentary rocks that were scraped from the subducting plate in Jurassic to Cretaceous time. The Great

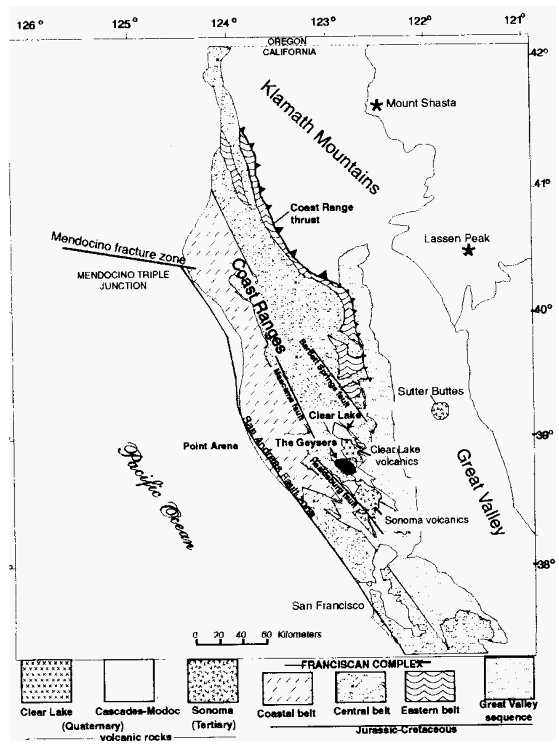

Figure 1–Geologic map of northern California Coast Range, with location of The Geysers geothermal area, Clear Lake volcanic field, Sonoma volcanic field, Sutter Buttes; and major strike-slip faults. Modified from McLaughlin (1981).

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, with the basal part derived from the underlying Coast Range ophiolite (McLaughlin and Pessagno, 1978).

At the scale of The Geysers-Clear Lake region, McLaughlin and Ohlin (1984) have described tectonostratigraphic subterranes of the Franciscan Complex and the lower part of the Great Valley sequence. These terranes are bounded by segments of the regional strike-slip fault system that include the Maacama, Healdsburg, and Bartlett Springs fault zones (Figs. 1,2). The Collayomi fault (Fig. 2) separates central Franciscan terrane units that encompass The Geysers production area from Great Valley sequence and eastern Francscian terrane units of the Mt Hannah and Clear Lake region, but is not seismically active. Extensive ophiolitic serpentinites occur along the Collayomi fault (Fig. 2).

The rocks of the Clear Lake volcanic field are partially Pliocene, but mostly Pleistocene, in age (Donnelly-Nolan et al., 1981). The nearest similar volcanic rocks are those 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 Range. The nearest Quaternary volcanic centers are at Sutter Buttes and in the Lassen Peak region (Fig. 1). The eruptive rocks of

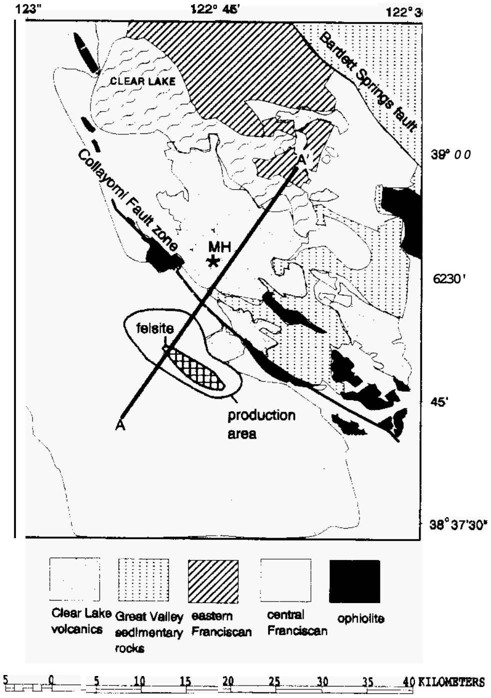

Figure 2-Detailed geology of The Geysers-Clear Lake area. Outline of "felsite" body in the production area is shown by the cross-hatched pattern (from Thompson, 1992). MH=Mt. Hannah. The bold black line **AA'** is a profile used to construct gravity, magnetic, seismicity, and geoelectric cross-sections.

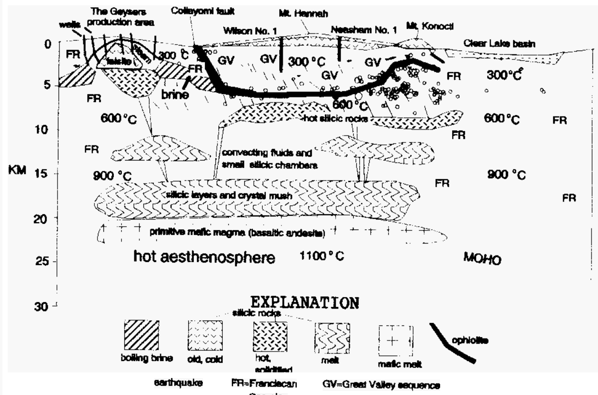

Figure 3-Geological cross-section (along **AA'**, Fig. 1) schematic based upon geoelectrical models, new gravity and magnetic models, P-wave delay and attenuation results (from Stanley and Blakely, 1994), and recent drilling information and volcanology research. **A** cross-section of seismicity is superimposed (circles); earthquake locations from The Geysers Production area have been deleted for clarity. Two deep **wells** that provided geological information *are* shown on the section (Neasham and Wilson).

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). The most recent volcanism in the Clear Lake volcanics appears to be migrating to the northeast, related to zones of crustal extension that we interpret in this paper and analogous to those previously suggested by McLaughlin (1981)

The only known intrusive rocks in The Geysers production are in a felsic body (Fig. **2**) described by (Thompson, 1992) and commonly referred to as the "felsite" The age of the intrusion has been determined as 0.9 Ma-2.4 Ma by Schreiner and Suemnicht (1980) and more recently at 1.3 Ma by Dalrymple (1992); ages in this range make the pluton too old to be directly responsible for heat in the production area. Younger magma bodies may have been emplaced close to or within the "felsite" of the production area and they might be the source of heat in the area.

The structural history of The Geysers-Clear Lake area is complex. The late Mesozoic subduction system along western North America was replaced in the Eocene period with the triple junction that-evolved as the San Andreas transform system came into contact with the Pacific and Farallon oceanic plates about 40 Ma (Atwater, 1970). This triplejunction system migrated along the North American plate margin from southern California to its present position near Cape Mendocino in northern California (Fig. 1). Movement of the Mendocino triplejunction (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). 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 MTJ (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.

Several geophysical anomalies are centered near the Mt Hannah area (Fig. 2). **A** residual Bouguer gravity low of about **-30** mgal amplitude has been interpreted by Isherwood (1975) to be caused by a magma chamber whose top is at 7 km depth. Earlier models of the geophysical data which attributed gravity and teleseismic delay-time anomalies strictly to mid-crustal properties may have neglected the effects of upper-crustal inhomogeneities. Recent models for an electrical resistivity anomaly centered on Mt. Hannah (Fig. 2) and deeper information from magnetotelluric (MT) soundings suggest that the minimum depth to a large magma chamber in the Mt. Hannah region is closer to 15 km than 7 km (Stanley and Blakely, 1994). Forward modeling, multidimensional inversions, and ideal body analysis of gravity data, electrical resistivity models, and other geophysical data sets were used to infer that much of the gravity and electrica! anomalies, as well as teleseismic P-wave delays not shown, may be attributable to rock property and physical state variations in the upper 7 km and not to "magma" at greater depths. A geological/geophysical cross section through the Geysers-Clear Lake area (Fig. **3**) summarizes interpretations of the geophysical, geological, and petrological data by Stanley and Blakely (1994). The key features of the section include a thick (4-7 km) section of overpressured Great Valley argillite in the Mt. Hannah region that is documented in key wells and complicated thrust geometries of Franciscan rocks to the east This conceptual geological model places the primary magma chamber related to the slab window formed after MTJ passage at deeper than 15 km.

Stimac et al. (1992) 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. 3) and 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 (Fig. **2)** can be explained by northward-stepping basaltic dike injection at depth. In this paper we conclude that much of the magmatic activity was concentrated along active northwest strike-slip zones and cross-cutting transtensional faults. Transtensional faults are extensional features that develop by shearing action between parallel strike-slip faults. The directions of least-principal and maximum stress shown in Fig. 4 illustrate the shearing directions across The Geysers-Clear Lake area. Basaltic and basaltic-andesite vents (Hearn et al., 1981) line up along the direction of least-principal stress, σ_3, and the Konocti Harbor fault zone, which is parallel to the maximum-principal stress, σ_1, (Fig. 4). Mafic and some felsic magmatism seems to have found preferential pathways along faults and appears to be propagating mainly to the northeast along the direction of maximum-principal stress (Fig. 4). If the northeast-trending extensional zone has truly been under extension for some time, then it may provide an enhanced degree of deep fracturing. Further geophysical studies and detailed structural mapping, combined with additional geochemical studies are needed to better understand this tectonic feature and its geothermal implications.

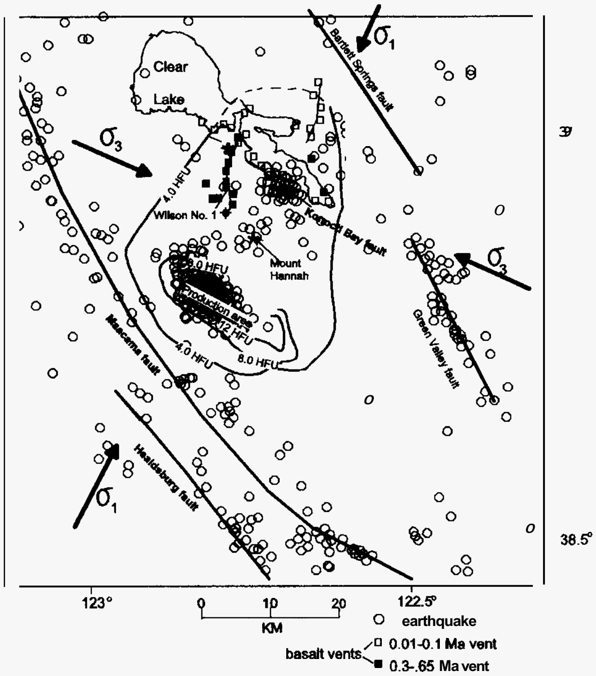

Figure 4-Heat flow, seismicity, and recent basaltic volcanic vents in the Geysers-Clear Lake region. Heat flow contours in heat flow units taken from Walters and Combs (1992). Seismicity taken from CALNET (U.C. Berkeley) data base for period 1970-1994 with magnitudes >1.5. Solid squares are the locations of basaltic and basaltic andesite volcanic vents from 0.3-.65Ma and open squares are vents from 0.01-0.1 Ma taken from Hearn et al. (1981). Lines drawn through series of vents represent postulated extensional faults. Direction of maximum (8,) and least (8,) principal stresses from earthquake focal mechanisms as determined by Bufe (1981) are shown by bold arrows.

HEAT FLOW DATA

Walters and Combs (1992) describe results of heat flow measurements from 1971 to 1984 in 620 boreholes over The Geysers-Clear Lake region. They described an area 750 km^2 where heat flow values of >168 milliWatts/m^2 (mWm^{-2}) or 4 heat-flow-units (HFU), occur (Fig. 4). The Geysers production area is within the southwestern corner of this broad anomalous area, and is enclosed by an 8 HFU contour. The tight correspondence of the heat-flow contours with the production area indicates that heat-flow values are affected by drilling activity in which steam is brought to the surface Elongation of the heat-flow contours to the northeast is evident and we infer that the elongation is due to increased volcanism and deep circulation in a northeast-trending zone of extension.

High temperatures (>200°C) have been measured at depths of slightly over 1 km in wells in the Borax Lake area, which may indicate a local heat source. We hypothesize that the overall heat flow anomaly may be related to a number of small, high level plutons and zones of deep circulation in both northwest and northeast tectonic features. A rather narrow zone of heat input may occur along the postulated northeast zone of extension defined by the seismicity lineament, the northeast alignment ofbasaltic vents (Fig. 4), and the northeast trend of the heat flow contours. High lake-bottom temperatures were found (Walters and Combs, 1992) in the southeast arm of Clear Lake where the basaltic vent lineaments indicated in figure 4 cross the Konocti Harbor fault. This suggests the possibility of upflow from a hydrothermal system or local intrusions along these lineaments.

SEISMICITY PATTERNS

Local earthquakes in The Geysers-Clear Lake region are concentrated (Fig. 4) along the Maacama, Healdsburg, Green Valley, Konocti Harbor, and Bartlett Springs faults. Dense seismicity in The Geysers production area is related to steam production and waste-water reinjection. A northeast-trending belt of earthquakes extends from the northern part ofthe production area through Mt. Hannah and across the south end of Clear Lake. The principal stress directions derived from focal mechanisms by Bufe (1981) are shown in figure 4. These stress directions are related to the present oblique nature of plate convergence along the continental margin, involving the San

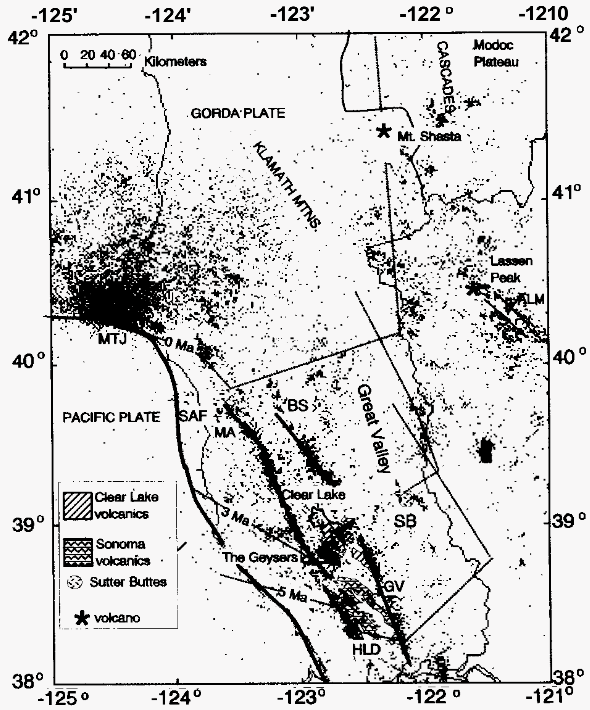

Figure 5-Seismicity of northern California from U.C. Berkeley data base for period 1970-1994 using best located events with magnitudes >1.5. The postulated locations of the Gorda Plate at 5, 3, and 0 Ma are shown by the dotted lines. SAF=San Andreas fault, MAC=Maacama fault, BS=Bartlett Springs fault, HLD=Healdsburg fault, GV=Green Valley fault, SB=Sutter Buttes, ALM=Lake Almanor fault zone.

Andreas fault, and were probably typical of stress orientation during passage of the MTJ. Extensional features and "stepover" faults are common between parallel fault systems like the Maacama and the Bartlett Springs faults due to shearing and block rotation caused by different rates of slip on the two faults (Crowell, 1974). We infer that the current and past stress field favored extension along the northeast direction occupied by the young basaltic vents and the seismicity trend that crosses the production area and the southern part of Clear Lake. A number of extensional basins of Pliocene and Pleistocene age occur in the region, including the Clear Lake basin that now contains a lake (Hearn et al., 1988). The general extensional regime that allowed these basins to form also permitted volcanic flows to reach the surface along northwest, as well as northeast, oriented faults.

We initially considered the northeast-trending seismicity zone in The Geysers-Clear Lake area to be a possible transpressive stepover feature between the Maacama-Healdsburg faults and the Bartlett Springs-Green Valley faults. Because of the oblique nature of Pacific plate subduction, this transpressive development is characteristic of parts of the San Andreas fault system. However, regional seismicity patterns as indicated in figure 5 suggest to us that the northeastern seismicity trend through the Mt. Hannah region extends across the northern Great Valley to a point near Sutter Buttes. This northeastern belt of seismicity appears to intersect a northerly zone of seismicity in the eastern Great Valley region.

Most of the earthquakes along the key northwest trending faults parallel to the San Andreas fault are less than 15 km deep and in the Geysers-ClearLake area are less than 10 km deep (Fig 3). The maximum depth for earthquakes in the geothermal area is controlled largely by high temperatures. Several deeper quakes occurred at 20-25 km depth south and west of the northwest part of Clear Lake. These deeper quakes may be associated with magmatic activity as suggested by Castillo and Ellsworth (1993). Quakes along the zone along the eastern Great Valley margin from Sutter Buttes north are distributed throughout the crust at depths from 5-30 km and have both thrust and

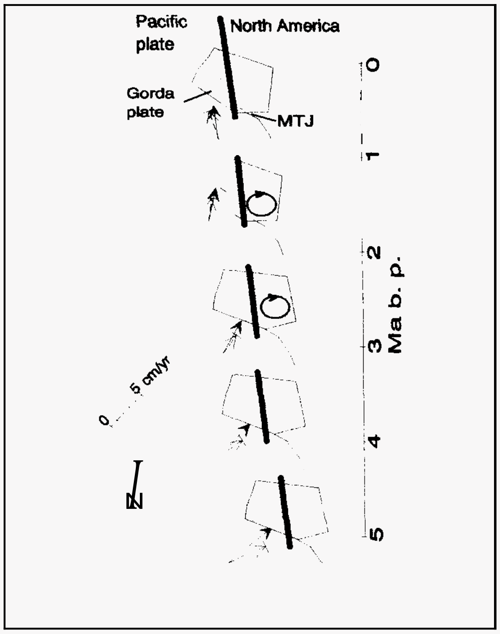

Figure 6-Relative plate motion vectors between the southem Gorda plate and North American plate versus time **for** the interval *5* Ma-0 Ma, assuming a distant Pacific-Gorda pole **of** rotation (reproduced from Riddihough, **1980). Dashed** vectors **are** vectors at the continental margin if the southern Gorda rotated relative to the Pacific plate about **a** local pole to the south. Errors were estimated by Riddihough to be ±5° and ±3 cm/yr. Rotations at **2 5** and 1.5 Ma from Riddihough **(1984)** are indicated by circles.

strike-slip mechanisms. The intense seismicity in the present MTJ region is caused by intense compression at the point of maximum convergence of the Pacific plate and the Gorda Plate. In the region between the active northern end of the Maacama-Bartlett Springs fault pair and the MTJ, earthquakes become less numerous and focal mechanisms change from vertical strike-slip to more thrust character (Castillo and Ellsworth, **1993).**

Of possible significance is the northwest zone of earthquakes (Fig. *5)* centered at about 39° N-123.3°W (along the inferred **3** Ma Gorda Plate position northwest of The Geysers). Castillo and Ellsworth **(1993)** have also noted this seismicity feature and relate it to a dipping fault plane coincident with a contact between coastal belt Franciscan units and the central Franciscan melange belt. This fault zone may be a reactivated thrust within the Franciscan Complex, but also may be compatible with the geometry of the Gorda Plate at about **3** Ma. It may also have some relationship to the felsic intrusion in The Geysers production area. Hulen and Nielson **(1993)** have done a thorough study of the felsite body using well data from The Geysers production area and show that the **2.4-1.3** Ma intrusion is actually comprised of multiple bodies of different lithology, with the complex aligned in the approximate direction of the seismically active fault at **39°N-123.3°W**. We suggest that the multiple intrusions that make up the production area felsite body were injected along one or more of the numerous northwest trending thrusts that extend through the production area, as mapped by McLaughlin **(1981).** These thrusts may have been reactivated and placed in an extensional stress field after passage of the MTJ at about **3** Ma. We infer that infilling by mantle material in the slab window led to thermally induced uplift of the Coast Ranges in this area and this uplift kept the upper crust under tension for **an** adequate time necessary for injection of the felsic magmas. These felsic magmas were generated from heating of the crust by underplated mafic magma and by mafic injection along northwest strike-slip faults and northeast extensional zones,

CONFIGURATION OF THE GORDA PLATE, PAST AND PRESENT

Because the Quaternary volcanism in the California Coast Ranges is believed to be related to passage of the Mendocino triple junction (MTJ), it is important to know more about the paleo-geometry of the MTJ. Several pieces of evidence may be used to map the past and present positions of the Gorda Plate. 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 entire Juan de Fuca system (Riddihough, **1984)** using such analyses. In his **1980** paper, Riddihough 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 (Fig. 6), 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 (Fig. *6)*. 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. Based upon Riddihough's **(1980, 1984)** analyses, we indicate the approximate paleo-positions and rotation of the southern part of the Gorda Plate (Fig. ***6)*** with respect to the continental margin at **5** Ma, **3** Ma, and 0 Ma in Fig. **5.**

The present southern margin of the Gorda Plate as interpreted in Fig. **5** is based upon several lines of evidence. Jachens and Griscom **(1983)** used the southern edge of an isostatic gravity low to interpret the location of the southern Gorda margin as a **S60°E** trending feature to **123.25"W** where it becomes an east-west boundary. We prefer to extend the present southern edge of the Gorda Plate along an approximately S60°E trend to intersection with the Maacama-Bartlett Springs fault pair and then slightly to the northeast along a zone that appears to truncate distributed seismicity in the northern Great Valley (Fig. **5).** This is only slightly different from the interpretation by Jachens and Griscom **(1983). A** P-wave velocity model of northern California has been developed by Benz et al. **(1992)** from teleseismic tomography and distinct gradients occur at several depth levels in the model across the approximate boundary of the southern part of the Gorda plate that we indicate in Fig. 5. Thus, the gravity, teleseismic topography, and seismicity patterns all suggest that the present southern boundary of the Gorda plate is approximately as shown in Fig. **5.**

Using criteria from the previous paragraphs for the present location of the southem edge of the Gorda Plate, we indicate inferred paleo-positions at **5** Ma and **3** Ma. These positions represent a straightforward back projection with time for the Gorda plate, combined with the rotation inferred by Riddihough **(1984).** The Sonoma volcanic field developed in the interval from **5**.3 Ma to **2.9** Ma, in between the two Gorda Plate positions shown. The epoch from **5** to **2** Ma was one of major changes in triple junction velocity (Fig. *6),* 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. The Clear Lake volcanic field and present northeast zone of extension and seismicity may be related to the rapid change in velocity and rotation of the Gorda Plate starting at about **3 Ma.** The rotation and focusing of subcrustal heat may have produced a zone of crustal weakness that controlled the location of tensional stepovers between the two parallel strike slip zones (Fig. **5).** The trend between the **1-2** Ma felsite in The Geysers production area across to the intrusive rocks at Sutter Buttes **(1.4-2.4**Ma) can be modeled with our interpreted geometry of the Gorda Plate. This model invokes post 3 Ma magmatic events as occurring from heating caused by mantle upwelling (slab window) in the lee of the northward moving triple junction. **This** slab window formed along the southern margin of the Gorda Plate and east of the San Andreas fault system.

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 suggested by Stimac et al. (1992) and Stanley and Blakely **(1994).** Their numerical models show that incremental magma production following passage ofthe MTJ peaks at about 0.4 Ma post-passage, but continues 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 longer gap between passage of the MTJ and Cenozoic volcanism in the Coast Ranges. They interpret that this gap may reflect the time required for crustal melt extraction and transportation. High viscosity silicic melts require 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.

DISCUSSION AND CONCLUSIONS

Dickinson and Snyder (1979) and McLaughlin (1981) noted that the timing of Clear Lake volcanism closely followed passage of the Mendocino triplejunction and propagation of San Andreas-related extensional structures. The clear relation of basaltic and·basaltic-andesite vents to extensional features, especially the northeast-trending zone of Fig. **4,** indicates that control of magmatisrn by crustal zones may be traced back to the dynamics and position of the triple junction at 3 Ma. Dickinson and Snyder (1979) demonstrated that triangular areas of extension can be left in the wake of an unstable triple junction such as the Mendocino triple junction. Figure *6* taken from Riddihough (1980) shows that there was a major change in Gorda Plate motion starting after about 2.5 Ma. This sudden shift in Gorda Plate motion from one of oblique, northeast thrusting beneath North America to one of largely north-south shearing would have produced an active extensional zone oriented east-west or northeast-southwest. We infer that this active extensional zone was a key conduit for the Clear Lake volcanic field.

The present northeast seismicity trend and the alignment of volcanic vents and stretching of heat-flow contours to the northeast is interpreted by us to be related to the past and present effects of this extensional zone. The present extensional zone is maintained by the current direction of stress in the stepover region between the Maacama-Healdsburg and Bartlett Springs faults (Fig. 4). Future volcanism in the Coast Range of northern California is expected to follow the patterns observed in the Clear Lake and Sonoma volcanic fields, with the magma channelled to the surface along northwest and northeast extensional features. The increased northward velocity starting at **0.5** Ma (Fig. **6)** suggested to Riddihough that the Pacific and Gorda Plate are now moving together; thus, the extent of extensional zones formed in the lee of the migrating triple junction may be less than when the two plates moved more independently.

The complex felsite and related plutons in The Geysers production area may have been emplaced along the intersection of reactivated, northwest-trending thrusts and northeast-trending zones of extension. Future exploration for such heat sources may profitably look north and east of the current steam production area for high temperature zones related to young, upper-crustal plutons.

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