*Neotectonics and Seismicity of the
Clearlake Region in Northern California*

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Kerry L. Burns

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by

Kerry L. Burns

ABSTRACT

Geological, topographic, and seismic methods were used to locate faults in the vicinity of Clearlake in northern California. The geological method, which seeks faults as discontinuities in the lithotope, found faults in the Tertiary-Cretaceous rocks east of Burns Valley. The topographic method, which is used to produce Fault Evaluation Reports, found a very active fault zone, the Konocti Bay fault zone, south of Highlands arm. It also found some active faults north of Highlands arm, in the eastern part of Burns Valley and on the lakeshore near Oak Park. The seismic method is the most enduring of the three methods but is limited by location accuracy; the results improve as monitoring continues because of increases in the density of events and improvements in the crustal velocity model. The seismic method identified faulting along the valley at Borax Lake and possibly also on a line running northeast from the city of Clearlake. The latter may be associated with the Burns Valley fault or with the line of scoria domes which runs parallel to it. Seismic observations over longer periods at higher resolution will be required in order to determine the location of active faults near the city.

I. INTRODUCTION

The Geysers steamfield in northern California is surrounded by a large regional geothermal anomaly and several satellite anomalies (the shaded areas of Figure 1). Those areas of high heat flow exterior to the steamfield are candidates for application of hot dry rock (HDR) production technology. The purpose of the Clearlake HDR project is to find a suitable site for a demonstration HDR geothermal power plant within the area controlled by the city government. The area of most interest is northeast of the Highlands (southeast) arm of Clear Lake, shown by a rectangle inset in Figure 1. Studies of the geohydrology indicate that faults are an important pathway for fluid flow in this area. This study examines the distribution of faults as detected by geologic, topographic, and seismic techniques.

Figure 1. Locality map of part of northern California. The shaded areas are regions of high heat flow. The largest such area is The Geysers-Clear Lake geothermal anomaly. The unshaded area inside The Geysers-Clear Lake anomaly is The Geysers steamfield. County boundaries are shown by solid lines, highways by double solid lines. Townships denoted by triangles are CA Calistoga, CD Cloverdale, GS Geyserville, HD Healdsburg, HP Hopland, LP Lakeport, MD Middletown, NP Napa, SO Sonoma, SR Santa Rosa, UK Ukiah, VJ Vallejo, WHS Wilbur Hot Springs. Inset rectangle is the environs of the city of Clearlake. From Burns (1991, Fig.1, p. 311).

II. GEOLOGY AND FAULTS

A. General Geology

The general geology of the Clearlake region is shown in Figure 2. On the southwest side of Clear Lake, the basement rocks are melanges assigned to the central belt of the Franciscan Complex. On the northeast side of the lake, the basement rocks are coherent units of the Franciscan Complex assigned to the eastern belt. The boundary, or suture between the central and eastern terranes, runs northwest-southeast approximately along the Highlands arm of Clear Lake. The exact location is

Figure 2. General geology of the Clearlake region. From Hearn, McLaughlin and Donnelly-Nolan (1988, Fig. 2, p. 12-13).

uncertain. It may run along the north shore, the center of the lake, the south shore, or several miles inland of the south shore.

Intruded into, through, and overlying the Franciscan Complex are the Clear Lake volcanics, which occupy lowlands on the southwest side of Clear Lake. The volcanics overly and interfinger with Plio-Pleistocene sediments which were deposited in fault-controlled depressions adjoining the present lake.

B. Faults in the Clear Lake Region

Various researchers have mapped the Clear Lake area several times, in whole or part (Brice, 1953; McNitt, 1967, 1968a, and 1968b; Hearn, Donnelly-Nolan and Goff, 1975; Ciancanelli 1970; McLaughlin and Ohlin, 1984; Beall, 1985; and Manson 1989, 1990). The most recent, accurate, and comprehensive compilations are by McLaughlin and Donnelly-Nolan (1981) for the region close to the city, as shown in Figure 2, and by Manson (1989) for a wider area. Figure 3 shows the faults recorded on Manson's map.

Figure 3. Faults in the region of Clearlake. From Burns (1992, Fig. 2, p. 127), after Manson (1989). Solid, dashed, and dotted lines indicate degree of mapping certainty: observed, approximate, inferred. Ticks indicate throw, towards downthrown rocks.

C. Faults in the Lithotope

A lithotope is a boundary representation of lithological units (Burns, 1992). The lithotope for the Clearlake area is illustrated in Figure 4.

The lithotope is a topologically structured representation of the geology in which each cell represents an isolated occurrence of a defined rock formation. There are five types of boundaries between cells, which are stratigraphic superposition, metamorphic replacement, magmatic intrusion, fault, and fault line.

Figure 4. Lithotope for the Clearlake region. The thin lines are lithological boundaries. Solid, dashed, and dotted lines indicate degree of mapping certainty: observed, approximate, inferred. Ticks indicate facing of the boundary toward younger rocks. Heavy lines indicate lithological discontinuities (faults). From Burns (1992, Fig. 3, p. 128), after Manson (1989).

In explanation, suppose a cell of formation A adjoins a cell of formation B. If B simply overlies A, so that the cell boundary, A to B, is a normal depositional boundary, the relationship between the cells is stratigraphic superposition. If B is a sediment, it was deposited on A, if B is a lava, if flowed out over A. The cell boundary is then a simple stratigraphic contact.

If B replaces A, then the cell boundary marks the position of the replacement front. There are several small patches of hydrothermal alteration on the map, which replace Franciscan rocks.

If B was intruded into A, then the cell boundary is an intrusive contact. The boundaries of the cinder cones are the nearest to intrusive contacts on the map. Strictly speaking, however, the intrusive contact is probably hidden inside the cone, and the outer edge of the cone may represent scoria deposited on the country rock, but this is a less-instructive construction.

If B is faulted against A, then the cell boundary is a fault. Topologically, it is a discontinuity in the lithotope. Geometrically, it is a displacement discontinuity which brings fragments of otherwise unrelated cells into juxtaposition. It can be recognized because there is no lithogenetic relationship between the rocks in the two adjacent cells; the only relationship they have is the purely geometric one of juxtaposition.

The fifth and final relationship is where faults generated scarps on topography, and rock formations were deposited up against the scarp. The boundary is then a fault-line contact. Some of the contacts marked as faults in Figure 3 are probably fault-line boundaries.

Any fault detected during constructing the lithotope is a discontinuity in the lithotope. The fault then has stratigraphic expression. The result is that two formations are in faulted contact, so the existence of the fault can be proved on stratigraphic grounds.

Thus, the faults shown in Figure 4 have stratigraphic expression. We refer to them as "faults in the stratigraphy," or more precisely, "faults in the lithotope."

D. Oaks Arm Controversy

Hearn, McLaughlin and Donnelly-Nolan (1988, pp. 15-16) consider Oaks Arm to be a fault-bounded graben. Their curved faults bounding each side of the arm are shown in Figure 2. They cited as evidence the existence of two gaseous springs on the south arm (Smith and Rymer 1976), and a fault at Sulphur Bank mine (White and Roberson 1962; Donnelly-Nolan, Hearn, Curtis, and Drake 1981; and Sims and White 1981).

However Burns, Potter, and Zyvoloski (1992, Fig. 5) considered that the major fault through the mine ran in quite a different direction and was intersected by the Audrey well at depth. Everhardt's band of breccia, which was taken by White and Roberson (1962) to be due to faulting, may be due to other causes. Burns (1992, Fig. 8) gave a reinterpretation of the geology in which faults of the San Andreas system crossed Oaks Arm.

III. TOPOGRAPHY AND FAULTS

A. Detection in the Topography

A comparison of Figures 3 and 4 shows that many more faults were extracted from the geological map (Figure 3) than occur in the lithotop (Figure 4). Faults without stratigraphic expression are detected by other means, such as an examination of the topography. As shown in Figure 5, in a topography affected by faults, linear valleys replace meandering channels; shutterridges, linear scarps, and faceted spurs replace interlocking spurs; and so on.

The topographic features are detected by visual inspection on the ground or from the air. In high altitude and satellite photography the details are lost, and individual topographic features may not be identifiable, but a linear pattern of features may be observed. This is called a topographic lineament.

According to Jennings (1985, p. 36), strong north-west trending lineaments, expressed by the major river drainages, are an indication of the structural grain of the country. Linear v-shaped valleys are characteristic of large faults around the Pacific rim, and are distinctive features of terrains from Japan to Peru. The shape is possibly due to rock fracturing along the fault surface, which generates a dyke-like band of mechanically weak rock along the fault line. Normal channel and slope erosion processes give way to mass movements, generating a distinctive fault-line topography.

Figure 5. Typical landforms indicative of recent movement along active faults. From Bortugno 1982, sheet 5.

Jennings concludes that to "extend precisely the mapping of faults paralleling the San Andreas trend northward into the terra incognita of the northern Coast Ranges block will be difficult because of the numerous and gigantic landslides. However...the major faults coming up from the south must continue into this landslide terrain. Indeed, many of the landslides are in all probability a reflection of the weak rock crushed by the suspected faults...the river undercutting of the steep slopes in this high rainfall area, releases the landslides which can easily mask fault traces."

The geomorphologist Joe Jennings (pers. comm.) used the term "Riegel slopes" to describe these valleysides. The geological maps of the Clearlake area by McNitt (1967, 1968 a,b) are notable because they show a series of arcuate traces along the line of major faults. This map pattern reflects the association between faulting and mass movement of slopes into fault-line valleys.

B. Fault Evaluation Reports

The fault evaluation program consisted of detailed study of the geomorphology along the traces of major fault zones suspected of being active. The program was mandated by the Alquist-Priolo Special Studies Zone Act of 1972 (amended in 1974 and 1975). This Act required the State Geologist to delineate zones to encompass all potentially and recently active faults. The resulting maps were termed Special Studies Zone maps (Jennings, 1992).

The program produced detailed maps of the fault traces deduced from geomorphic information and zoned a strip along each fault as a region of high seismic risk. In some cases, topographic methods were supplemented by trenching across the fault, in order to measure a detailed history of fault displacement. The fault evaluation criteria were described in the California Division of Mines and Geology Note no. 49, printed as Appendix L in Bedrossian (1980).

Bryant (1982) evaluated the Collayomi and Konocti Bay fault zone southwest of Clear Lake. For the Collayomi fault, he reported a significant, right-lateral strike-slip fault zone truncating Pleistocene Clear Lake Volcanics, which may cut late Pleistocene deposits in some areas. The fault lacks geomorphic evidence indicative of Holocene displacement and is well-defined only in parts of its length. Bryant recommended against seismic zoning (that is, zoned for special studies as potentially hazardous). For the Konocti Bay fault zone, he reported a broad zone of discontinuous, well-defined faults that offset volcanic units as young as latest Pleistocene age. Youthful scarps indicate Holocene normal faulting for some strands. He recommended that selected faults be zoned. Bryant also evaluated faults on Quackenbush Mountain and Schoolteacher Hill and at Pearce Airport on the northeast side of Clear Lake. He rated parts of all of these as "well-defined."

Hearn, Donnelly-Nolan and Goff (1975) mapped faults within the city of Clearlake and both sides of Borax Lake. Bryant's evaluation of these was usually "not well-defined." The 1975 Fault Map of California (Jennings, 1975) dates their "recency of faulting" (time of last movement) as Quaternary prehistoric, that is, older than 200 years, but younger than about two million years.

The criterion for zoning faults under the Alquist-Priolo Special Studies Zone Act is that they be "sufficiently active and well-defined." In his fault evaluation report, Bryant (1982) recommended that no faults be zoned for special studies in The Geysers, Whispering Pines, or Lower Lake quadrangles. For Kelseyville and Clearlake quadrangles, he recommended against zoning the Collayomi fault but did recommend zoning the Big Valley fault near Kelseyville, a NE-trending fault zone south of Mt. Konocti, the Red Hill Road fault, and portions of the Konocti Bay fault zone.

IV. FAULTING AND SEISMICITY

A. Earthquake Faults in California

Earthquakes have always been a matter of concern to Californians. In the Owens Valley earthquake of 1872, Josiah Whitney thought that ground fractures were an inconsequential result of earthquakes. The first to realize that faults were generatrices of earthquakes was Lawson in his report on the San Francisco earthquake of 1906. Bailey Willis felt so strongly about the relationship of earthquakes to faults that he described his 1923 fault map of California as an "Earthquake Map of California" (Jennings, 1975).

The modern assumption seems to be a one-to-one correspondence between earthquakes and faults. If an earthquake occurs where no fault is known, the event is taken as evidence of an unmapped fault. If a fault occurs where no earthquakes are known, it is taken as an indication of seismic risk.

Since 1908, fault lines have been mapped as a means of identifying areas of seismic risk. Efforts are made to determine the date of last movement on each fault, the "recency" of faulting, as a means of evaluating the likelihood of recurrence and the degree of risk. The most recent compilations were by Jennings (1975, 1985, 1992) and Wallace (1990).

However, not all seismicity is due to slip on faults. Areas of volcanic and hydrothermal activity such as Long Valley are seismically noisy. Frequent small earthquakes are also associated with hydrothermal power production at The Geysers and with raising of the water level in major impoundments.

B. First-Order Quaternary Faults

Figure 6 shows the first-order faults of northern California. Most of these trend generally parallel to the San Andreas fault and have the same dextral strike-slip displacement. We refer to them collectively, as the San Andreas fault system. The Pliocene-Pleistocene basins were formed by subsidence associated with the faulting.

Within the northern Coast Ranges, the major Quaternary strike-slip faults show a right-stepping en echelon pattern. The Hayward, Rodgers Creek, and Maacama appear to be right-stepping segments of one fault, whereas the Calaveras, Concord, Green Valley, and other segments, appear to be right-stepping segments of another fault. Jennings (1985) has no explanation for this, but such a finding would be consistent with horizontal propagation of the faults from north to south.

Despite the stepping effect, the major Quaternary fault zones retain parallelism over great distances. In the northern Coast Ranges, fault separations are 37, 37, 39, 33, and 35 km (Jennings, 1985, Plate 2B). In the Clear Lake area, the distance from the Bartlett Springs to Maacama Fault is 37 km (Figure 6). The cause of the regularity of spacing is discussed by Jennings (1985, p. 36).

Figure 6. First-order Quaternary faults of northern California. From Hearn, McLaughlin, and Donnelly-Nolan (1988, Fig. 1 p. 11).

C. Neotectonic Structural Provinces

California may be divided into structural provinces characterized by faults of a predominant trend or pattern, and often, the trends of young folds.

Jennings (1985) divided the state into eight structural provinces. Structural province I includes the Coast Ranges (block Ia) and is characterized by faults with a strong northwest orientation, as in the San Andreas fault. The faults display right-lateral (dextral) slip, usually with a vertical component.

The eastern boundary of the Coast Ranges block lies beneath alluvium in the Great Valley and the western boundary lies underwater in the Pacific Ocean. The northern end of the pattern is the Mendocino fault, near the Eel River at latitude 40.2 deg. N. The southern end is the Big Pine fault, near Santa Barbara at latitude 35.2 deg. N.

Jennings (1985) recognized seven subblocks within the Coast Ranges block. The Clearlake area lies within the Berkeley subblock (subblock Ia4), as illustrated in Figure 7. The Berkeley subblock is bounded on the west by the Maacama - Rodgers Creek - Hayward - Calaveras fault zone. It is bounded on the east by the Bartlett Springs - Green Valley fault zone. These faults are intimately related to the San Andreas system. The Calaveras splays off the San Andreas near Hollister at latitude 36.7 deg. N, and the Green Valley splays off the Calaveras near San Jose at latitude 37.4 deg. N.

D. Patterns of Second-Order Quaternary Faulting

Jennings (1985, pp. 35-36) noted that between faults of the San Andreas system in northern California, smaller diagonal faults appear within the blocks. It appears that these have little or no Quaternary displacement. These faults do not occur where the rocks are strong granites and metamorphics, they may be related to the relative ductility in the Franciscan Complex rocks. Jennings interprets the absence of earthquakes on these faults as due to relief of stress, which implies ductile material.

E. Patterns of Quaternary Folding

The possibility of ductile deformation between Quaternary faults is confirmed by the location and orientation of Quaternary folds. Jennings (1975, p. 38) shows diagonal folds between the Rinconada and San Andreas faults near San Lucas at latitude 36.1 deg. N.

Figure 8 is a circular histogram showing fold trends in central California. The mode is northwest (315 deg. E of N), which is 6 deg. from the San Andreas (321 deg. E of N).

Northwest-trending folds at The Geysers (McLaughlin, 1981) and near Lower Lake (Brice, 1953; Swe and Dickinson, 1970; and Wagner and Bortugno, 1982) may be assigned to this neotectonic regime.

It follows from the discussion of Jennings (1975), that the existence of folds and lack of seismicity implies a ductile basement. This agrees with the 'diapiric' or 'piercement' fold style observed in this central belt at The Geysers (McLaughlin, 1981, Fig. 12, p. 21), New Idria (Page, 1966), and Mount Diablo (Bailey, Irwin and Jones, 1964, Fig. 30, p. 156).

Figure 7. Major Quaternary fault-blocks in northern California. From Jennings (1985, Plate 2B, in pocket).

Figure 8. Circular histogram showing fold trends in central California. From Page (1966, Fig. 10, p. 273).

F. Relation of Faults to Seismicity

The most recent review of seismicity in California is the collection of papers in Wallace (1990). They contain epicenter maps and sections throughout California, demonstrating very striking associations between earthquakes and faults of the San Andreas system. Eberhart-Phillips' (1988) map of epicenters of seismic events (Figure 9) shows a concentration of events along the traces of the first-order faults of the San Andreas system. The cluster of seismicity at The Geysers is associated with geothermal power production. The cluster near Clear Lake on the southwest side of the Highlands arm is due to activity on the Konocti Bay fault zone.

V. SEISMIC MONITORING IN NORTHERN CALIFORNIA

A. Monitoring The Geysers

The induced seismicity at The Geysers has led to erection of close-range seismic stations to monitor the events and publication of a number of reports on seismic activity (Lange and Westphal 1969; Hamilton and Muffler 1972; Bufe, Marks, Lester, Ludwin and Stickney 1980, 1981; Ludwin and Bufe 1980; Eberhart-Phillips and Oppenheimer 1984; and Oppenheimer 1986).

Lange and Westphal (1969) observed microearthquakes originating from a fault system on Big Sulphur Creek. They differentiate these events from steam-generated seismic noise. They suggest that the earthquakes are generated on "active faults that maintain zones of high permeability."

Figure 9. Epicenters of earthquakes in northern California. Circles are epicenters of earthquakes with a magnitude greater than or equal to 1.5 for the period March 1972 to December 1981. The dashed line encloses a region of 8% velocity decrease determined by delays in arrival of teleseisms. From Eberhart-Phillips (1988, Fig. 1, p. 196).

Hamilton and Muffler (1972) found a similar distribution of earthquakes but were unable to determine whether the cause was natural or induced. They did not think that either water injection or steam withdrawal would be a cause. They suggested, after Brace and Byerlee (1966), that absence of deep earthquakes could be an indication of high heat flow. They found the first motions to be dextral strike-slip on a north-northwest-trending fault plane, which is consistent with the San Andreas fault system.

Bufe, Marks, Lester, Ludwin, and Stickney (1980, 1981) found two clusters of seismicity in the producing steamfield. The seismicity within the clusters was essentially continuous, with large numbers of small events, compared to the episodic nature of events in the surrounding region. First motions gave a minimum horizontal axis of stress trending 110 deg. E of N. In 1977, the pattern of deep events changed from predominantly strike-slip to predominantly normal faulting; such a change suggests a decrease in magnitude of the maximum horizontal stress. Longer monitoring (Ludwin and Bufe 1980) sustained the interpretation that the seismicity was induced by fluid injection, possibly by changing pore pressure and localized cooling.

Eberhart-Phillips and Oppenheimer (1984) confirmed the association of seismicity with power production but ruled out both fluid injection volume and steam production as direct causes. They suggested instead volumetric contraction due to steam withdrawal, or increased friction on faults due to silica deposition. Oppenheimer (1986) established that The Geysers area, below 1 km depth, is undergoing uniaxial extension with the least principal stress oriented 105 deg. E of N (Figure 10a). This agrees (see Figure 10b) with the azimuth range of 90-120 deg. E of N for the principal axis of extension strain deduced by McLaughlin (1981, Fig. 7, p. 11).

Figure 10. (a) Present stress field in The Geysers-Clear Lake region from focal plane solutions; (b) Stresses on the San Andreas fault system for the past 5 million years. From Hearn, McLaughlin and Donnelly-Nolan 1988, Fig. 2, p. 13.

B. Monitoring at Clearlake

The spatial distribution of earthquakes near Clear Lake (Figure 11) was recently reviewed by Eberhart-Phillips (1988). Eberhart-Phillips dates activity on the fault zones as younger than 2.0 million years and possibly younger than 0.7 million years for the Bartlett Springs fault zone; younger than 0.1 million years for the Konocti Bay fault zone, and younger than 1.1 million years for the Collayomi fault zone. For the southern part of Clear Lake, the mean depth was 2.6 km for the observing period, while the maximum depth was 5.8 km. It is interesting to note that an HDR reservoir at 3-km depth would be within the source region of natural earthquakes.

Figure 11. Epicenters of earthquakes in the Clear Lake area. Circles are epicenters of earthquakes with magnitude greater than or equal to 1.0 for the period March 1975 to March 1983. From Eberhardt-Phillips (1988, Fig. 5, p. 200).

The map of epicenters in Figure 9 shows a prominent cluster near Konocti Bay, the cluster is associated with the Konocti Fault zone. On a broader scale, the map also appears to show events on a line trending northeast from The Geysers through Konocti Bay, across Highland Arm, and continuing northeast beyond the city. According to Eberhart-Phillips (1988), the trend coincides with no known fault zone although it may be associated with the row of cinder cones shown in Burns (1992, Fig. 6), the Burns Valley fault shown in Burns, Potter and Zyvoloski (1992, Fig.12), the Cross Spring Fault (shown here in Figure 2), or to a deep basement structure detected by electrical sounding (Keller, Pritchard, Jacobson, and Harthill, 1984). The alignment is, however, less obvious in Figure 11, which uses the same data.

On behalf of a geothermal explorer, a high-gain seismic monitoring network was operated at Clearlake for five days in late June 1975, recording 13 events. Some of the epicenters were located on a northeast-trending fault zone running approximately through Burns Valley. Others were located on a northwest-trending fault running through Borax Lake. The work gave results consistent with Figure 11, which supersedes that work.

The focal mechanisms illustrated in Figure 12 are dextral strike-slip with a normal component of dip-slip. This is compatible with the regional San Andreas system.

Figure 12. Diagrams of focal mechanisms for well-constrained events at Clear Lake. From Eberhart-Phillips (1988, Fig. 8, p. 203).

The pressure and tension axes are illustrated in Figure 13. The tension axes form a bipolar cluster with (linear) mean trend of 115 deg. E of N, and the pressure axes form a girdle about the tension axes. This is consistent with the "uniaxial tension" regime of Oppenheimer (1986), which Eberhart-Phillips (1988) suggests might be caused by a crustal magma chamber.

F. Klein (personal communication) has pointed out that the major strike-slip faults are weak, with low internal friction, so that shear stresses along the fault are relieved by displacement along the fault until the least compressive stress in the adjacent plate rotates and becomes parallel to the fault. The rotated focal mechanisms in Figure 12 (such as those numbered 4, 6, 9, 10, 12, 13, 16, 17, and 18) show this effect, indicating that those events might be located in plates between the main faults.

Figure 13. Pressure and tension axes at Clear Lake. From Eberhart-Phillips (1988, Fig. 7, p. 202).

C. Geothermal versus Faulting Activity

There remains the question of whether seismic activity indicates geothermal action, faulting, or fracture-controlled geothermal action along faults. Hadley and Cavit (1982) made a statistical comparison of earthquake catalogs from Imperial Valley, Coso, The Geysers, and Lassen Peak, to the San Jacinto fault. They arrived at a "geothermal discriminant" which might enable seismic data to be used in exploration for geothermal areas, but their procedure appears not to have been tested.

F. Klein (personal communication) has pointed out that the elevated temperature and pore pressure associated with a hydrothermal anomaly could locally trigger a cluster of earthquakes, but their failure mechanism could still be controlled by the regional shear stress. So a hydrothermal anomaly might show itself as a cluster of faults with strike-slip, rather than some alternative focal mechanism.

The earthquake faults of California are confined to an upper-crustal brittle zone, or "seismogenic" layer, resting on a ductile zone, or "subseismogenic" layer. Thus, according to

Lachenbruch and Sass (1980), these faults "bottom" on a zone of decoupling, or detachment, forming an "inverted T" structure. Castle and Gilmore (1992) show how, in the Transverse Ranges of southern California, strike-slip motions of faults in the upper layer set up tractions at the detachment which lead to subhorizontal shearing and accompanying upwarping and uplift. They could also lead to subhorizontal or low-angle, reverse faults, which would be "blind" because they do not appear at the surface. The Northridge quake sustains this concept. Recently, Brocher et al. (1994), in the BASIX experiment conducted in San Francisco Bay, found a well-defined subhorizontal reflector at depths of 10-15 km which they interpret as probably also a detachment surface. Thus, horizontal, blind faults could also occur in the northern Coast Ranges and might pose a hazard in HDR development. They would be expected to occur as circular or oval clusters of seismic epicenters showing predominantly thrust motions. That description does not apply to the faults near Clearlake.

VI. CONCLUSIONS

The seismic activity at Clear Lake is associated with known faults and with an undetermined structure trending northeast of the city of Clearlake. The most active region is the Konocti Bay fault zone, where currently-active faults have been found by the Fault Evaluation program.

There are occasional events in the Borax Lake and Burns Bay fault zones. These faults also show geothermal activity.

The map of epicenters in Figure 9 is not sufficiently precise for the positive determination of structures associated with earthquakes. Because the procedure for finding the location of earthquake epicenters is very sensitive to small errors in timing, the number and geometry of recording stations, and to crustal velocity structure, a strong association is needed to positively identify a cause. In this case, the data are insufficient to clearly assign structural causes.

Available data indicate that earthquake epicenters are associated with faults. Any possible association with volcanic features has not been established. Some seismically-active faults also contain geothermal activity in the form of hot springs or fumeroles. Earthquakes may indicate the presence of faults alone or of faults plus geothermal activity. The discriminant of Hadley and Cavit (1982) remains to be tested in the Clearlake area.

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