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Pre-Tertiary Geology and Structural Control of Geothermal Resources, The Geysers Steam Field, California

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ABSTRACT

In the Geysers steam field of northern California, Upper Jurassic and Cretaceous rocks of the Franciscan assemblage form the core of a southeastward-plunging antiform that has been highly modified by late Tertiary and Quaternary faulting. These intensely deformed volcanic and sedimentary rocks are metamorphosed to assemblages containing pumpellyite, lawsonite, and jadeite, and exhibit textural reconstitution that generally increases in the direction of structurally higher rocks.

Comparison of the structure of these Franciscan rocks with microearthquake and resistivity data suggests that economically significant steam reservoirs are in part related to local fault-controlled structural traps. In an area of shallow steam production near Geysers Resort, the epicenters and foci of numerous microearthquakes and extensive hydrothermal alteration are associated with a zone of N 30°-35°W-trending faults that dip steeply to the northeast. The microearthquakes and hydrothermal alteration may be related to hot water- or steam-saturated rock in the fault zone. Structural control of steam resources is also indicated near Castle Rock Spring, approximately 4 miles southeast of Geysers Resort. A low resistivity anomaly over the Castle Rock Spring steam field is probably due to rock saturated with hot water. This presumed zone of water-saturated rock occupies an anticlinal warp between steeply dipping faults trending N 80°W in foliate metagraywacke, basaltic volcanic rocks, and serpentine. Steeply dipping faults trending N 50°W may bound the east side of the Castle Rock Spring steam reservoir.

INTRODUCTION

The Geysers steam field is located in the Mayacmas Mountains of northern California, about 110 km northwest of San Francisco. The field is a few kilometres south of Clear Lake basin, a center of major Quaternary volcanism, and a few kilometres northwest of Mount Saint Helena, the locus of late Tertiary volcanism (Fig. 1). The Geysers geothermal area is particularly significant since it is now the world's largest geothermal producer of electrical power (greater than 500 MW generating capacity by 1975), and it is also one of the few areas known to have vapor-dominated hydrothermal systems (White, Muffler, and Truesdell, 1971). The next largest vapor-dominated hydrothermal system is in the Larderello and Monte Amiata areas, Italy.

The Geysers-Clear Lake area is one of several geothermal systems selected by the U.S. Geological Survey for detailed study. Detailed mapping of the pre-Tertiary rocks in the area was begun in 1973, and other geologic mapping and geochronologic studies of the Quaternary volcanic rocks by Carter B. Hearn and Julie Donnelly are also in progress. Similar work is also in progress in the Tertiary volcanic rocks to the southeast of The Geysers area, by K. F. Fox (Fig. 1). These mapping projects are providing the geologic data base to which geochemical, geophysical, and hydrologic studies will be applied for interpreting the mechanics of The Geysers geothermal system.

LATE MESOZOIC TECTONIC FRAMEWORK

Late Mesozoic rocks in The Geysers-Clear Lake area are assigned to two approximately coeval assemblages considered to have originally been deposited in widely separated basins to the east of a mid-ocean rift system. The late Mesozoic and early Tertiary Franciscan assemblage forms the basement complex of much of the California Coast Range, and is composed of a volcanic-sedimentary sequence, thought to represent a deep ocean trench or arc-trench gap deposit (Blake and Jones, 1974).The Great Valley sequence and the ophiolite complex present beneath its base are thought to represent rocks originally deposited and emplaced east of the Franciscan assemblage site of deposition. Deposition of Great Valley sequence strata presumably was upon continental granitic crust along the east side of the basin, but it overlapped onto ophiolite (oceanic crust) along the west margin of the basin.

The Franciscan assemblage has been highly tectonized and subjected to regional metamorphism related to abnormally high pressure and deep burial, resulting in the development of pumpellyite and lawsonite-bearing metamorphic mineral assemblages (Ernst, 1971; Blake, Irwin, and Coleman, 1967). In contrast to the Franciscan assemblage, the Great Valley sequence is only mildly deformed by folding and faulting, and metamorphism is confined to low-temperature zeolites attributable to deep burial (Dickinson, Ojakangas, and Stewart, 1969; Bailey and Jones, 1973). Present

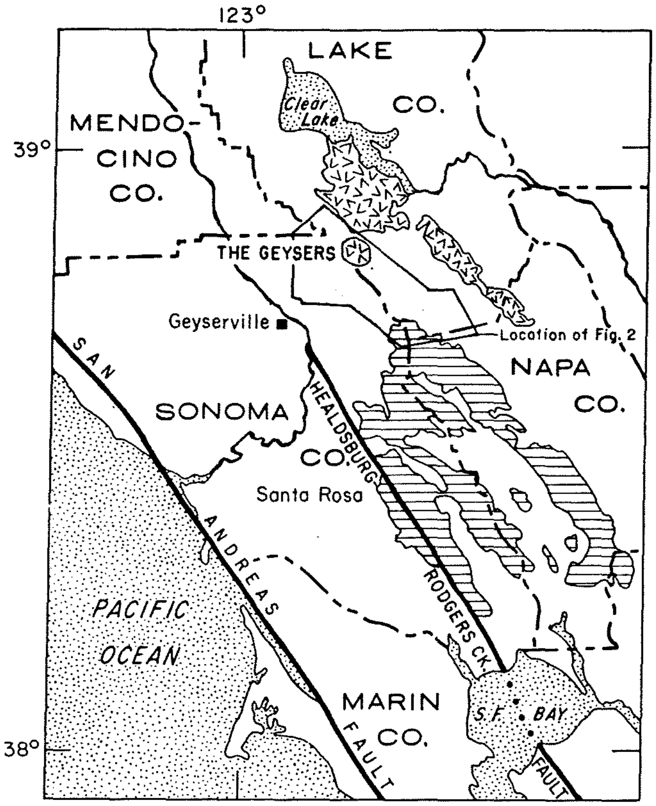


Figure 1. Location of The Geysers geothermal area and nearby late Tertiary and Quaternary volcanic rocks. The V pattern indicates location of Quaternary volcanic rocks; line pattern, late Tertiary volcanic rocks.

distribution and structural relations of the Great Valley sequence and the Franciscan assemblage indicate that the Great Valley sequence now overlies Franciscan rocks of equivalent age along a zone of regional thrust faulting, although in many areas this thrust relation is confused by later high-angle faults of probable Tertiary and Quaternary age. The regional thrust relation has been explained by many workers (Hamilton, 1969; Bailey, Blake, and Jones, 1970; Blake, Irwin, and Coleman, 1967) as a result of eastward subduction of the Franciscan assemblage beneath oceanic crustal rocks and Great Valley sequence strata deposited upon it. This subduction is thought to have begun during the mid-Cretaceous, presumably the result of convergence of an oceanic plate upon which Franciscan sediments were deposited, with the continental margin east of the Franciscan sediments. As this plate convergence progressed, the Franciscan deposits were subducted eastward beneath adjacent oceanic crustal rocks, eventually underriding the Great Valley sequence. Deformation and high-pressure metamorphism in the Franciscan assemblage are thought to have occurred during this period of subduction (Blake, Irwin, and Coleman, 1967). The process of subduction is thought to have ceased about 30 million years (m.y.) before present (Atwater, 1970), when convergent motion between the oceanic and continental plate boundaries changed to transform motion, initiating the San Andreas strike-slip system. Large scale strike-slip faulting has continued to the present day, obscuring the earlier thrust fault relations produced during the late Mesozoic and early Tertiary.

PRE-TERTIARY ROCK UNITS

Franciscan Assemblage

The Franciscan assemblage in The Geysers area is typical of Franciscan rocks over a large part of California. It consists largely of graywacke and minor shale, with shale being somewhat more abundant in the structurally higher, most deformed part of the assemblage (Fig. 2). The essential compositions of the graywackes vary widely with quartz 10-55%, total feldspar (plagioclase) 25-55%, and total lithics 20-55%. Nonautoclastic lithic fragments consist largely of chert and subequal amounts of mafic and silicic volcanic rocks (the ratio of chert to volcanic detritus varies between 1:1 and 5:1).

Altered intrusive and extrusive igneous rocks commonly referred to as greenstone, and consisting largely of pillow basalt, basaltic pillow breccia, basaltic tuff, and minor diabase and gabbro, are second in order of abundance in the Franciscan assemblage. These igneous rocks are now confined to the structurally higher parts of the assemblage and their contacts are in most instances tectonic, so that their original relation to the sedimentary rocks is largely undetermined. Radiolarian cherts associated with the graywacke and volcanic rocks and conglomerate are locally prominent constituents in structurally higher parts of the Franciscan assemblage.

The occurrence of blueschist metamorphic mineral assemblages in the Franciscan assemblage has been the object of many studies by others (Coleman and Lee, 1963; Blake, Irwin, and Coleman, 1967; Ernst, 1971; Coleman and Lanphere, 1971). In general, two modes of occurrence of blueschist are recognized in The Geysers area: (1) in schistose to gneissose tectonic inclusions from less than a meter up to several hundreds of meters long that are associated with other tectonic inclusions of eclogite or amphibolite along highly sheared zones and serpentinite contacts, and (2) in graywacke and interlayered volcanic rocks and chert that regionally have weak to highly developed metamorphic textural fabrics. These two modes of occurrence of blueschist minerals in the Franciscan assemblage were shown by Coleman and Lanphere (1971) and Lanphere, Blake, and Irwin (1975) to represent metamorphic events of different ages. The schistose and gneissose blueschist tectonic inclusions were shown to have been metamorphosed about 150 m.y. ago (Late Jurassic), whereas the rocks with regionally developed metamorphic textural fabrics were shown to have been metamorphosed 114-120 m.y. ago (Early Cretaceous) in northern California. Elsewhere in the Coast Ranges Franciscan rocks may have been subjected to even younger regional blueschist metamorphism.

Serpentinite is present along most faults and within highly sheared zones in the Franciscan assemblage (Fig. 2). A few serpentinite bodies are metamorphosed and contain the mineral assemblages antigorite ± talc ± actinolite ± chlorite. Other partially to completely serpentinized peridotite bodies containing chrysotile and clinochrysotile are present either along steep dipping faults completely enclosed by Franciscan rocks or as klippen of the ophiolite below the base of the Great Valley sequence.

The Franciscan assemblage is known to range in age from Late Jurassic to early Tertiary (Eocene) (Blake and Jones, 1974). Within The Geysers area, however, fossil control is present only in the structurally higher parts of the

Franciscan assemblage, and strata in the structurally lower part of the section are of unknown age and separated by faults from the higher strata. Several dates have been obtained from radiolaria in cherts interlayered with volcanic and sedimentary rocks from the upper parts of the Franciscan assemblage in The Geysers area. These dates indicate a range in age of Late Jurassic (early Tithonian) to Early Cretaceous (late Hauterivian or early Barremian) (Emile A. Pessagno, written comm., 1973-74). One of these dates, obtained from a conglomerate clast of chert, yielded a Hauterivian or Barremian age, indicating that at least some of the structurally high clastic Franciscan rocks are younger than Hauterivian or Barremian.

Elsewhere in the Coast Ranges similar Franciscan rocks have been found to be no older than Tithonian (Blake and Jones, 1974), and therefore the Franciscan assemblage in The Geysers area is regarded to be Late Jurassic (early Tithonian) or younger. Franciscan sandstones of Tertiary age have been reported west of The Geysers area (Blake and Jones, 1974), but these rocks are arkosic in composition and generally contain significant (>3%) potassium feldspar (Bailey, Irwin, and Jones, 1964). Since the structurally low undated Franciscan rocks in The Geysers area are graywackes containing less than 1/2% potassium feldspar, and generally lithic to quartzose in composition, they are considered here to be no younger than Cretaceous.

Ophiolite complex. Ophiolite present below the base of the Great Valley sequence underlies Mount Saint Helena to the southeast, the prominent ridge between Geyser Peak and Black Mountain in the southwest part of the map area, and also outcrops for several kilometres along the north side of Cobb and Collayomi Valleys (Fig. 2). Ophiolite exposed at Geyser Peak consists of about 120 m of a basal sheared peridotite, above which is about 365 m of poorly exposed microgabbro and diabase, above which is an undetermined thickness of basalt pillows, tuff, pillow breccia, and diabase. The ophiolite of Mount Saint Helena is composed of about 600 m of peridotite in the lower part, above which is 520 m of gabbroic rock, above which is 300 m of diabase breccia (Bezore, 1969). Most of the peridotite and as much as 150 m of the overlying gabbro section present at Mount Saint Helena are missing from the ophiolite of Geyser Peak. Radiolaria from chert interlayered with the basaltic rocks of Black Mountain have been assigned a Late Jurassic (late Kimmeridgian and early Tithonian) age by Emile Pessagno (written comm., 1975), suggesting a Late Jurassic age for that part of the ophiolite.

Great Valley Sequence

Knoxville formation. A few small tectonically isolated patches of strata assignable to the Knoxville formation are present in the southwest and southeast parts of the map area in depositional contact with underlying ophiolite (Fig. 2).

Assignment of these isolated strata to the Knoxville formation is based on their age, lithologic similarity to the Knoxville elsewhere in the Coast Ranges, and upon the depositional contact relationship of these strata with underlying ophiolite. Considerable thicknesses of Knoxville strata are exposed to the north, in the Clear Lake area (Brice, 1953; Swe and Dickinson, 1970). The Knoxville formation in the map area is composed largely of dark green to black mudstone and siltstone and less abundant fine-grained interbedded basaltic sandstone. Sporadic carbonate concretions in the mudstone exposed along The Geysers-Healdsburg road contain rare dinoflagellates of Early Cretaceous age (W. R. Evitt, written comm., 1973).

Although later faults now obscure the relation, mudstone interbedded with a sedimentary breccia composed largely of angular basalt and diabase detritus is locally present at the base of the Knoxville formation in depositional contact with underlying basaltic volcanic rocks of the ophiolite complex. This depositional relation can be observed along The Geysers-Healdsburg road near Black Mountain.

STRUCTURE OF PRE-TERTIARY ROCKS

Pre-Tertiary rocks in The Geysers area compose an extremely complex southeastward-plunging antiform, here referred to as the Mayacmas antiform. The Mayacmas antiform is a secondary flexure in the northward extension of the broader Diablo antiform (Bailey et al., 1964, Fig. 29), and its core is composed of deformed Franciscan rocks. The Franciscan core rocks are overlain to the northeast, southeast, and southwest by ophiolite and rocks of the Great Valley sequence. The distribution of these overlying rocks roughly outlines the southeastward plunge of the Mayacmas antiform. On the southwest this feature is flanked by a system of steeply dipping, northwest-trending strike-slip faults alined with Alexander Valley—Geyser Peak and Little Sulphur Creek fault zones (Fig. 3).

Deformation of Franciscan rocks in the core of the Mayacmas antiform, as elsewhere in the Coast Ranges, largely predated the late Cenozoic regional warping and block faulting associated with formation of the Mayacmas and Diablo antiforms. The early deformation is thought to have occurred during eastward subduction and metamorphism of Franciscan rocks beneath the Great Valley sequence during the late Mesozoic and early Tertiary, or prior to about 30 million years ago (Atwater, 1970). Also present in the area, however, are prominent steeply dipping northwest- and east-west-trending fault sets that traverse the Mayacmas antiform and locally displace late Pliocene and Holocene deposits. Owing to the complexity of this faulting, it is difficult or impossible in some areas to distinguish faults produced during the late Mesozoic and early Tertiary from those produced during the late Tertiary and Quaternary. It is in fact probable that some of the more recent faulting in the area occurred along the older faults.

The dominant northwest structural grain in The Geysers region is due largely to the prevailing fault pattern (Fig. 3). This northwest-trending fault pattern consists of at least two components: (1) imbricate northeast- southeast- and southwest-dipping high- to low-angle thrust faults that separate tectonic slabs in the Franciscan assemblage, and (2) later, steeply dipping northwest-trending faults with vertical and strike-slip components overprinted upon the earlier thrust faults.

A prominent component of strike-slip movement on several of the later high-angle faults is inferred from several lines of evidence. Linear features on the surfaces of many of these steeply dipping faults indicate a strong lateral shear component, if it is assumed that these faults were not tilted from the horizontal or folded. Elsewhere, the distribution, structural dip, and compositions of the Geyser Peak and Mount Saint Helena ophiolite masses and associated overly-

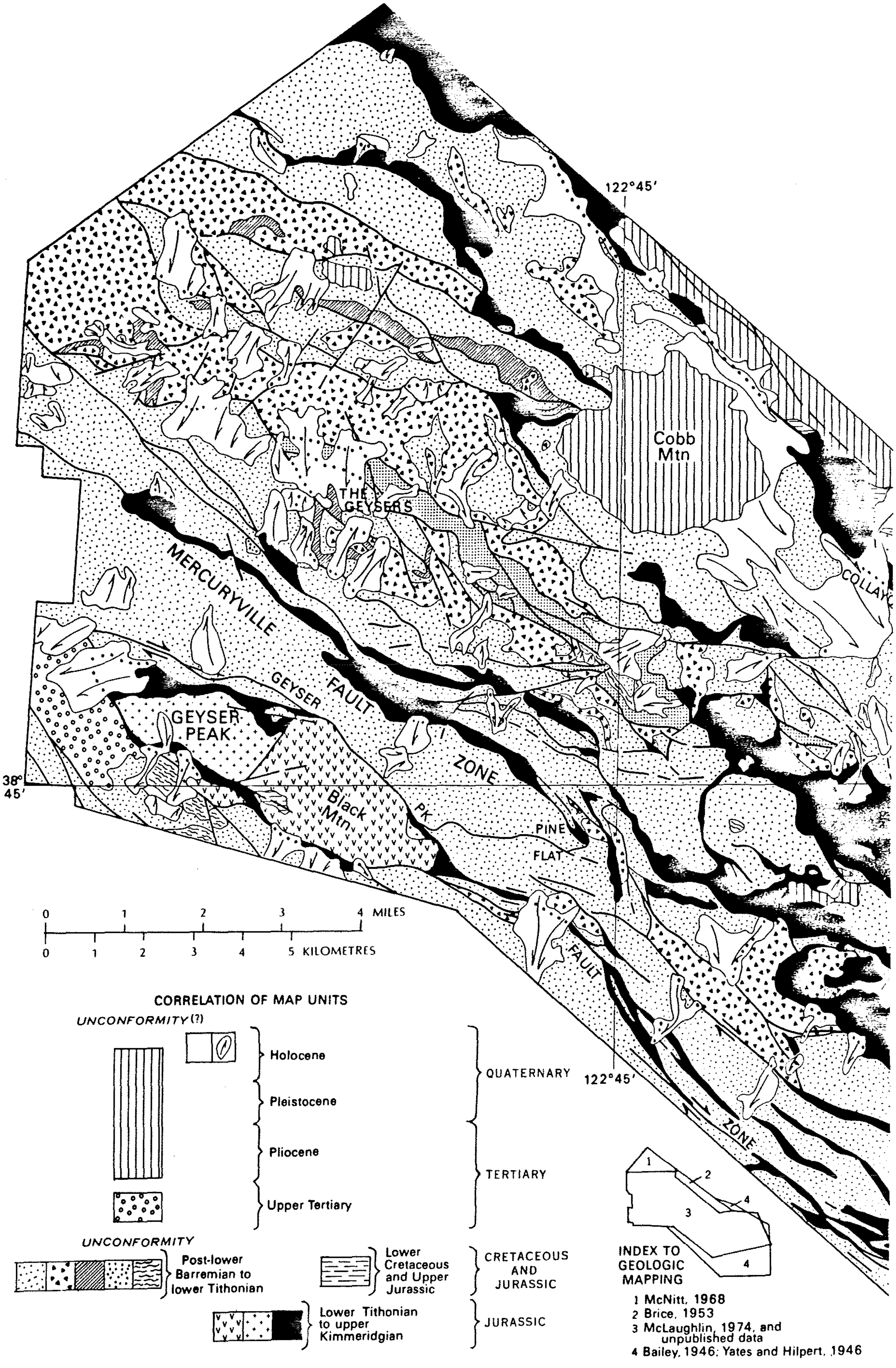


Figure 2. Generalized geologic map of the Geysers area, emphasizing the pre-Tertiary rocks.

EXPLANATION

Landslide deposits (Quaternary)

Alluvium (Quaternary)

Volcanic rocks of Clear Lake (Quaternary) and Sonoma volcanics (Pliocene)

Nonmarine gravel (Upper Tertiary)

FRANCISCAN ASSEMBLAGE (UPPER JURASSIC AND CRETACEOUS)

Largely graywacke, shale, and conglomerate, in places pervasively sheared into melanges containing tectonic blocks of basaltic volcanic rock, chert, blueschist, amphibolite, or eclogite

Basaltic volcanic rocks, including pillow basalt, pillow breccia, diabase, and basaltic tuff

Chert, red, green, and white in color, locally containing abundant radiolaria

Prominent tectonic blocks of blueschist, amphibolite, and eclogite

Metamorphosed serpentine (antigorite ± talc ± actinolite ± chlorite mineral assemblage) exposed along Big Sulphur Creek

GREAT VALLEY SEQUENCE (Upper Jurassic and Lower Cretaceous)

Knoxville Formation; mudstone, siltstone, and fine-grained basaltic sandstone with minor carbonate concretions; sedimentary breccia composed largely of volcanic detritus locally present at base

OPHIOLITE (Upper Jurassic)

Basalt pillows, tuffs, and pillow breccias, locally with interlayered radiolarian chert of Late Kimmeridgian to Early Tithonian age

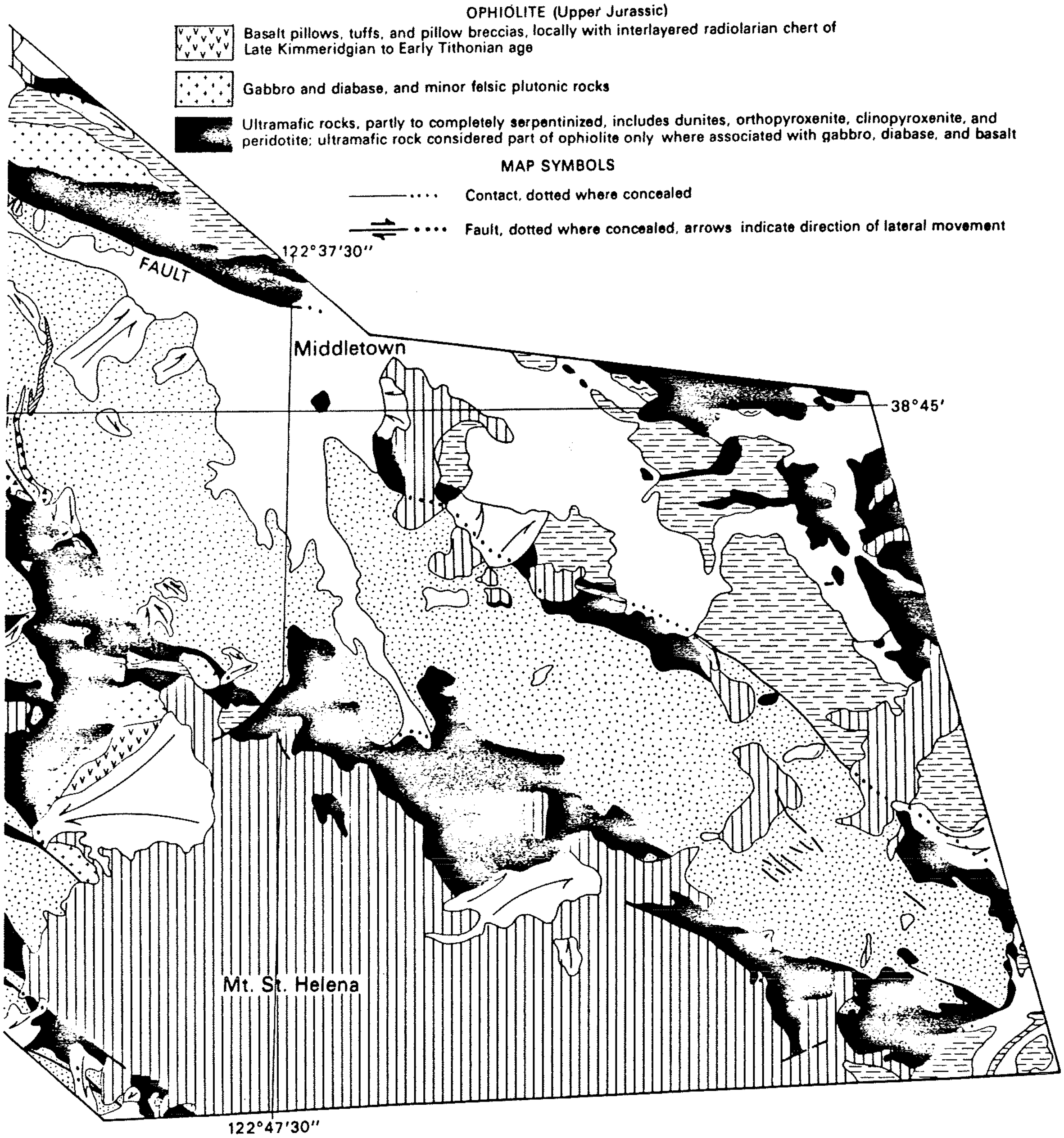
Gabbro and diabase, and minor felsic plutonic rocks

Ultramafic rocks, partly to completely serpentinized, includes dunites, orthopyroxenite, clinopyroxenite, and peridotite; ultramafic rock considered part of ophiolite only where associated with gabbro, diabase, and basalt

MAP SYMBOLS

Contact, dotted where concealed

Fault, dotted where concealed, arrows indicate direction of lateral movement



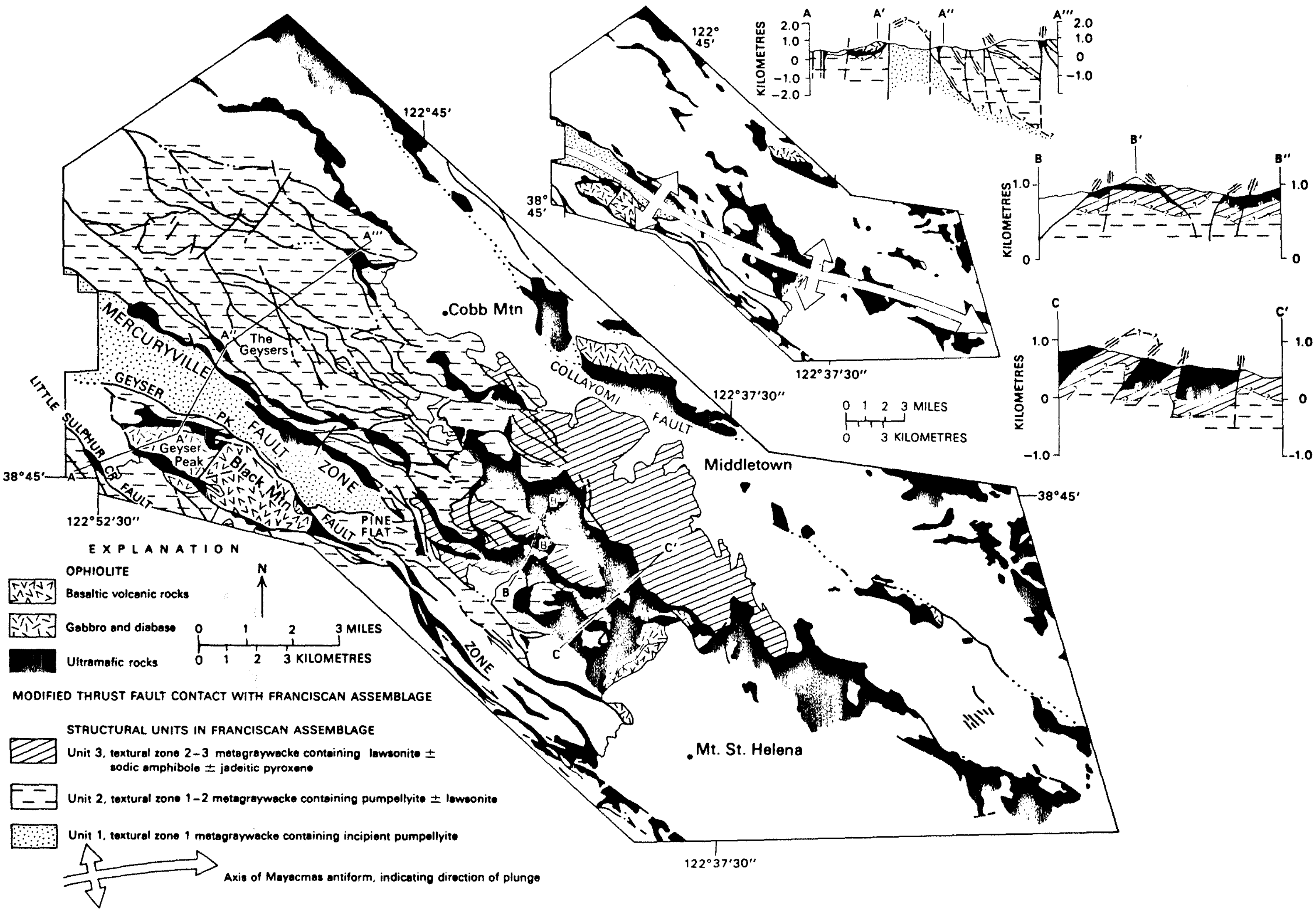


Figure 3. Map showing major structural units of the Fransciscan assemblage in the Geysers steam field and vicinity, with respect to distribution of ophiolite and faults.

ing basal strata of the Great Valley sequence strongly suggest that a minimum right-lateral offset of 8-9 km has occurred along the Geyser Peak fault zone (Fig. 3).

Evidence for recent fault activity is also present in some areas. Southwest of Geyser Peak, along Little Sulphur Creek, the northwest-trending Little Sulphur Creek fault truncates late Tertiary nonmarine strata. Such physiographic features as sag ponds, linear trenches, and a right-laterally offset fence line (D. H. Radbruch, oral commun., 1974) along this fault suggest Holocene offsets. Elsewhere, near Geysers Resort (Fig. 4), Holocene alluvial terrace deposits are steeply tilted against a steep northwest-trending fault along Big Sulphur Creek. Associated with the faulting along Big Sulphur Creek are numerous microearthquakes (Hamilton and Muffler, 1972), further suggesting recent fault activity in that area.

Franciscan rocks in the core of the Mayacmas antiform are divided into three fault-bounded structural units (Fig. 3). The lowest, structural unit 1, is composed of strata of unknown age exposed along a N 40°W-trending belt between the steeply-dipping Mercuryville and Geyser Peak fault zones. Unit 1 is a relatively intact, flysch-like sequence of graywacke and minor interbedded concretionary black shale, compressed into tight southeast-trending folds. The graywacke of structural unit 1 is feebly reconstituted to textural zone 1 of Blake, Irwin, and Coleman (1967), and it contains the metamorphic mineral assemblage quartz (SiO_2) + albite ($NaAlSI_3O_8$) + phengite [$K_2Al_4(Si_6Al_2)O_{20}(OH)_4$] ± pumpellyite [$Ca_4MgAl_5O(OH)_3(Si_2O_7)_2(SiO_4)_2 \cdot 2H_2O$].

Structural unit 2 overlies unit 1 north of the Mercuryville fault zone and south of the Geyser Peak fault zone. In the vicinity of Pine Flat, in the south part of the area, unit 1 terminates and is enclosed by unit 2. In contrast to the lower structural unit, unit 2 is highly tectonized, lithologically heterogeneous, and locally chaotic. Unit 2 is characterized as a broken formation of imbricate tectonic slabs up to several kilometres long. These slabs generally are composed of relatively intact well-bedded graywacke, minor interbedded shale, conglomerate, and locally abundant basaltic volcanic rocks and chert. The larger intact slabs are separated by highly sheared shaly zones of tectonic melange containing smaller sheared masses of graywacke, conglomerate, basaltic volcanics, chert, locally abundant sporadic masses of foliate blueschist and eclogite, and prominent elongate serpentinite bodies. The rocks in structural unit 2 are feebly to moderately reconstituted, with the graywackes assigned to textural zones 1 to 2 of Blake, Irwin, and Coleman (1967). The metamorphic mineral assemblage recognized to date in graywackes of unit 2 includes quartz + albite + phengite ± pumpellyite ± lawsonite [$CaAl_2Si_2O_7(OH)_2 \cdot H_2O$].

The highest structural unit mapped in the Franciscan, unit 3, overlies unit 2, wrapping over it to the northeast and southeast beneath the overthrust ophiolite complex at the base of the Great Valley sequence. Unit 3 appears to be terminated against the southeastward extension of the Geyser Peak and Mercuryville fault zones in the south part of the area. Lithologies present in tectonic unit 3 are identical to those in unit 2, except that all rocks in unit 3 are moderately to highly reconstituted texturally, with all the graywackes assigned to textural zones 2 to 3 of Blake, Irwin, and Coleman (1967). The metamorphic mineral assemblages quartz + phengite + lawsonite ± albite ± sodic amphibole [$Na_2(Mg,Fe,Al)_5Si_8O_{22}(OH)_2$] ± jadeitic pyroxene ($NaAlSi_2O_5$) has been recognized in graywackes of unit 3, with jadeitic pyroxene present only locally. Basaltic volcanic rocks and cherts interlayered with the graywackes may contain abundant sodic amphibole; the cherts may, in addition, contain stilpnomelane [$K(Fe,Al)_{10}Si_{12}O_{30}(O,OH)_{12}$].

RELATION OF STRUCTURE TO RESOURCES

Figure 5A illustrates the generalized structural model for a geothermal system indicated by Muffler and White (1972)

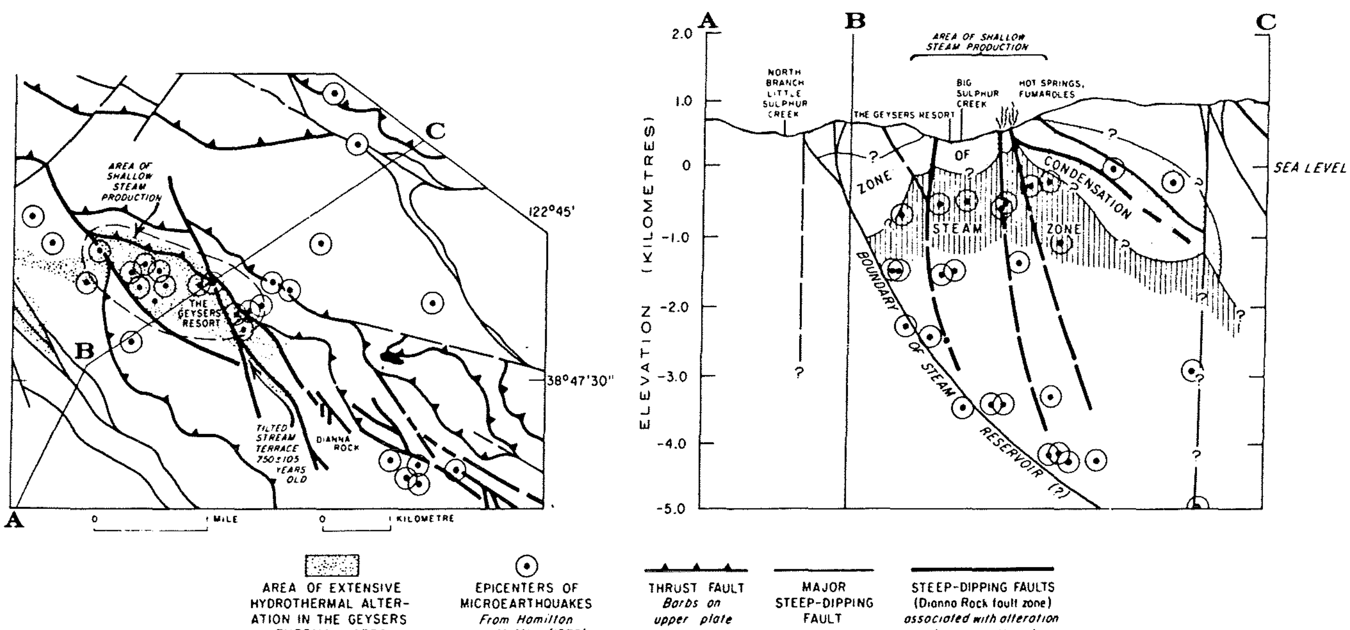


Figure 4. Map showing relation of hydrothermal alteration and microearthquakes to the Dianna Rock fault zone near Geysers Resort. *Left:* map view. *Right:* vertical cross section showing distribution of microearthquake hypocenters and inferred relation to steam reservoir.

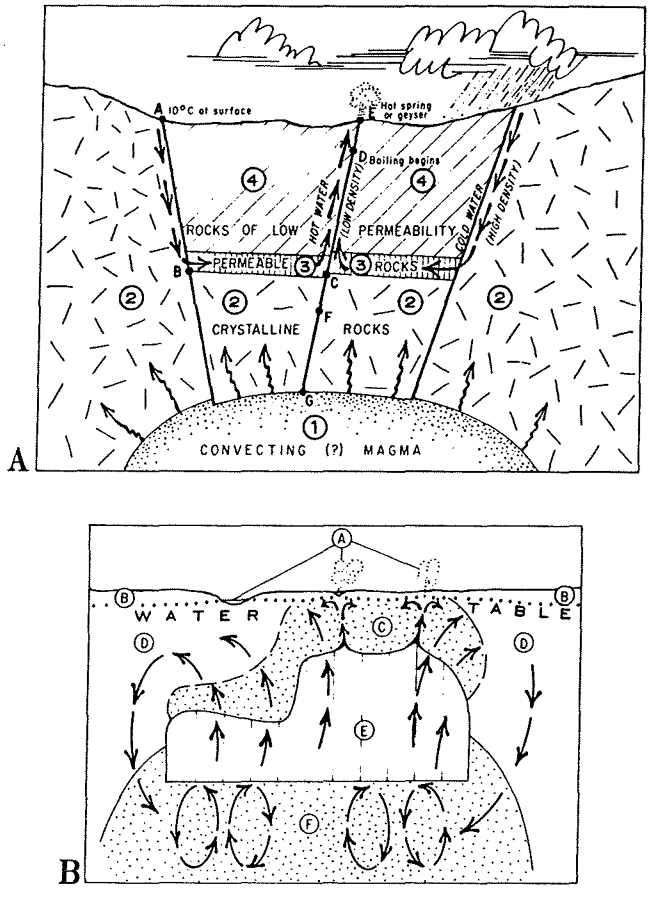


Figure 5. Idealized structural and dynamic models of a vapor-dominated geothermal system. *A*: Structural model; numbers correspond to references in text (from Muffler and White, 1972). *B*: Dynamic model (A) springs and fumaroles, (B) zone between ground surface and water table; (C) zone of steam condensation; (D) zone of convective and/or conductive heat flow; (E) zone of vapor-dominated reservoir; (F) deep zone of convective heat flow below a boiling water table (from White and others, 1971).

and Fig. 5B illustrates the generalized dynamic model of a vapor-dominated hydrothermal system as proposed by White, Muffler, and Truesdell in 1971. The essential structural components of a vapor-dominated geothermal system from these models appear to be: (1) a potent heat source within a few kilometres of the surface, overlain or enclosed by (2) thermally conductive crystalline rocks, overlain by (3) a reservoir rock that is overlain by (4) impermeable cap rocks that prevent excessive influx of water, or loss of steam and heat from the reservoir. In a vapor-dominated hydrothermal system the permeability of the reservoir rocks need not be high, so long as there can be sufficient convective circulation of steam and hot water in the zone of condensation above the steam reservoir (Fig. 5B). In The Geysers area this permeability in the reservoir rocks largely results from channelways produced by faults and fractures. At least some of these faults and fractures must have communication with the surface water table in order for there to be adequate, but not excessive, meteoric recharge to the system (White, Muffler, and Truesdell, 1971).

Available subsurface data indicate that steam production in The Geysers region is largely from fracture zones in Franciscan graywacke. Since imbricate structure is characteristic of the Franciscan assemblage (Fig. 3) a model relating the structure to steam resources would be favored that provides for steam accumulation in graywacke at any of several structural levels. Steam production at The Geysers is largely from wells drilled to depths of 1.5-1.8 km (Hamilton and Muffler, 1972, p. 2084), but some producing wells as shallow as 150 m (McNitt, 1963) have been drilled near Geysers Resort. The reservoir rock for steam in the area of Geysers Resort may be provided in part by the thick slab of graywacke flysch of structural unit 1 that should be present at depth beneath this area (Fig. 3). However, slabs of fractured graywacke are also present in unit 2 rocks overlying unit 1, interlayered with relatively impermeable basaltic volcanic rock, sheared serpentinite, and melange. These structurally higher graywacke slabs may also provide the reservoirs for steam accumulation north and east of Geysers Resort.

Given the presence of suitable reservoir rocks at any of several structural levels, the structural conditions determining the presence of steam would appear to depend upon: (1) the presence of channelways such as faults, fractures, or bedding planes that allow percolation of meteoric water to some depth and provide an adequate but not excessive supply of water to the system, (2) the presence of structural traps for steam accumulation, and (3) a potent heat source.

Field relations and geophysical evidence in two areas illustrate the significance of local structure in controlling steam distribution. In the area of Geysers Resort a zone of N 30°-35°W-trending *en echelon* faults (Dianna Rock fault zone), along which numerous hot springs vent, crosses Big Sulphur Creek and extends into an area of extensive hydrothermal alteration and fumarolic activity (Fig. 4). Steeply tilted alluvial terrace deposits within the fault zone that contain carbonized wood with a radiocarbon age of 750 ± 105 years indicate that the fault zone is active. Recent activity along these faults is also indicated by the epicenters of numerous microearthquakes (Hamilton and Muffler, 1972) that are aligned along the Dianna Rock fault zone. First-motion fault plane solutions for the microearthquakes (Hamilton and Muffler, 1972, p. 2083-84) do not correspond directly to the mapped fault zone, but a plot of the microearthquake hypocenters projected horizontally onto a vertical cross section oriented roughly normal to the trend of epicenters (Fig. 4) suggests the presence of a boundary fault zone above which the microearthquakes occur. The boundary fault zone is inclined at about 55°-60° to the northeast.

Ward and Bjornsson (1971) showed that high frequencies of microearthquakes commonly are associated with geothermal areas, and they concluded that this activity results from the weakening and chemical alteration of rocks along faults and fracture zones owing to saturation by geothermal fluids.

By application of the findings of Ward and Bjornssen to The Geysers area, the Dianna Rock fault zone may be interpreted as a fracture zone lubricated by hot water. The fracture zone is interpreted to extend from the surface downward to a bounding fault inclined steeply to the northeast. The upper part of this fracture zone may correspond to a shallow zone of condensation above the steam reservoir (Fig. 4) since many steam wells near Geysers Resort were drilled to relatively shallow depths of between 50-360 m (McNitt, 1963, p. 14).

Further evidence of significant structural control of steam distribution in The Geysers region is present in the Castle

Rock Springs steam field, approximately 6.5 km southeast of Geysers Resort. The distribution of steam wells in this area indicates that a geothermal reservoir occupies the region of an anticlinical warp in eastward dipping foliate metagraywacke and shale interlayered with minor basaltic volcanic rock and serpentinite (Fig. 6). Steep dipping N 80°W-trending faults approximately bound the north and south sides of this structural high, possibly providing conduits for recharge of the reservoir with meteoric water. The presence of a closed low resistivity anomaly (Stanley, Jackson, and Hearn, 1973) in this area reinforces the interpretation that conductive fluid is locally concentrated in the crest of this structural high (Fig. 6). This low resistivity anomaly within 2-3 km of the surface probably indicates a structurally high zone of hot water-saturated hydrothermally altered rocks above the steam reservoir, corresponding to the zone of condensation indicated by White, Muffler, and Truesdell (1971) (Fig. 5B and Fig. 6). Leakage of geothermal water from the reservoir apparently occurs along several steeply dipping N 50°W-trending faults and fractures to the east of Castle Rock Springs, evidenced by the presence of Anderson hot spring and prominent zones of hydrothermal alteration along these faults. In addition to their acting as conduits for thermal leakage, some of these N 50°W-trending faults may also act as conduits for downward percolation of meteoric water for reservoir recharge and for upward migration and entrapment of steam at different structural horizons in the reservoir rocks, although there is no definite evidence to indicate that this occurs. The N 50°W-trending faults may also form the eastern structural boundary of the Castle Rock Springs steam reservoir.

In the two areas discussed, local structure appears to have considerable bearing on the local distribution of steam. It seems probable that such structures are also important

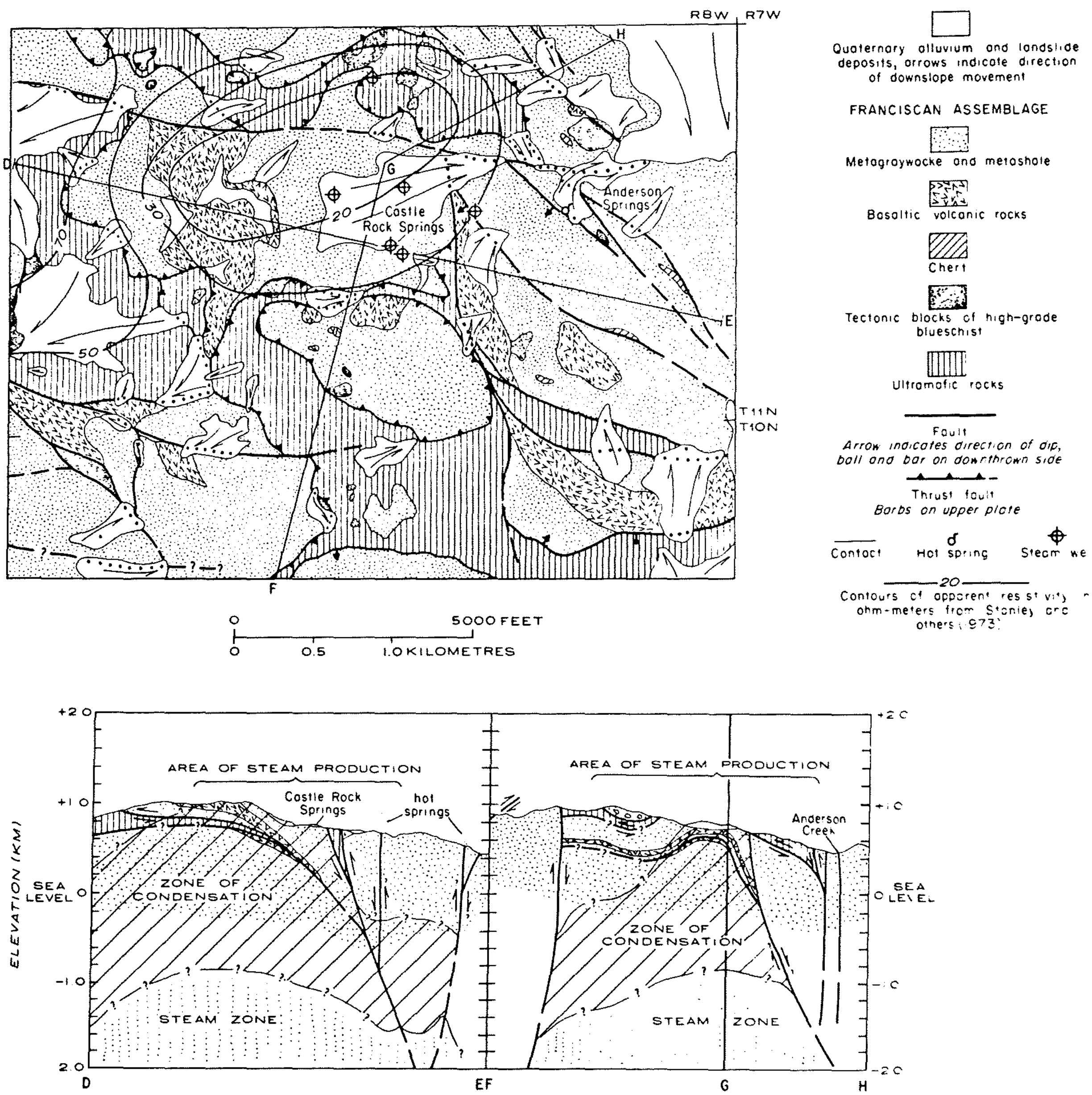


Figure 6. Geologic map and structural sections through the Castle Rock Springs steam field, showing inferred relation of structure and low resistivity anomaly to steam reservoir. *Top*: map view. *Bottom left*: structural section D-E. *Bottom right*: structural section F-G-H.

features of economically significant geothermal reservoirs elsewhere in The Geysers steam field, even though high heat flow and favorable reservoir rocks exist regionally over a vast area.

CONCLUSIONS

Detailed geologic mapping in The Geysers area of the Mayacmas Mountains indicates that the Franciscan assemblage is separable into three approximately stratiform structural units that form the core of a southeastward plunging antiform. A steeply dipping northwest-trending strike-slip fault zone bounds this antiform on the southwest. Textural reconstitution in Franciscan graywackes increases structurally upward, with the corresponding appearance of pumpellyite, lawsonite, and glaucophane, and/or jadeite, respectively, in structurally higher rocks. The Franciscan assemblage is overlain by a fragmented ophiolite complex in the Mount Saint Helena and Geyser Peak areas, and 8-9 km of right-lateral offset of the Mount Saint Helena and Geyser Peak ophiolite masses has occurred along the Geyser Peak fault zone. Elsewhere, the lower part of the ophiolite mass has been sheared into underlying Franciscan rocks along steeply dipping faults, possibly of middle-Tertiary or younger age.

Geothermal resources in The Geysers area tend to be concentrated within imbricated north-northeast- to southeast-dipping slabs of Franciscan graywacke. Critical parameters for economic concentrations of steam in the region appear to be: (1) the presence of channelways that allow percolation of meteoric water to some depth, providing an adequate but not excessive recharge of water to the system; (2) the presence of favorable local structural traps for steam accumulation in fault and fracture zones (such as in the Geysers Resort area) or in the crests of structural highs (such as in the Castle Rock Springs area); and (3) a potent heat source.

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REFERENCES CITED

Atwater, T., 1970, Implications of plate tectonics for the Cenozoic tectonic evolution of western America: Geol. Soc. America Bull., v. 81, no. 12, p. 3513-3536.

Bailey, E. H., 1946, Quicksilver deposits of the western Mayacmas District, Sonoma County, California: Calif. Jour. Mines and Geology, v. 42, no. 3, p. 199-230.

Bailey, E. H., Blake, M. C., Jr., and Jones, D. L., 1970, On-land Mesozoic oceanic crust in California Coast Ranges: U.S. Geol. Survey Prof. Paper 700-C, p. C70-C81.

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

Bailey, E. H., and Jones, D. L., 1973, Metamorphic facies indicated by vein minerals in basal beds of the Great Valley Sequence, northern California: U.S. Geol. Survey Jour. Research, v. 1, no. 4, p. 383-385.

Bezore, S. P., 1969, The Mount Saint Helena ultramafic-mafic complex of the northern California Coast Ranges: Geol. Soc. America, Abs. (65th Ann. Mtg., Cordilleran Sec.), p. 5.

Blake, M. C., Jr., Irwin, W. P., and Coleman, R. G., 1967, Upside-down metamorphic zonation, blueschist facies, along a regional thrust in California and Oregon: U.S. Geol. Survey Prof. Paper 575-C, p. C1-C9.

Blake, M. C., Jr., and Jones, D. L., 1974, Origin of Franciscan melanges in northern California: Soc. Econ. Paleontologists and Mineralogists Spec. Pub. 19, p. 345-357.

Brice, J. C., 1953, Geology of Lower Lake quandrangle, California: Calif. Div. Mines Bull. 166, 72 pp.

Coleman, R. G., and Lanphere, M. A., 1971, Distribution of age of high-grade blueschists, associated eclogites, and amphibolites from Oregon and California: Geol. Soc. Amer. Bull., v. 82, no. 9, p. 2397-2412.

Coleman, R. G., and Lee, D. E., 1963, Glaucophane-bearing metamorphic rocks of the Cazadero, California: Jour. Petrology, v. 4, p. 260-301.

Dickinson, W. R., Ojakangas, R. W., and Stewart, R. J., 1969, Burial metamorphism of the Late Mesozoic Great Valley sequence, Cache Creek, California: Geol. Soc. Amer. Bull., v. 80, no. 3, p. 519-526.

Ernst, W. C., 1971, Do mineral parageneses reflect unusually high-pressure conditions of Franciscan metamorphism?: Amer. Jour. Sci., v. 270, p. 81-108.

Hamilton, R. M., and Muffler, L. J. P., 1972, Microearthquakes at The Geysers geothermal area, California: Jour. Geophys. Research, v. 77, no. 11, p. 2081-2086.

Hamilton. W., 1969, Mesozoic California and the underflow of Pacific mantle: Geol. Soc. Amer. Bull., v. 80, no. 12, p. 2909-2429.

Lanphere, M. A., Blake, M. C., and Irwin, W. P., 1975, Early Cretaceous metamorphic age of the South Fork Mountain schist in the northern Coast Ranges of California: Geol. Soc. America, Abs. (71st Ann. Mtg., Cordilleran Sec.), p. 840.

McLaughlin, R. J., 1974, Preliminary geologic map of The Geysers steam field and vicinity, Sonoma County, Calif.: U.S. Geol. Survey Open-file Map 74-238.

McNitt, J. R., 1963, Exploration and development of geothermal power in California: Calif. Div. Mines and Geology Spec. Rept. 75, 44 p.

McNitt, J. R., 1968, Geology of the Kelseyville quadrangle, Sonoma, Lake, and Mendocino Counties, Calif: Calif. Div. Mines and Geology, Map sheet 8.

Muffler, L. J. P., and White, D. E., 1972, Geothermal energy: The Science Teacher, v. 39, no. 3, p. 1-4.

Stanley, W. D., Jackson, D. B., and Hearn, C. B., Jr., 1973, Preliminary results of geoelectrical investigations near Clear Lake, California: U.S. Geol. Survey Open-file Rept.

Swe, W., and Dickinson, W. R., 1970, Sedimentation and thrusting of late Mesozoic rocks in the Coast Ranges near Clear Lake, California: Geol. Soc. America Bull., v. 81, no. 1, p. 165–188.

Ward, P. L., and Bjornsson, S., 1971, Microearthquakes, swarms, and the geothermal areas of Iceland: Jour Geophys. Research, v. 76, no. 17, p. 3953-3982.

White, D. E., Muffler, L. J. P., and Truesdell, A. H., 1971, Vapor dominated hydrothermal systems compared with hot water systems: Econ. Geology, v. 66, no. 1, p. 75-97.

Yates, R. G., and Hilpert, L. S., 1946, Quicksilver deposits of eastern Mayacmas District, Lake and Napa Counties, Calif: Calif. Jour. Mines and Geology, v. 42, no. 3, p. 231-286