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RESEARCH IN THE GEYSERS-CLEAR LAKE GEOTHERMAL AREA, NORTHERN CALIFORNIA

INTRODUCTION

By R. J. McLaughlin and J. M. Donnelly-Nolan

The Geysers-Clear Lake area is one of two places in the world where major vapor-dominated hydrothermal reservoirs are commercially exploited for electric power production. Because energy can be extracted more efficiently from steam than from hot water, vapor-dominated systems are preferable for electric power generation, although most geothermal electric power facilities tap water-dominated systems. The Geysers-Clear Lake geothermal system has therefore been of great interest to the geothermal industry.

This geothermal area straddles the deeply dissected Mayacmas Mountains, which rise to over 1,500 meters (4,600 feet) on the southwest, and other northwest-trending ridges of the Coast Ranges that range in elevation from 1,800 m (6,000 ft) to less than 600 m (2,000 ft) to the north, east, and south. Clear Lake basin is a volcanotectonic depression bounded by these elevated areas. The climate and vegetation of this part of the Coast Ranges is typical of the Mediterranean area, with moderate to heavy annual precipitation that locally exceeds 250 centimeters (100 inches) in the Mayacmas Mountains, but is as low as 50 cm (20 in.) in Clear Lake basin. Most precipitation occurs between the months of October and May, commonly accompanied by snow above 900-m elevations. Mean annual temperatures are about 15°C (60°F), with summer temperatures ranging to well above 37°C (100°F) and winter temperatures locally reaching well below freezing. Vegetation patterns are affected by climate, elevation, and soil type. Grassland, scrub oak, stands of cypress, manzanita, and other chaparral-type plants are distributed between the lowlands and the moderately high ridges. Evergreen conifers and some deciduous plants, such as dogwood, are restricted to higher elevations and often are specific to soils developed on certain rock types, such as serpentinite and rhyolite.

The Geysers-Clear Lake area was famous for its thermal springs long before interest in geothermal development. From the late 1860's to the early 1900's, when mineral baths and spas were in their heyday in the United States, those in Lake and Sonoma Counties were known internationally, including The Geysers Resort. Present tourism in the area now revolves around interest in the geothermal industry, although there has been a recent revival in the recreational use of some hot springs. Generating electricity from natural steam was seriously considered as early as the 1920's by the Geysers Development Company. Allen and Day demonstrated the feasibility of such a venture by drilling the first wells at The Geysers Resort in 1927. However, the technology for large-scale transport of steam for production of electrical energy did not then exist in the United States, and it was not until the late 1950's that Magma Power Company and Thermal Power Company entered into an agreement with Pacific Gas and Electric Company and built a commercially competitive geothermal power plant at The Geysers, which went into production in 1960. Since then, many private companies have been involved in exploration and expansion of the Geysers steam field. Presently, proven steam resources underlie an area of approximately 600 square kilometers defined by more than 130 productive steam wells that produce about 700 megawatts of electricity. By 1983, production will reach 1,238 megawatts.

Geologic investigations that largely predate the U.S. Geological Survey's geothermal research program in the Geysers-Clear Lake area began at least as early as the quicksilver investigations of G. F. Becker in 1888. Later, more thorough investigations of mercury deposits in the Mayacmas Mountains and Clear Lake area include those of Bailey, Yates, and Hilpert in 1946, A. N. Moisseeff in 1966, and papers by D. E. White and various coworkers in the 1960's. A paper by C. A. Anderson, published in 1936, is perhaps the most comprehensive study of the chemistry, petrography, and geologic relations of the Clear Lake Volcanics before the recent investigations by the U.S. Geological Survey. The geochronologic and paleomagnetic work of E. A. Mankinen on the Sonoma Volcanics in 1972 remains a chief reference for these rocks. Previous regional invest-

igations of similar geologic and tectonic significance include that of J. C. Brice in 1953, several short papers and maps by J. R. McNitt in the 1960's, and a paper by Win Swe and W. R. Dickinson in 1970. Important published investigations of the geochemistry of thermal and mineral springs include those of G. A. Waring in 1951 and 1968, and many papers by Ivan Barnes, D. E. White, and their coworkers in the 1960's and 1970's. These previous investigations are cited throughout this volume.

The U.S. Geological Survey began a long-term research program in the Geysers-Clear Lake area in 1972 under the direction of L. J. P. Muffler and later by R. L. Christiansen and W. A. Duffield, coordinators of all geothermal research for the Geologic Division of the U.S.G.S. from 1972 to 1980. The range of this program is evident in the table of contents of this volume. Papers in this volume present many of the main results of this endeavor as well as contributions from researchers outside the U.S. Geological Survey. Some papers are not directly related to geothermal research but nevertheless characterize important aspects of the geologic history and tectonics of the Geysers-Clear Lake area.

In most respects the reader will find agreement among the various authors about the nature and extent of the geothermal system and its heat source. However, in detail, the reader will find differences in geophysical and geologic models. We hope that such differences in interpretation will stimulate further research to test various hypotheses. The models presented here to explain different aspects of the Geysers-Clear Lake geothermal system are by no means the only ones that can explain the data, and they will undoubtedly be tested and improved with further exploration and development in the area. The validity of such models and their endurance in the literature depend respectively on the present data upon which the models are based and on how they hold up under the accumulation of new data and theories that will surely follow publication of these papers.

TECTONIC SETTING OF PRE-TERTIARY ROCKS AND ITS RELATION TO GEOTHERMAL RESOURCES IN THE GEYSERS-CLEAR LAKE AREA

By Robert J. McLaughlin

ABSTRACT

The Geysers-Clear Lake geothermal area lies within the central belt of the Franciscan assemblage in northern California. The structure of this terrane is characterized by northeast-dipping imbricate thrust slices that have been warped and cut by steeply dipping strike-slip and normal faults. Introduction of magma into the crust beneath the Geysers-Clear Lake area can be related to east-southeast extension accompanying northward propagation of the San Andreas transform system between the Clear Lake region and Cape Mendocino within the last 3 million years. The initiation of strike-slip faulting during this time terminated subduction of elements of the Farallon plate beneath North America as strike-slip motion was taken up along the Pacific-North American plate boundary. The mechanism for magma generation appears to require a heat source in the mantle that mixed mantle-derived melts with various crustal rocks. These crustal rocks may have included the Franciscan central and coastal belts, ophiolite, Great Valley sequence, and possibly middle and late Tertiary rocks subducted before initiation of strike-slip faulting.

The Geysers steam reservoir is on the northeast limb of a major southeast-plunging antiform in late Mesozoic rocks of the Franciscan assemblage. The reservoir also coincides with the southwest side of a major negative gravity anomaly interpreted to delineate the presence of magma within the upper crust. The most significant factors limiting the extent of the steam reservoir seem to be the distribution of heat and open-fracture networks, the presence of cap rocks that retain fluid in the reservoir rocks, and the presence of areas of adequate hydrothermal leakage that allow the system to remain vapor-dominated.

The orientation of regional stress determined from earthquake studies in the Geysers area implies that north- to northeast-oriented steeply dipping faults and fractures should produce maximum horizontal extension in the steam reservoir. Vertical extension may also be significant in gently dipping or subhorizontal fractures in the axial regions of anticlinal warps and horstlike structures. Local structures of probable significance to steam production include a structural high associated with the Castle Rock Springs area, and southeast-plunging folds in Franciscan rocks overthrust by serpentinite near The Geysers Resort.

Specific areas and mechanisms of natural recharge to the Geysers steam reservoir are poorly known. However, the vent areas for rhyolite and dacite that cap Cobb Mountain may provide conduits that allow deep circulation into the reservoir rocks. Northeast of the steam field, the numerous vents underlying a thick cover of volcanic rocks may have promoted the development of a hot-water-dominated geothermal system due to an excess of recharge.

INTRODUCTION

The Geysers steam field of northern California is the world's largest commercial geothermal development exploited for the purpose of electrical production. The area of commercial development lies within a roughly circular 600-km^2 area over which young volcanism and active hydrothermal manifestations are apparent. The vapor-dominated Geysers steam reservoir occupies about 300 km^2 along the southwest side of the geothermal region, extending to unknown depths below about 3 km. The steam reservoir is entirely within an allochthonous basement of complexly deformed and metamorphosed marine sedimentary and igneous rocks assigned to the Franciscan assemblage and to the largely coeval Great Valley sequence.

The structure of these late Mesozoic and early Tertiary rocks and present regional tectonics strongly influence the geothermal system. In this report I describe these structural and tectonic relations, with particular reference to the recent studies of the U.S. Geological Survey and to plate-tectonic concepts.

TECTONIC SETTING OF THE GREAT VALLEY SEQUENCE AND THE FRANCISCAN ASSEMBLAGE

The northern California Coast Ranges east of the San Andreas fault (fig. 1) consist mainly of two approximately coeval units now separated by a great regional thrust referred to as the Coast Range thrust (Bailey and others, 1970). The upper plate of the Coast Range thrust consists of a fragmented ophiolite complex of Late Jurassic age (the Coast Range ophiolite), considered to represent oceanic crust (Bailey and others, 1970; McLaughlin and Pessagno, 1978), overlain depositionally by moderately deformed marine sedimentary rocks referred to as the Great Valley sequence (Bailey and others, 1964). The Great Valley sequence ranges in age from Late Jurassic to Late Cretaceous and consists of coarse ophiolite breccia or tuff near the base (McLaughlin and Pessagno, 1978) overlain by conglomerate, mudstone, and sandstone. The Great Valley sequence is interpreted to represent arc-trench gap or fore-arc basin deposits that were derived from Klamath and Sierran island-arc terranes as a series of coalescing submarine fans (Dickinson, 1970; Ingersoll
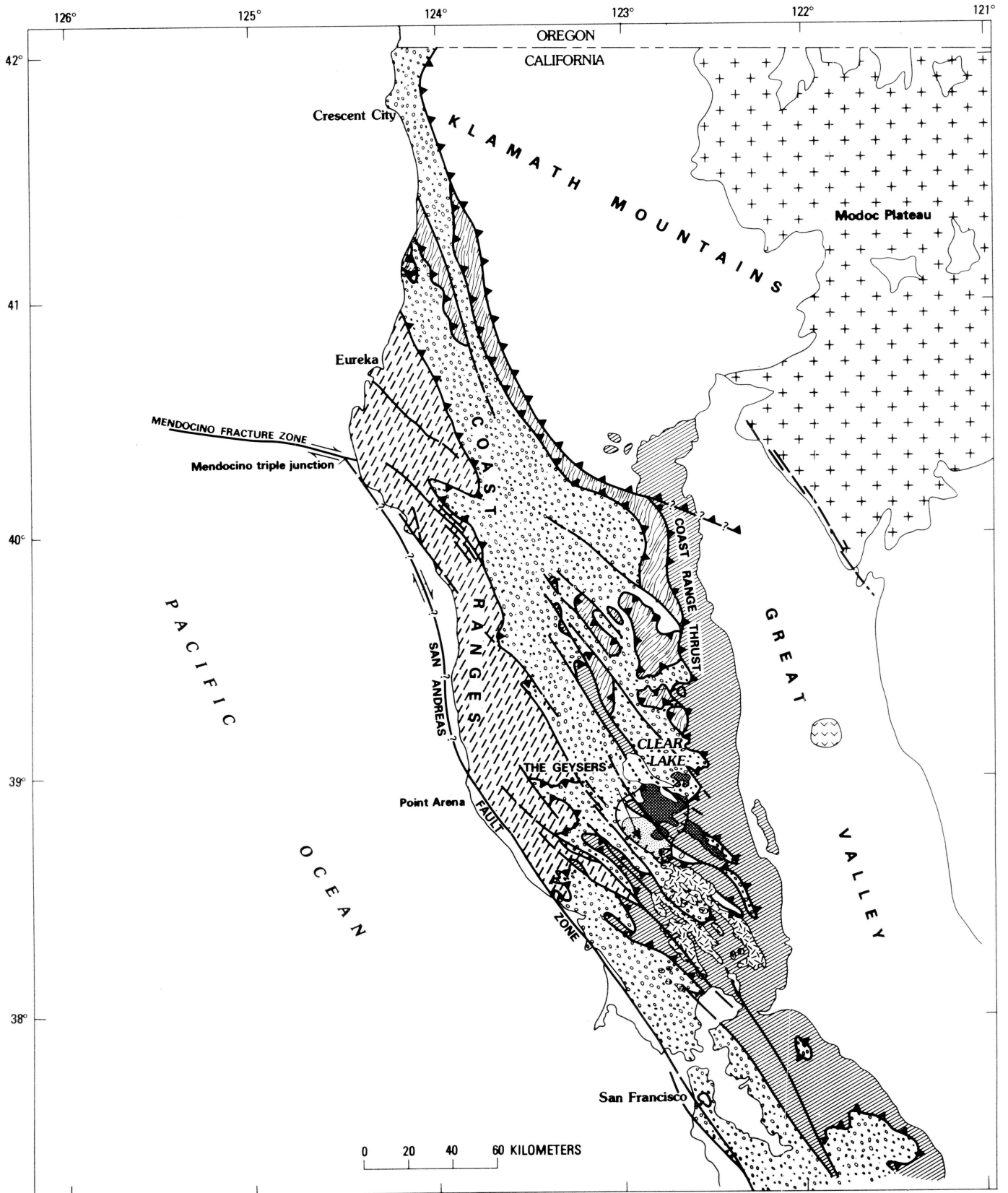
and others, 1977). The basal part of the Great Valley sequence was largely derived from the depositionally underlying Coast Range ophiolite (McLaughlin and Pessagno, 1978).

Rocks in the lower plate of the Coast Range thrust have been assigned to the Franciscan assemblage (or Franciscan Complex of Berkland and others, 1972) and consist of a heterogeneous assemblage of intensely deformed and mildly to moderately metamorphosed sandstone, shale, chert, and mafic igneous rocks. Serpentinite, limestone, amphibolite, eclogite, and high-grade blueschist are minor but significant constituents. Franciscan rocks and their equivalents are now known to extend along the Pacific coast of North America at least from Baja California, Mexico, to southern Alaska (Jones and others, 1977). Initial deformation and metamorphism of these rocks apparently occurred in Cretaceous and early Tertiary time, as the result of oblique northeast-directed subduction and strike-slip. Popular plate-tectonic models (Hamil-

ton, 1969; Dickinson, 1970; Blake and Jones, 1974) interpreted rocks of the Franciscan assemblage to have been deposited in a trench over an east-dipping subduction zone located to the west of the fore-arc basin of the Great Valley sequence. However, paleomagnetic evidence presented recently by Jones and others (1977) and Alvarez and others (1979), and arguments put forth by McLaughlin and Pessagno (1978), suggested that this model is overly simplistic. The paleomagnetic data indicate that as much as 30° of northward translation of Mesozoic plate elements occurred along the Pacific margin in pre-Late Cretaceous time (Jones and others, 1977). The data of Alvarez and others (1979) imply 56°–57° of late Cretaceous or younger northward translation. It is not clear what the relative importance of transforms and oblique subduction were in these displacements, but by implication, elements of the Franciscan assemblage and possibly even the Great Valley sequence may have sustained large-scale northward displacement from their original sites of deposition before, during, or after periods of pre-Late Cretaceous subduction.

In northern California, the Franciscan assemblage has been divided into broad northwest-trending thrust-fault-bounded structural belts by Berkland and others (1972), Blake and Jones (1974), and Jones, Blake, Bailey, and McLaughlin (1978). (1) The eastern (Yolla Bolly) belt of Late Jurassic and Early Cretaceous age (fig. 1) is composed of intact lawsonite-grade metamorphosed sandstone, with minor interbedded chert and very minor interbedded metamorphosed igneous rocks. (2) The somewhat younger central belt to the west is composed of rocks of Late Jurassic to Late Cretaceous age that were probably deformed into extensive melanges and broken formations in later Cretaceous time. The broken formations of the central belt consist of pumpellyite to lawsonite-grade metamorphosed sandstone and argillite, basaltic igneous rocks, and chert; they differ from the melanges in displaying local stratal continuity, in being significantly less penetratively sheared, in having less argillite in relation to sandstone, and generally in not containing exotic blocks such as eclogite, amphibolite, high-grade blueschist, or serpentinite. (3) The youngest western (coastal) belt of Late Cretaceous to Miocene age consists mainly of broken formations of K-feldspar-bearing laumontite-grade arkosic sandstone and shale. Basaltic igneous rocks, blueschist, eclogite, amphibolite, limestone, and chert are rare in the coastal belt. These various belts of Franciscan rocks have probably sustained large components of strike-slip movement relative to one another and to the upper plate of the Coast Range thrust, in addition to major crustal shortening associated with subduction.
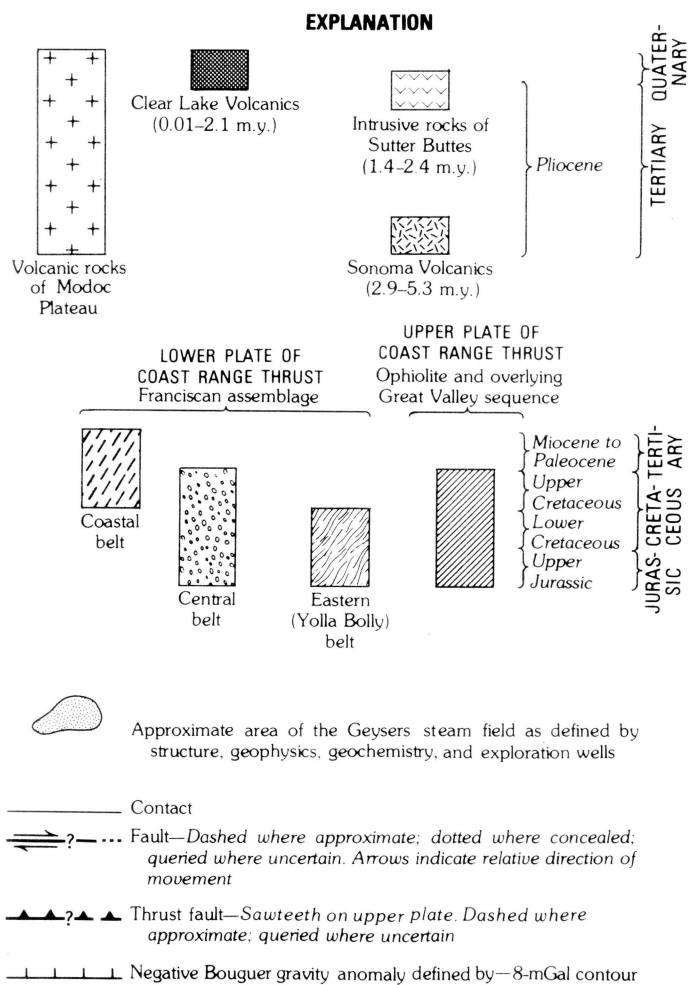

EXPLANATION

Volcanic rocks of Modoc Plateau

Clear Lake Volcanics (0.01–2.1 m.y.)

Intrusive rocks of Sutter Buttes (1.4–2.4 m.y.) } Pliocene

Sonoma Volcanics (2.9–5.3 m.y.)

TERTIARY QUATERNARY

LOWER PLATE OF COAST RANGE THRUST
Franciscan assemblage

Coastal belt

Central belt

Eastern (Yolla Bolly) belt

UPPER PLATE OF COAST RANGE THRUST
Ophiolite and overlying Great Valley sequence

Miocene to Paleocene
Upper Cretaceous
Lower Cretaceous
Upper Jurassic

JURAS-SIC CRETA-CEOUS TERTI-ARY

Approximate area of the Geysers steam field as defined by structure, geophysics, geochemistry, and exploration wells

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⇒?—··· Fault—*Dashed where approximate; dotted where concealed; queried where uncertain. Arrows indicate relative direction of movement*

▲▲?▲ ▲ Thrust fault—*Sawteeth on upper plate. Dashed where approximate; queried where uncertain*

⊥⊥⊥⊥⊥ Negative Bouguer gravity anomaly defined by −8-mGal contour

FIGURE 1.—Generalized regional geology of northern Coast Ranges of California, showing location of the Geysers steam field.

BLUESCHIST METAMORPHISM AND EMPLACEMENT OF THE COAST RANGE THRUST

Two principal occurrences of blueschist are recognized in the Franciscan assemblage: (1) displaced blocks of high-grade fine-grained to coarsely crystalline blueschist that were derived from metamorphosed basalt, eclogite, amphibolite, or rocks with more siliceous protoliths; and (2) extensive intact terranes of graywacke and minor interbedded chert and igneous rocks that have been metamorphosed to blueschist grade and contain lawsonite. The first type of blueschist is most common as blocks in melange terranes, especially along the west side of the central belt. High-grade blueschist blocks are rare in the coastal belt but occur sporadically in some melanges in the eastern Franciscan belt. The second type of blueschist is typical of most of the eastern belt and also occurs in several large slabs in the central belt.

The unusual depressed temperature and high pressure gradients necessary to produce blueschist mineral assemblages (Coleman and Lee, 1963; Bailey and others, 1964) are widely regarded as indicative of conditions encountered in subduction zones (Bailey and others, 1970; Ernst, 1970, 1971; Platt, 1975). The age of this blueschist metamorphism is thought to constrain the timing of subduction. Coleman and Lanphere (1971) dated glaucophane and white mica from high-grade blueschist blocks in the Franciscan assemblage by K-Ar methods and demonstrated that the metamorphism took place in the Late Jurassic, about 150 m.y. ago. In contrast, dating of highly reconstituted blueschist-grade metamorphosed graywacke from the South Fork Mountain Schist of the eastern belt by conventional and ^{40}Ar/^{39}Ar methods (Lanphere and others, 1978) suggests a metamorphic age of 115–120 m.y. for these rocks. Suppe and Armstrong (1972) found a wide age range of 150 to 70 m.y. for blueschist metamorphism of eastern and central belt rocks, and they interpreted this wide age range to indicate that subduction occurred in the Late Jurassic and sporadically throughout most of the Cretaceous simultaneously with sedimentation.

Blake, Irwin, and Coleman (1967) documented a regional increase in the degree of schistosity in graywackes of the eastern Franciscan belt that corresponds to an increase in abundance of blueschist minerals such as lawsonite. It was found that both degree of schistosity and development of high-pressure mineral assemblages increase structurally upward toward the Coast Range thrust. This inverted metamorphic zonation was related by them to emplacement of the Coast Range thrust. Bailey, Blake, and Jones (1970) later interpreted the Coast Range thrust as the hanging wall of a subduction zone. By this interpretation, the age of blueschist metamorphism gave a maximum age of 115–120 m.y. for emplacement of the Coast Range thrust above rocks of the eastern Franciscan belt (about Aptian or Albian time). However, in the Geysers-Clear Lake area inverted metamorphic zonation adjacent to the Coast Range thrust cannot be demonstrated except locally because of postmetamorphic imbrication of eastern belt rocks with central belt rocks. Furthermore, paleontologic evidence from the Geysers area demonstrates that emplacement of the Coast Range ophiolite above the Franciscan central belt occurred no earlier than Cenomanian time, or less than about 96 m.y. ago in that area (McLaughlin and Pessagno, 1978).

SOURCE TERRANES FOR THE FRANCISCAN ASSEMBLAGE

The source areas for Franciscan detritus have been eliminated by subduction or transform faulting or both. The original location and composition of these source areas are unknown, although some insights can be obtained from study of the petrology and sedimentology of Franciscan sandstone and conglomerate.

In spite of the association of Franciscan sandstone with mafic igneous rocks and chert of oceanic affinity, the sandstone compositions reflect island-arc or continental sources. These sandstones are arkosic to subarkosic in composition, although some are also volcanic-lithic (R. J. McLaughlin and H. N. Ohlin, unpub. data; Blake and Jones, 1978). The ages of radiolarians present in abundant chert detritus in conglomerate of the central belt indicate that the chert detritus is derived partly from older Franciscan chert interbedded with graywacke and greenstone of the central belt (McLaughlin and Pessagno, 1978) and partly from older Mesozoic sources (Seiders and others, 1979). More than 20 percent K-feldspar is typically found in sandstone of the coastal belt, 0–6 percent is typical of sandstone along the west side of the central Franciscan belt, and usually only 1 percent or less in the sandstone in the main part of the central and eastern belt. This eastward regional decrease in K-feldspar may be partly due to development of white mica at the expense of K-feldspar with increasing metamorphism.

The presence of early Mesozoic hypabyssal silicic and intermediate plutonic rocks and of pelagic sedimentary clasts in several conglomerates in the central Franciscan belt and lower part of the Great Valley sequence led Seiders, Pessagno, and Harris (1979) to suggest the Calaveras Formation and its equivalents in the Sierra Nevada and Klamath Mountains as possible sources for this detritus. An island arc active to the west in the early Tertiary has been proposed by Beutner (1977) to explain the bimodal compositions of andesitic and quartzofeldspathic graywacke sequences in the Franciscan coastal belt. Other island-arc terranes, includ-

ing Early Cretaceous arc-related rocks at Trinidad Head in northern California and an arc thought to have been the source for the Late Jurassic Otter Point Formation in southwestern Oregon (Blake and Jones, 1978), are also possible sources of Franciscan sandstone detritus.

The provenance of the blocks of amphibolite and eclogite present in melange of the Franciscan central belt is unknown. The high temperatures and pressures of formation of the mineral assemblages in these rocks suggest that they are displaced from lower crust and upper mantle levels. Many of the blocks have sheared and polished rinds of actinolite and serpentinite, and other blocks contain retrograde blueschist mineral assemblages. Emplacement of these rocks into the melanges must have involved large vertical displacements and at least partial transport within serpentinite, possibly accompanied by large-scale gravity or submarine sliding.

TERTIARY AND QUATERNARY TECTONICS

Plate-tectonic reconstructions (fig. 2) by Atwater (1970) and Blake and others (1978) trace the evolution of the San Andreas transform fault system from the time that the North American plate came into contact with the Pacific and Farallon oceanic plates about 40 m.y. ago. This triple junction (the Mendocino triple junction) migrated north along the North American plate margin from southern California to its present position at Cape Mendocino in northern California, terminating subduction that was occurring north of the triple junction and initiating a broad right-lateral transform shear (the San Andreas fault system) southeast of the propagating transform front.

The western part of the North American plate now consists largely of elements of the Farallon plate that were accreted by subduction and strike-slip during the Late Cretaceous and Tertiary before passage of the Mendocino triple junction. The Franciscan coastal belt and at least part of the Franciscan central belt probably consist of elements of the Farallon plate.

Data of E. A. Silver (published by Blake and others, 1978) show that the azimuth of shear between the Pacific and North American plates (fig. 2B) shifted westward between about 10 m.y. ago and the present, resulting in a slightly extensional regime along and within the San Andreas fault system. This change in motion facilitated creation of extensional basins within the San Andreas fault system and in the northern Coast Ranges. Examples of these basins in northern California are Ukiah and Little Lake Valleys, Round Valley, and Clear Lake basin, all of which are typical of the types of extensional basins proposed by Crowell (1974a, b) to lie within a major strike-slip fault system.

EXPLANATION

⊢⊣ Line of spreading—Arrows show relative direction of movement

⎯⎯ Line of subduction—Arrows on under-thrusting plate

⇌ Transform fault—Arrows show relative direction of movement

→ Movement of Pacific plate relative to North American

MZ Mazatlan
LA Los Angeles
SF San Francisco
S Seattle
WH White Horse
MFZ Mendocino fracture zone

A

EXPLANATION

═══ Spreading ridge

▼▼ Subducting plate margin

→ Movement of Pacific plate relative to North American
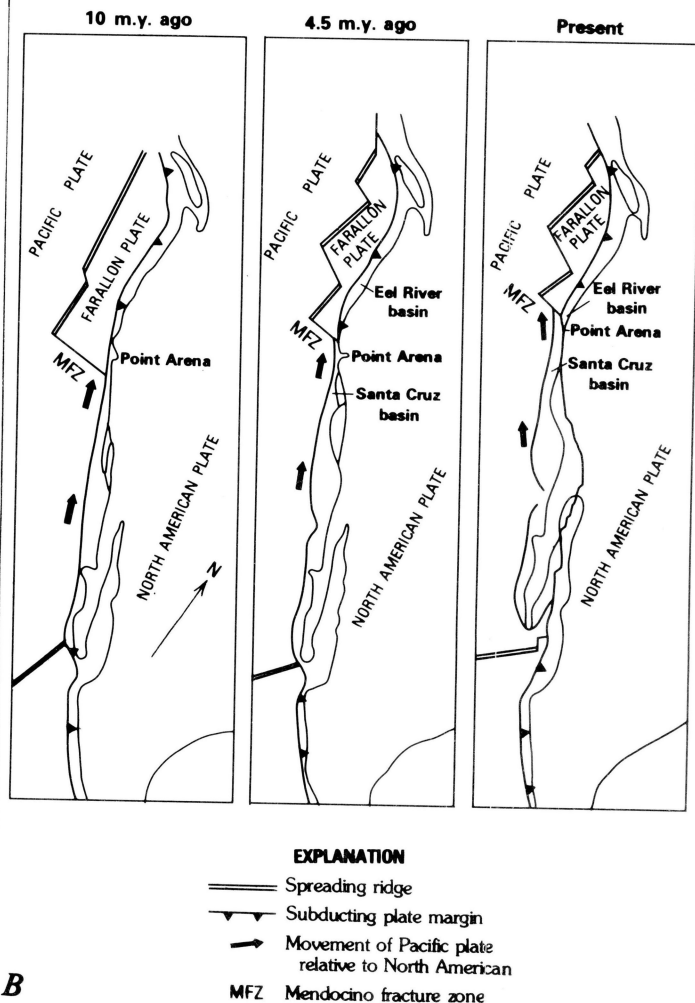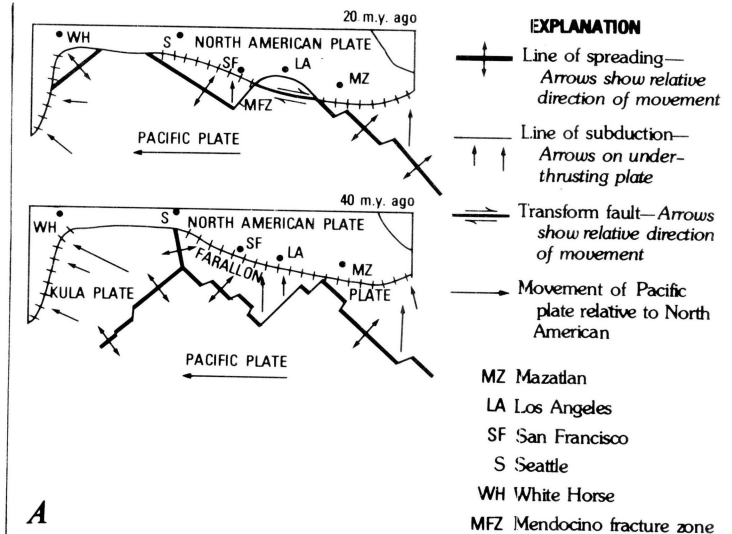
MFZ Mendocino fracture zone

B

FIGURE 2.—Plate-tectonic reconstruction of North American plate margin from 40 m.y. ago to present, using reconstructions of: A, Atwater (1970) from 40 to 20 m.y. ago; and B, those of Blake and others (1978) from 10 m.y. ago to present.

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Plate reconstructions by Silver further indicated that subduction terminated and that the San Andreas system was initiated in the northern Coast Ranges between Point Arena and Cape Mendocino within the last 10 m.y. (fig. 2B). The average rate of right-lateral motion for the last 4–6 m.y. between the Pacific and North American plates is estimated at about 5.5 cm/yr (Atwater and Molnar, 1973). Extrapolation of the Mendocino triple junction backward in time along the present boundary between the North American and
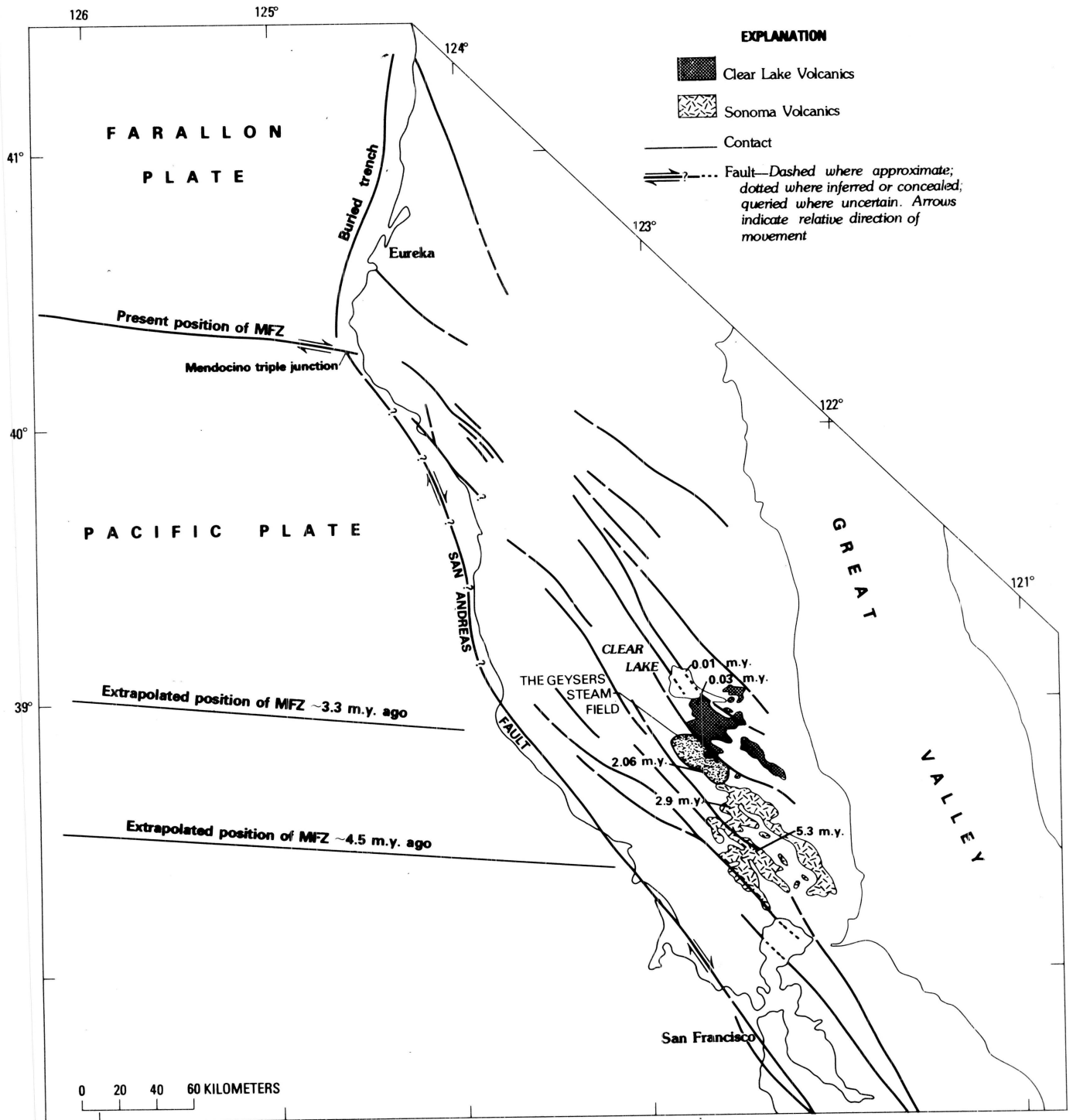

FIGURE 3.—Northward progression of Tertiary and Quaternary volcanism with time, major northwest-trending faults of San Andreas fault system, and extrapolated positions of Mendocino fracture zone (MFZ) between 3 and 5 m.y. ago. Ages of volcanic rocks from Donnelly-Nolan, Hearn, Curtis, and Drake (this volume) and Mankinen (1972).

Pacific plates (the San Andreas fault) at this rate suggests that the triple junction was opposite the latitude of the Geysers-Clear Lake area approximately 3 m.y. ago (fig. 3). Significant components of Pacific-North American plate motion apparently are also taken up by subsidiary faults in the strike-slip system east of the main San Andreas fault (fig. 3; Herd, 1979). This implies that Clear Lake basin and several other San Andreas-related extensional basins between Clear Lake and Cape Mendocino are less than 3 m.y. old. The orientation and position of the present Eel River basin north of Cape Mendocino (Ogle, 1953) suggests that it may be one of the basins suggested by Blake and others (1978) to have formed in front of the northward-propagating Mendocino triple junction (figs. 2B, 3, and 4).

The timing of Clear Lake volcanism indicates that it closely followed passage of the Mendocino triple junction and propagation of San Andreas-related extensional structures. Propagation of the triple junction past the Clear Lake area appears to have preceded the changeover from Sonoma to Clear Lake volcanism between 2.9 and 2.1 m.y. ago. Hearn, Donnelly-Nolan, and Goff (this volume) argue that volcanism in the northern Coast Ranges shifted northward with time (fig. 3) as the North American plate passed over a stationary mantle plume or hot spot.

I favor a model for emplacement of magma into the crust beneath the Geysers-Clear Lake area that is closely tied to passage of the Mendocino triple junction and crustal extension within the San Andreas fault system (McLaughlin, 1977a). Donnelly (1977) also related late Cenozoic volcanism and magma emplacement to propagation of the San Andreas fault system. Sonoma and Clear Lake volcanism might thus be characterized as magma leakage along a propagating land-bound transform fault system. North- to northeast-oriented normal faults associated with right-lateral shear couples within the San Andreas system apparently acted as the conduits for venting of the Clear Lake magmas (Hearn and others, this volume).

Magma sources for the region are highly conjectural, but strontium isotope and trace-element studies of the Clear Lake Volcanics (Futa and others, and Hearn and others, this volume) suggest that the lavas are derived at least in part from primitive mantle material that underwent considerable mixing with various crustal rocks, in addition to fractional crystallization and assimilation at different levels in the crust. A stationary hot spot or mantle plume might have provided the heat for these melts (Hearn and others, this volume). However, absolute motion of North America derived from assuming the presence of a mantle-stationary hot spot is significantly more complex than suggested in the simple hot-spot model of Morgan (1972), and crustal characteristics suggested by Morgan to be associated with most hot spots apparently cannot be applied to the Geysers-Clear Lake area.

In an alternative model to the hot-spot concept, mantle rocks are emplaced into the crust through extension near or at the propagating end of the San Andreas transform. Extension would thus allow rapid upward emplacement of mantle material into the crust, accompanied by pressure release, which would in turn allow the crust and mantle rocks to melt. Dickinson and Snyder (1979) demonstrated that triangular areas of extension can be left in the wake of an unstable migratory triple junction like the Mendocino triple junction.

In figure 4, I attempt to show the relations of regional tectonics and deep crustal conditions to the presence of magma beneath the Geysers-Clear Lake area. Clear Lake magmas have passed upward through the Franciscan central belt and rocks in the upper plate of the Coast Range thrust; they may also have passed through the Franciscan coastal belt and younger Tertiary rocks subducted with the Farallon plate before the onset of strike-slip.

THE GEYSERS STEAM RESERVOIR

GEOLOGIC SETTING

The Geysers steam reservoir occupies the northeast limb of a complexly faulted southeast-plunging antiform that forms the core of the Mayacmas Mountains (McLaughlin, 1975). The southwest limb of this antiform is sheared right-laterally along several Tertiary and Quaternary faults. The Maacama fault zone, a major active right-lateral fault of the San Andreas system, is the furthest southwest of the faults that bound the Mayacmas antiform. The northeast side of the Mayacmas uplift is bounded by the Collayomi fault zone, another major northwest-trending member of the San Andreas fault system. Major uplift of the Mayacmas Mountains between the Maacama and Collayomi fault zones is due to north-northeast-oriented compression.

Broad, southeast-plunging folds in the Geysers region trend somewhat more westerly than the San Andreas-related strike-slip faults. These folds are in large part the result of late Tertiary and Quaternary north-south compression that either preceded or accompanied strike-slip faulting. Contemporaneous sets of subtle east-trending warps are locally present in uplifted areas between east-west-trending normal and thrust faults (see structural section A–A' between geothermal wells CA–1862 and CA–956–1 in fig. 5).

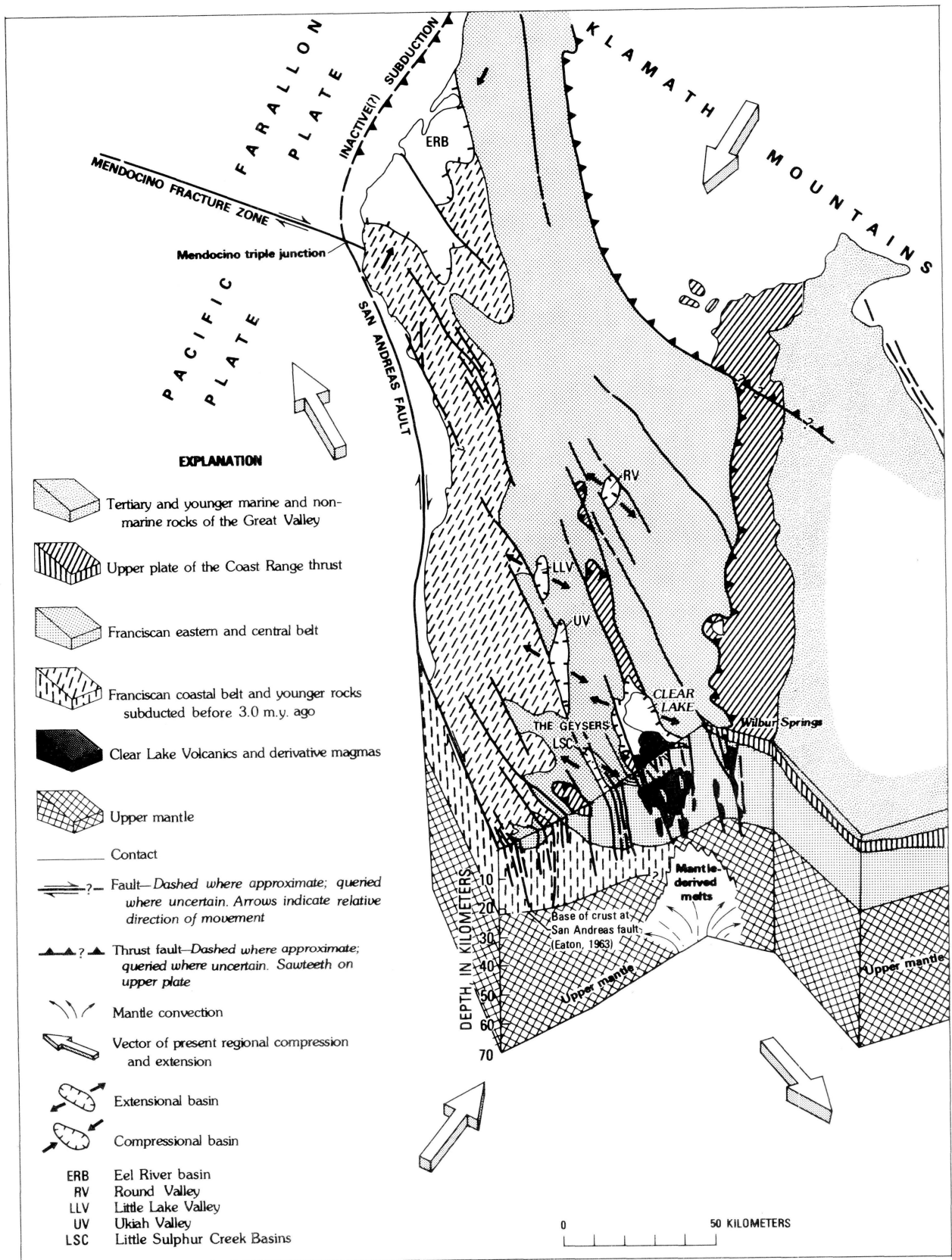The southeast-plunging folded regional structure of

FIGURE 4.—Major crustal features of northern California and their relation to emplacement of magma beneath the Geysers-Clear Lake area.

the area is apparent in the distribution of ophiolite in the upper plate of the Coast Range thrust, and the depositionally overlying strata of the Great Valley sequence (black areas in index map, fig. 5). A thick, folded, and imbricated section of ophiolite and Great Valley sequence is present northeast of the Collayomi fault zone, covered to a large extent by the Clear Lake Volcanics (fig. 5). The ophiolite and Great Valley sequence wrap over Franciscan rocks several kilometers southeast of the map area shown in figure 5 (see McLaughlin and Stanley, 1976) and over the crest of the Mayacmas Mountains just northwest of the summit of Mount St. Helena. On the southwest side of Mount St. Helena, the ophiolite is sheared and fragmented right-laterally along the broad Mercuryville-Geyser Peak-Maacama fault zones. One large mass of ophiolite, which composes Geyser Peak and Black Mountain, is separated right-laterally along this fault system about 18 km from the Mount St. Helena mass. A post-Pliocene right-lateral offset of about 20 km along the Mercuryville-Geyser Peak-Maacama fault zones is also implied by offset of the Sonoma Volcanics along the Maacama fault zone, although at least part of the apparent offset may be due to uplift across the fault zones.

FRANCISCAN ROCKS
ASSOCIATED WITH THE STEAM RESERVOIR

Rocks of the central and eastern Franciscan belts compose the uplifted core of the Mayacmas antiform and underlie the entire area of the Geysers steam field. In the Geysers area, these Franciscan rocks are subdivided into several fault-bounded slablike units on the basis of their lithology and their degree of metamorphism (fig. 5). The structurally lowest unit in the area may merely be an intact sandstone slab within the Franciscan central belt. The unit, which is exposed in the core of the Mayacmas antiform between the Mercuryville and Geyser Peak fault zones, consists of well-bedded fine- to coarse-grained graywacke and minor shale with a very weak metamorphic fabric (textural zone 1 of Blake and others, 1967). The rocks of this unit are penetratively sheared and well fractured and constitute a broken formation. The unit is characterized by weak metamorphism (pumpellyite grade) and an absence of chert, greenstone, polymict conglomerate, or exotic blocks. The lower unit extends at depth beneath the area of steam production and probably constitutes part of the reservoir rocks.

The lower structural unit is overlain on the northeast and southwest by an intermediate structural unit consisting in part of large slabs of conglomeratic and lithic graywacke interbedded with chert and 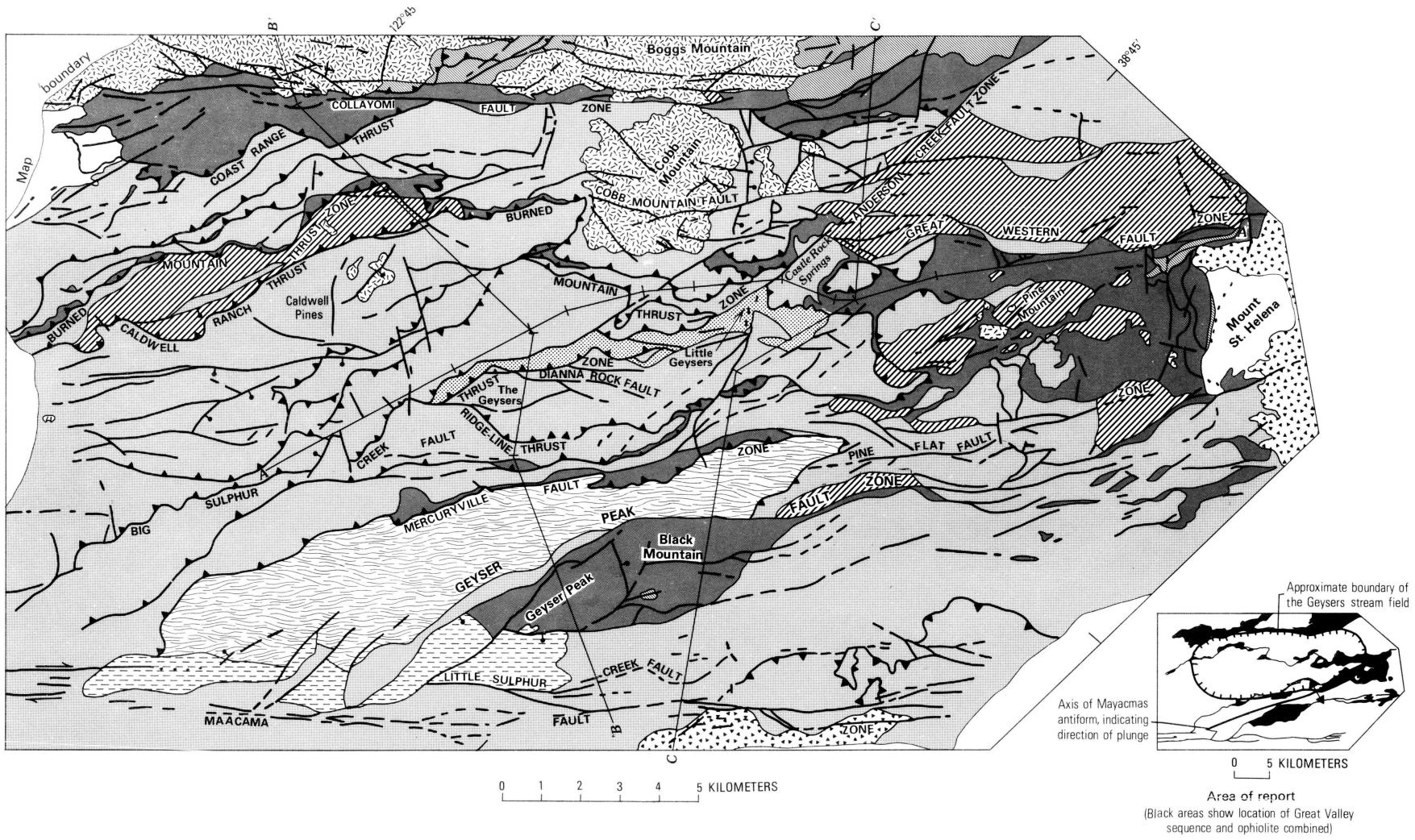basalt flows. These slabs are interleaved with melanges containing sporadic blocks of blueschist, amphibolite, and eclogite, in addition to chert, basalt, and graywacke. The graywacke of the intermediate structural unit is reconstituted to textural zones 1 and 2 of Blake, Irwin, and Coleman (1967) and contains pumpellyite and local lawsonite. Also intercalated in this intermediate structural unit is a thick northeast-dipping slab of actinolitic serpentinite extending about 10 km along strike and traceable northeastward in the subsurface for about 1.5 km from its surface exposure along Big Sulphur Creek (fig. 5). The serpentinite body, along with other highly sheared rocks of the intermediate structural unit, compose a series of thick, northeast-dipping impermeable cap rocks. The interleaved fractured slabs of graywacke in the intermediate structural unit apparently act as reservoir rocks at several different structural levels.

The structurally highest Franciscan rocks in the steam field locally consist of highly reconstituted lawsonitic metagraywacke (textural zone 2 to 3 of Blake and others, 1967) and minor metachert and metavolcanic rocks that may be correlative with the eastern (Yolla Bolly) belt. The metagraywacke of this upper structural unit is extensively recrystallized and may contain jadeite or glaucophane in addition to lawsonite. These rocks have a penetrative schistosity that makes them poorer reservoir rocks than structurally lower, less metamorphosed graywackes.

Large imbricate thrusts of Late Cretaceous and Tertiary age in the map area have juxtaposed rocks of the intermediate and upper Franciscan structural units with ophiolitic rocks in the upper plate of the Coast Range thrust. The lower ultramafic part of the ophiolite has in several places been downdropped along these thrusts and sheared laterally along the thrust boundaries, so that the original base of the upper plate of the Coast Range thrust is difficult or impossible to recognize in many places (fig. 5). These later thrusts may represent transitional structures produced during changes in plate motion from northeast-directed subduction to strike-slip fault movement. The late thrusts formed after initial emplacement of the Coast Range thrust and formation of melanges in the Franciscan central belt, and they include nearly all the thrusts that now separate major structural units in the Geysers area.

BOUNDARIES OF THE STEAM RESERVOIR

The Geysers steam reservoir is apparently confined to the northeast limb of the Mayacmas antiform (fig. 6). It is bounded on the southwest side by the northwest-trending Mercuryville fault zone and on the northeast by the Collayomi fault zone. A hot-water-dominated reservoir whose extent is unknown in detail is present

Axis of Mayacmas antiform, indicating direction of plunge

Approximate boundary of the Geysers stream field

0   5 KILOMETERS

Area of report
(Black areas show location of Great Valley
sequence and ophiolite combined)

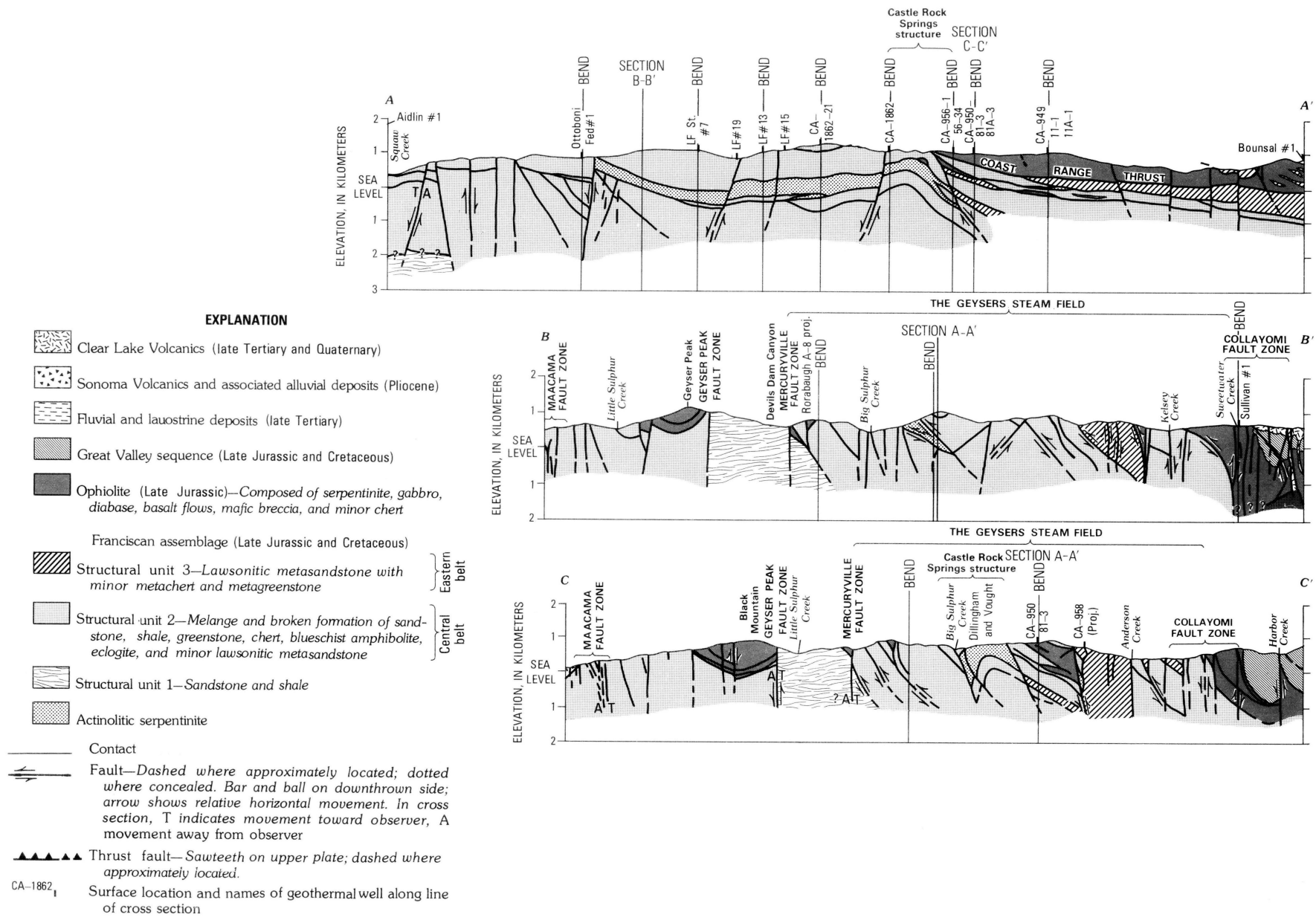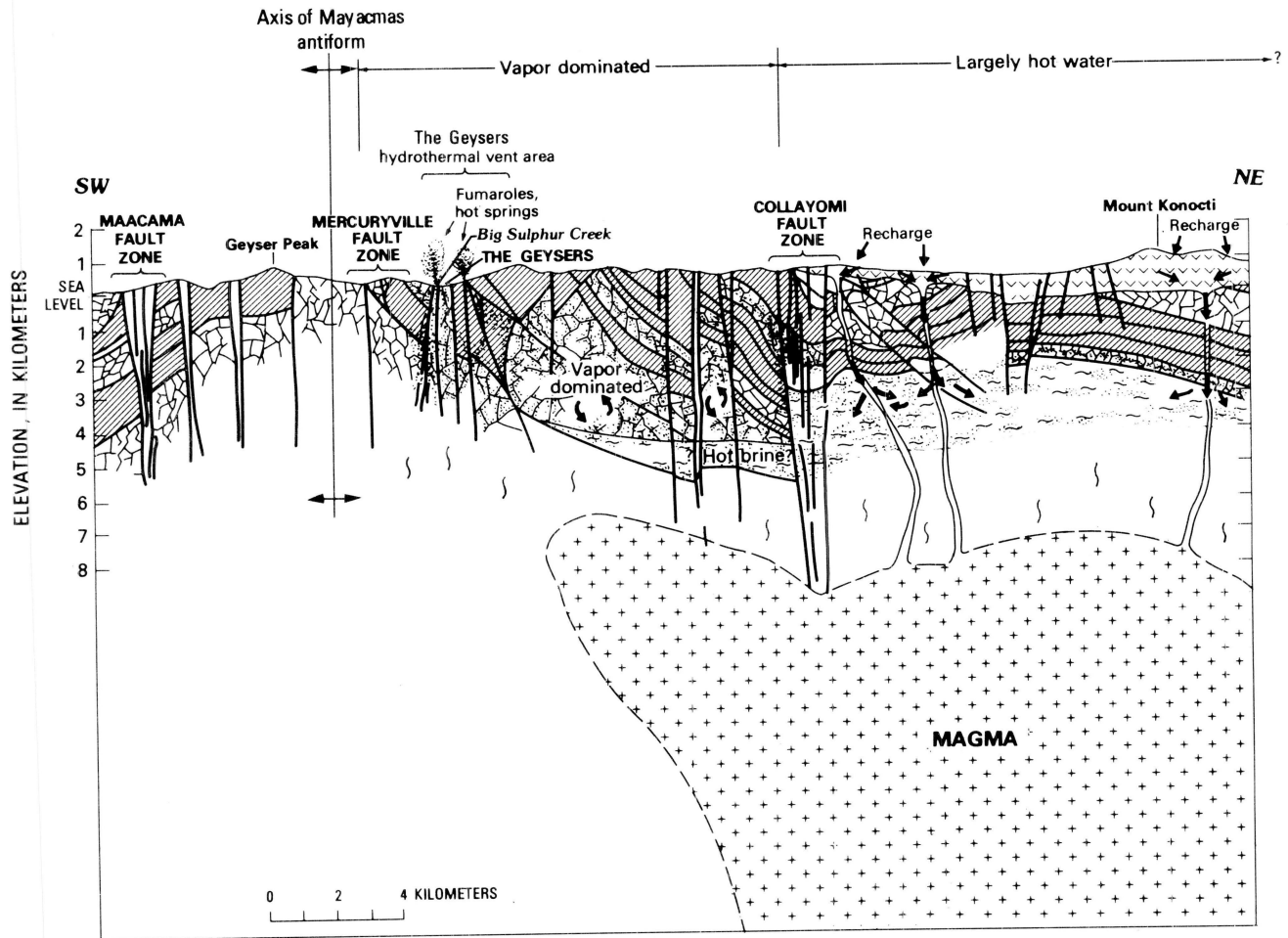0   1   2   3   4   5 KILOMETERS

FIGURE 5.—Generalized geologic map and cross sections of the Geysers steam field.

northeast of the Collayomi fault zone (Goff and others, 1977). On the northwest and southeast, the steam reservoir boundaries are less well determined. It is thought to extend no farther to the northwest than Tyler Valley. On the southeast, the reservoir may extend to the vicinity of the Helen-Wallstreet mercury mines of Dry Creek Canyon. Local inactive hydrothermal areas and several small rhyolite and dacite intrusions (including Pine Mountain and Pilot Knob) are present near the crest of the Mayacmas Mountains southwest of the Helen-Wallstreet mines. These areas may lie near the southeast boundary of the steam reservoir.

The Geysers-Clear Lake geothermal area is believed to be heated by a silicic magma body centered below 10 km depth, the top of which is within about 7 km of the surface (Isherwood, this volume). The distribution of this magma at depth is probably the most significant factor controlling the northwest, southeast, and southwest boundaries of the steam reservoir. Outside the area of potent heat conductance, the steam system presumably passes into a hot- and then cold-water-dominated system, except in areas where it is prevented from doing so by a lack of permeability. The presence and regional distribution of the magma is suggested geophysically by closure on a large-scale −30-mGal Bouguer gravity anomaly centered beneath the Clear Lake Volcanics, and by large delays in the traveltime of teleseismic P waves (Iyer and others, this volume). The Geysers steam field lies along the

FIGURE 6.—Structural model of the Geysers geothermal system. Modified after McLaughlin (1977b).

EXPLANATION

Impermeable cap rocks (serpentinite, greenstone, melange, metagraywacke)

Fracture networks in graywacke reservoir rocks

Clear Lake Volcanics and associated vents providing recharge to geothermal systems

Partially crystallized magma body inferred to be at depth, with center below 10 km

Water vapor in steam reservoir above boiling-water table

Hot water

southwest side of the gravity anomaly within the confines of closure on the gravity low (fig. 1).

The northeast-dipping Mercuryville fault zone also appears to have considerable local influence on the southwest boundary of the steam reservoir. Near The Geysers Resort, there is a marked decrease in the number of successful steam wells drilled near the fault zone, and intense hydrothermal alteration is not present southwest of the fault zone. In addition, the fault zone coincides approximately with closure on the southwest side of the regional gravity low. Extensive hydrothermal alteration along the trend of the Mercuryville fault zone suggests that in the past it was a major thermal vent area for the Geysers hydrothermal system, perhaps when there was a larger volume of water in the reservoir or heat supply to the system was greater. The hydrothermal reservoir may since have boiled down and shrunk down-structure and northeastward along the Mercuryville fault zone to where it now vents along steeply dipping faults in Big Sulphur Creek (fig. 6).

The Geysers steam field appears to be limited on the northeast by the Collayomi fault zone, according to the interpretation of thermal-water chemistry by Goff, Donnelly, Thompson, and Hearn (1977); they suggest that hot-water resources are present northeast of the Collayomi fault zone. Although reservoir rocks for the hot-water system are poorly known owing to their thick volcanic cover and a lack of deep drill hole data, they probably include both Franciscan rocks and marine strata of the Great Valley sequence. The hot-water system in this area has not yet been successfully developed, but it might include local vapor-dominated areas (Goff and others, 1977). The existence of a deep vapor-dominated system separated by impermeable rocks from the overlying hot-water system has been suggested as a remote exploration possibility by some geothermal companies. Regional structure probably accounts at least in part for the change in character of geothermal resources northeast of the Collayomi fault zone. Much of this area to the northeast is underlain by a thick folded and imbricated section of Great Valley sequence and ophiolitic rocks in the upper plate of the Coast Range thrust. This cover of Great Valley sequence rocks and ophiolite is on the downthrown side of the Collayomi fault zone and probably has acted as an impermeable cap to thermal fluid in the underlying Franciscan reservoir rocks (McLaughlin, 1977b). Goff, Donnelly, Thompson, and Hearn (1977) further suggest that numerous lava vents beneath the Clear Lake Volcanics provide conduits for recharge to deep structural levels. Although an extensive volcanic cover is present to the northeast, the uplifted Mayacmas Mountains southwest of the Collayomi fault zone

largely expose only Franciscan rocks. In this uplifted area, maintenance of a hot-water system is inhibited because little if any recharge occurs, and several of the fractures and fault zones that are significant reservoir structures at depth are also conduits for leakage of the reservoir at the surface in the hydrothermal areas.

STRUCTURE OF THE STEAM RESERVOIR

The most difficult structural features to delineate in the Geysers-Clear Lake region are those that control the local distribution of steam within the production area. Such structural control is best confirmed through interpretation of closely spaced drill holes in conjunction with the surface geology. Development of the Geysers steam field has not yet reached a stage where local structural features are known in detail. However, assuming that the reservoir will decline, as has the Larderello steam field in central Italy, more thorough evaluations of local structural features at The Geysers may soon be necessary to determine the more productive areas.

The steam reservoir is, in most instances, within interconnected fracture networks in intact slabs of graywacke in the intermediate and possibly the lower Franciscan structural units (figs. 5 and 6). These reservoir rocks, along with intercalated melanges, greenstone, semischistose metagraywacke, and serpentinite that act as the cap rocks, compose a stack of northeast- to southeast-dipping imbricate thrust sheets (McLaughlin, 1977b). Heat is convected in water and steam in the fracture networks of the reservoir rocks to the southwest and southeast, up-structure toward the Geysers steam field.

Of primary importance to the production of steam from the reservoir rocks is distribution, continuity, and density of the open fracture networks, as rocks in the steam reservoir are otherwise impermeable. Through-going fracture networks are statistically most abundant in the least reconstituted graywackes, although a few producing steam wells tap Franciscan greenstone.

It is apparent from the surface geology that within graywacke units there are very large lenses of more or less unfractured sandstone surrounded by more penetratively fractured and sheared sandstone. This characteristic strongly implies the presence in the subsurface of unproductive, unfractured regions within reservoir rocks. Thus boudinage and brittle shear fracture, in combination with original lenticularity of Franciscan sandstone units, may be of great significance in determining distribution of the open fracture networks. Discontinuous communication of reservoir rock fractures in the Geysers steam field was described by Lipman, Strobel, and Gulati (1978) in
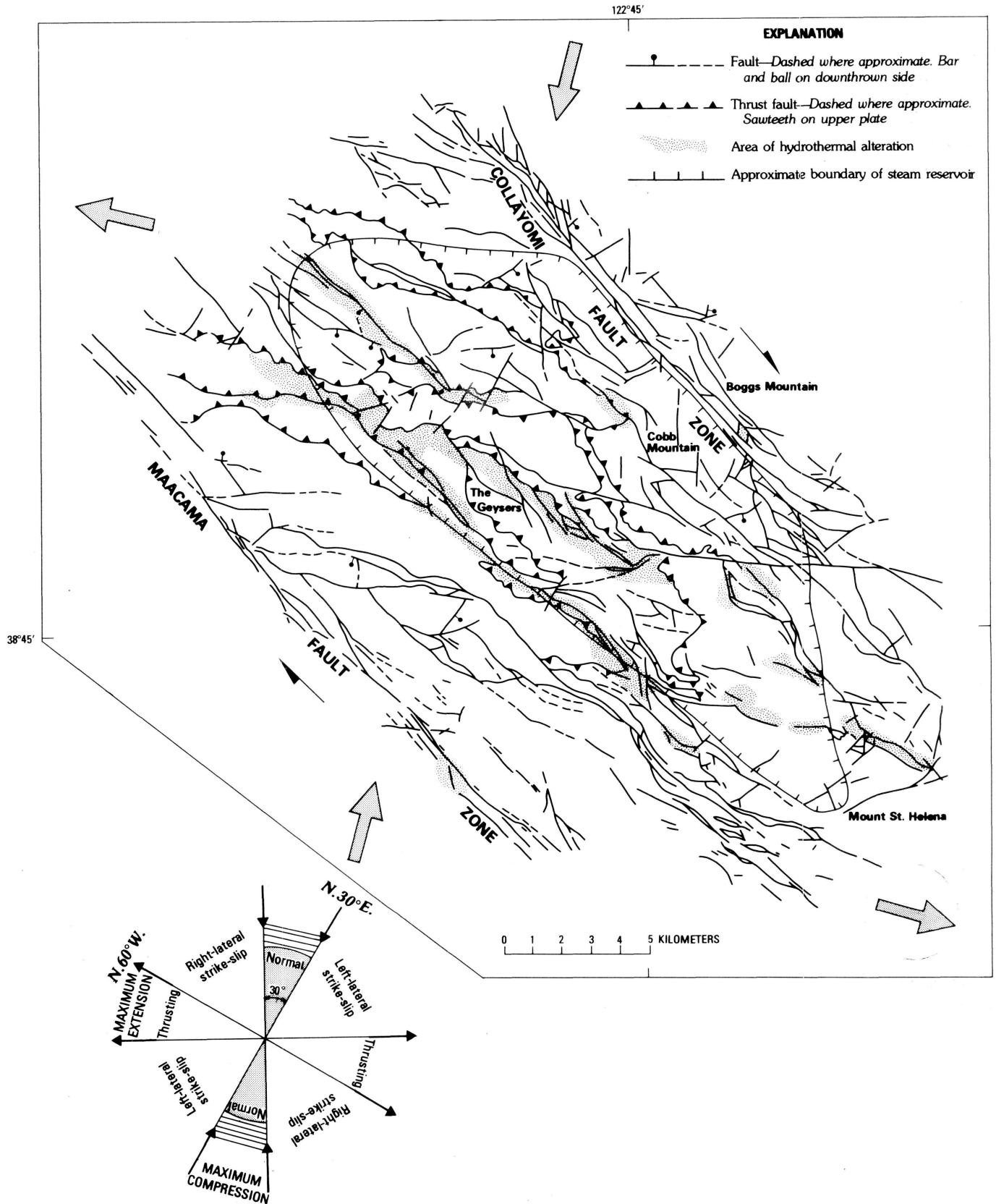
FIGURE 7.—Faulting over the Geysers steam reservoir. *A*, Black arrows show dominant right-lateral sense of faulting along Maacama and Collayomi fault zones. Large white arrows show approximate vectors of regional compression and extension. *B*, Principal horizontal vectors of stress field for the Geysers area, suggested by Bufe and others (this volume), and predicted displacements for vertical faults of various orientations.

their evaluation of reservoir performance in the Sulphur Bank and Happy Jack areas. Early steam wells drilled in these areas tapped shallow reservoir fractures at depths above 640 m that had static pressures much lower than the prevailing pressures in a separate, more extensive fracture system 183 m deeper. This discovery led to the early recognition of two discrete steam reservoirs at different structural levels. More recent studies of reservoir drainage by Lipman and his colleagues have demonstrated that while these fractured areas are separated locally by pendants of impermeable unfractured rock, the shallow fracture network is connected with the deeper more regional fracture zone elsewhere in the area.

INFLUENCE OF REGIONAL STRESS ON RESERVOIR STRUCTURE

The large number of shallow earthquakes associated with the Geysers steam field indicates that the region is tectonically active and that stress is locally relieved along zones of weakness in rocks of the steam reservoir. The steam reservoir occupies a more or less rigid uplifted block between two major strike-slip fault zones (fig. 7A). This uplifted block is broken by numerous faults, fractures, and joints formed before and during development of the San Andreas shear system.

McLaughlin and Stanley (1976) stated that the steeply dipping northwest-trending strike-slip and normal faults along which fumaroles and hot springs vent near The Geysers Resort may be major channels from the steam reservoir. They further suggested that the hydrothermal lubrication of these fault zones (fig. 7) promotes the release of regional stress and localization of shallow earthquakes.

Recent seismic studies (Bufe and others, this volume) and investigations of vertical and horizontal surface changes over the area of steam production (Lofgren, this volume) suggest that much seismic activity at The Geysers may also be due to fluid withdrawal and reservoir subsidence, probably along pre-existing faults in the area of steam production.

Earthquake first-motion studies by Bufe and others (this volume) indicate that the vectors of maximum regional compression in the Geysers area range from about N. 30° E. to more northerly orientations compatible with the right-lateral offsets observed on northwest-trending faults of the San Andreas system. An approximate north-south maximum compression vector (fig. 7A) agrees with the observed sense of offset on most of the major Quaternary faults in the Geysers area. The 30° of eastward scatter in the vectors of compression may be due wholly or in part to local factors such as (1) variable amounts of strain accumulated within the Geysers-Clear Lake region, (2) the release

of strain along fault segments of variable lengths and orientations, or (3) the effect of steam reservoir subsidence on the distribution of regional stress.

Optimum horizontal extension predicted from the earthquake studies is perpendicular to the vectors of principal compression (fig. 7B). Fractures oriented north to N. 30° E. are therefore highly favorable geothermal targets, since their orientation parallel to the vector of maximum regional compression should produce optimum northwest-southeast extension. Fractures oriented somewhat outside that range should exhibit lesser components of extension in addition to strike-slip and thrust faulting (fig. 7B).

INSIGHTS INTO RESERVOIR STRUCTURE FROM SURFACE GEOLOGY

Wells producing high volumes of steam in the Larderello area of central Italy are known to be associated with the crests of northwest-plunging horsts (Cataldi and others, 1963, 1978). Detailed well production records, necessary to demonstrate such a relation at The Geysers, are generally unavailable, but upwarps and other structural highs could be of considerable importance to reservoir permeability in the subsurface of the Geysers steam field. In the axial regions of structural highs, significant vertical extension can occur along gently dipping or subhorizontal bedding planes, joints, fractures, and thrust faults. These open subhorizontal features may be particularly significant where intersected by favorably oriented vertical fractures (fig. 8).

I have mapped structural highs over the Geysers steam reservoir (McLaughlin, 1978) and a horstlike structure in the Castle Rock Springs area of the steam field (McLaughlin and Stanley, 1976). Numerous producing wells are associated with the latter structural high, possibly due to localization of favorably oriented open-fracture networks (fig. 9).

The axial regions of folds similarly should be impor-
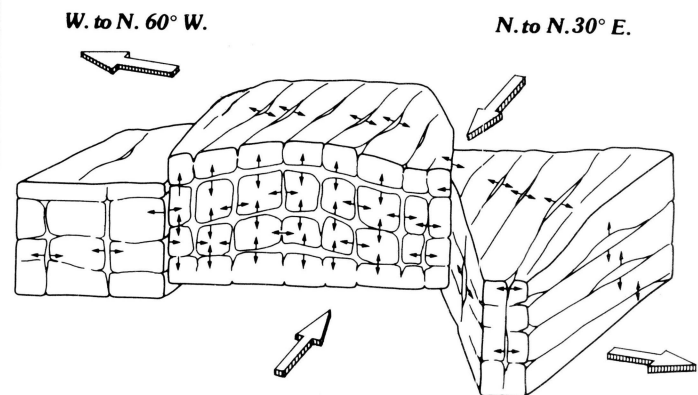

FIGURE 8.—Relation of open-fault and fracture networks of the Geysers steam reservoir to principal vectors of regional horizontal compression and extension.

tant in producing permeability in the subsurface. Folded Franciscan rocks of differing competency and permeability are present near The Geysers Resort, where interbedded graywacke, chert, greenstone, and melange are major constituents of the Franciscan assemblage (fig. 10). These rocks form a slab of relatively intact strata tightly folded into southeast-plunging anticlines and synclines. These rocks are overthrust by a thick sheet of serpentinite which acts as a cap rock (fig.

10). In the subsurface, the chert, greenstone, and melange are local impermeable barriers to hydrothermal circulation, and the graywacke composes the permeable reservoir rocks. Hinge areas of the southeast-plunging folds (fig. 10) should be the loci of tensional fractures and faults which probably provide important open fracture networks to the graywacke beds in the subsurface where they project beneath the serpentinite cap rock.

EXPLANATION

Quaternary alluvium and landslide deposits—Arrows indicate direction of downslope movement

Franciscan assemblage

Metagraywacke and metashale

Basaltic volcanic rocks

Chert

Blocks of high-grade blueschist

Ultramafic rocks

———— Contact

Fault—Dashed where approximate; dotted where concealed; queried where uncertain. Arrow indicates direction of dip. Bar and ball on downthrown side

Thrust fault—Dashed where approximate; dotted where concealed. Sawteeth on upper plate
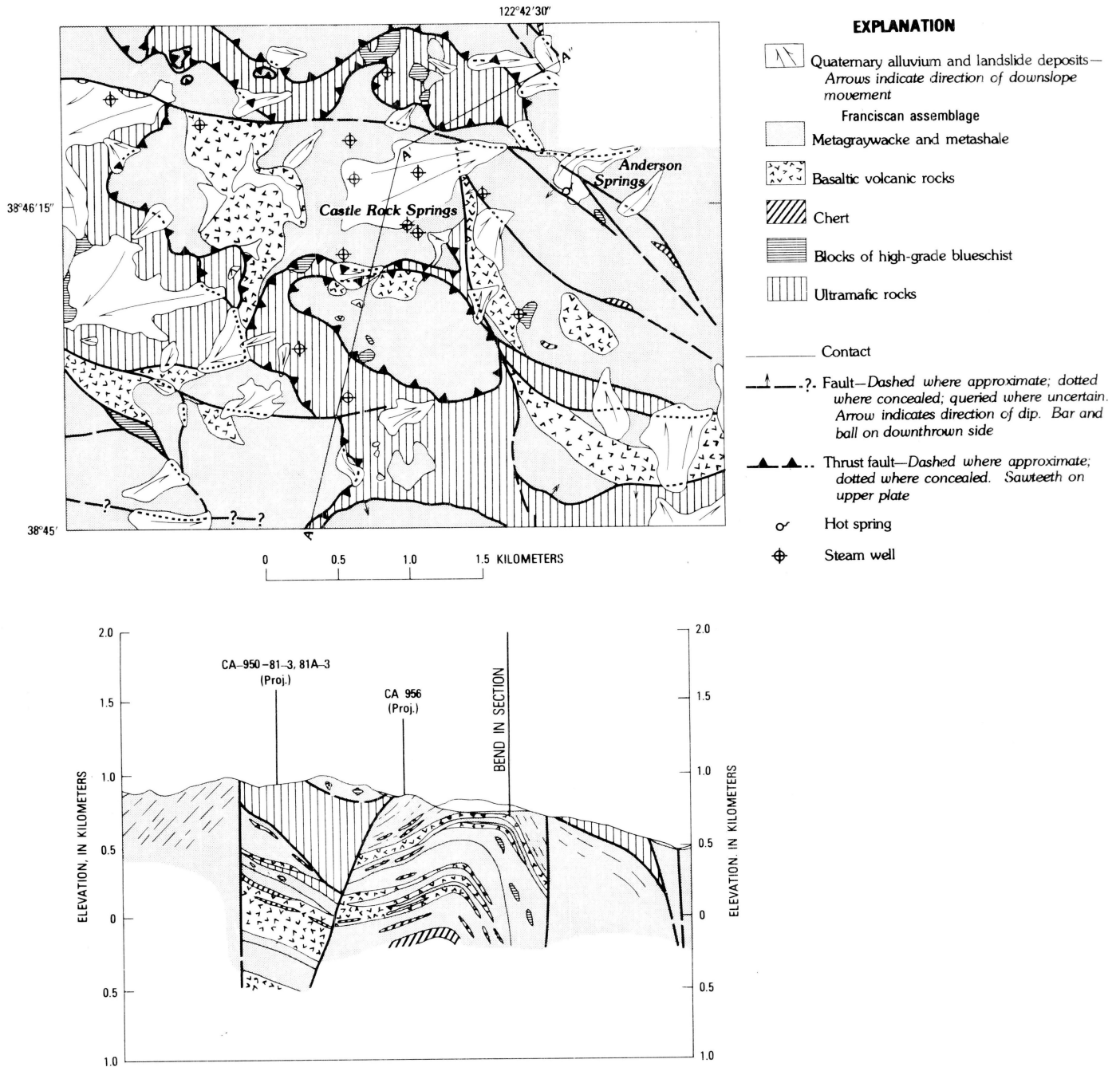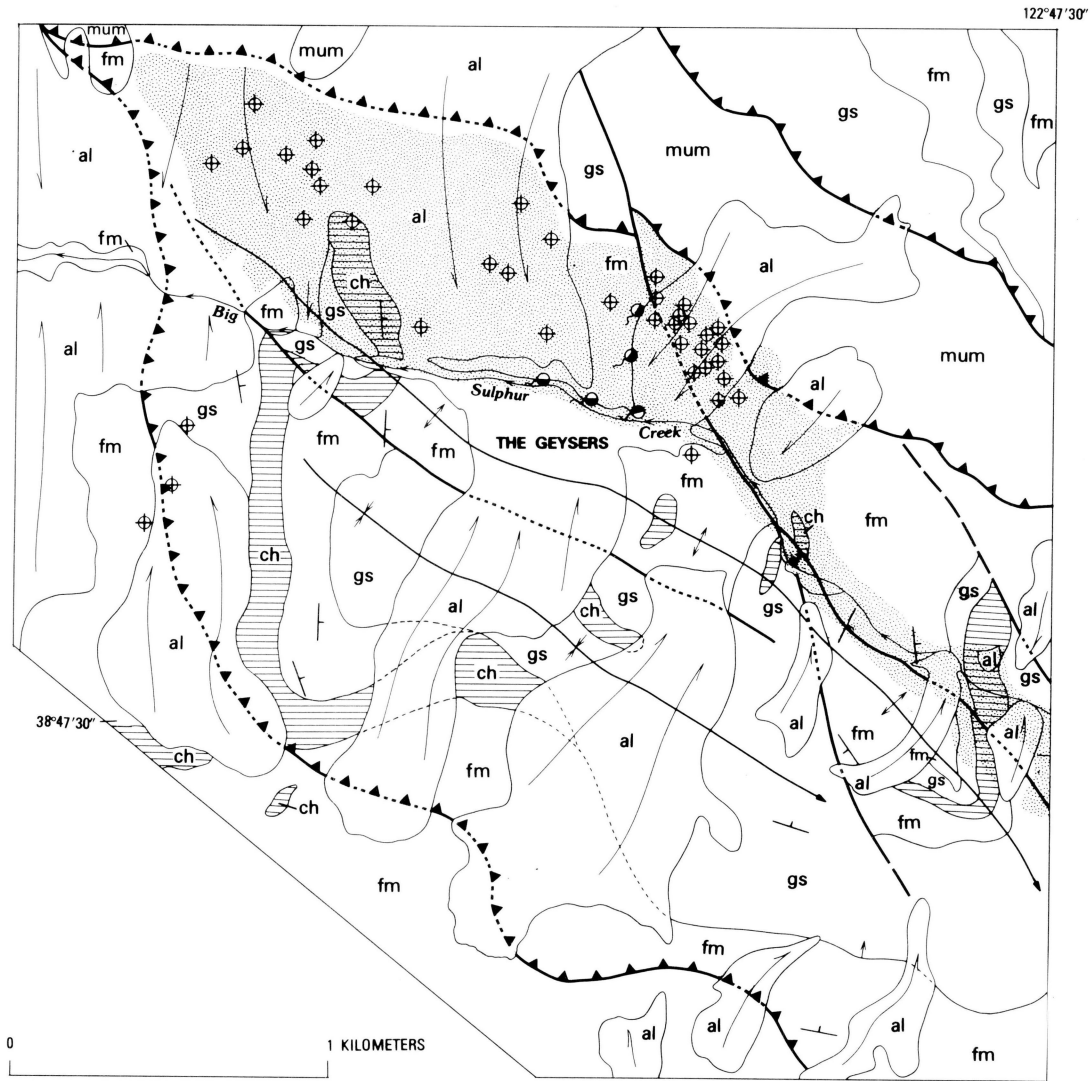
Hot spring

Steam well

FIGURE 9.—Complex structural high associated with Castle Rock Springs area of the Geysers steam field. Modified after McLaughlin and Stanley (1976).

EXPLANATION

al	Alluvial deposits, including landslides

Franciscan assemblage

fm	Melange, undivided
gs	Greenstone
ch	Chert
mum	Actinolitic serpentinite

Contact—*Showing dip where known. Dotted where concealed*

High-angle fault—*Dashed where approximate; dotted where concealed. Bar and ball on downthrown side*

Thrust fault—*Dashed where approximate; dotted where concealed. Sawteeth on upper plate*

Anticline—*Showing crestline and direction of plunge*

Syncline—*Showing troughline and direction of plunge*

Strike and dip of beds

Hydrothermal alteration

Steam well

Hot spring or fumarole area

FIGURE 10.—Geology of the Geysers area, illustrating folds in Franciscan chert and extensive hydrothermal activity along Big Sulphur Creek.

All fault-bounded uplifts do not necessarily contribute to the permeability of the Geysers steam reservoir. Figure 11 illustrates that downward-pinching uplifts formed through horizontal compression are likely to develop fracture networks that close with depth. These compressional features may be less desirable exploration targets than the downward-opening horstlike features resulting from extension, since extensional uplifts are more likely to contain fractures that open with depth. Shell Oil Company has extensively explored a diapirlike uplift in the southeast part of the Geysers steam field (fig. 12) and drilled three exploration wells. High temperature gradients were reported in these wells (Fehlberg, 1975), but no commercially significant open fracture networks were found. The failure of these wells to reach appreciable open fractures may be related to the diapiric compressional uplift over which the wells were sited.

Horizontal extension is also important along warps or irregularities in the trend of steeply dipping strike-slip faults (fig. 8). No specific examples of such a feature are known within the Geysers steam field, but significant extension is indicated southwest of the Geysers along the Maacama strike-slip fault zone, where late Tertiary fluvial and lacustrine sedimentary rocks are deposited in elongate fault-bounded depressions that formed contemporaneously with sedimentation. (see fig. 5).
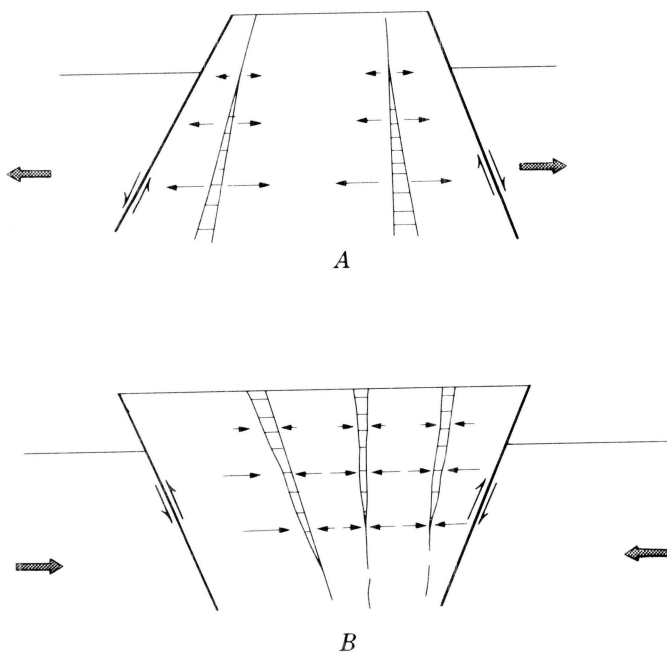

FIGURE 11.—Hypothetical relation of open fractures to structural highs. A, Downward-opening structural high produced by horizontal extension. B, Downward-pinching structural high produced by horizontal compression.

RESERVOIR RECHARGE

White, Muffler, and Truesdell (1971) showed that steam in the Geysers hydrothermal system is derived for the most part from meteoric water. They further hypothesized that vapor-dominated hydrothermal systems such as The Geysers may begin as hot-water systems and ultimately boil down to the vapor-dominated state. They argued that in such a system, the reservoir rocks must have a low recharge rate, and hydrothermal leakage in the form of hot springs and fumaroles (and presently, steam wells) must exceed recharge in order for the vapor state to be maintained. Some natural recharge is necessary in their model, however, to ensure that the system does not completely boil off. Vapor-dominated hydrothermal systems do not maintain a perfect balance between reservoir leakage and recharge; thereby they eventually do get drowned or boil off. However, the time framework for this is unknown.

Natural recharge to the Geysers system is constrained by the low permeability of the Franciscan reservoir rocks. However, since the steam reservoir is underpressured with respect to surrounding water-dominated parts of the system (White and others, 1971), meteoric water is readily absorbed, provided that conduits into the reservoir are present.

Induced recharge of the reservoir may be demonstrated by the numerous re-injection wells in the Geysers steam field. These wells recycle approximately 25 percent of the steam condensate collected from the cooling towers of the geothermal power plants. This reinjected condensate represents only a small proportion of the total volume of fluid mined from the system since a much larger volume is lost through evaporation. However, it is not known whether these reinjected fluids circulate into deep levels of the steam reservoir.

Specific areas of natural recharge in the Geysers region are subject to speculation. Goff, Donnelly, Thompson, and Hearn (1977) suggested that late Tertiary and Quaternary volcanic vents are major sources of reservoir recharge. Within the Geysers steam field, Cobb Mountain, a funnel-shaped volcanic dome composed of a rhyolite flow and two dacite flows of early Pleistocene age, may be a major source of this recharge. The silicic rocks of Cobb Mountain have a high porosity and are capable of absorbing large volumes of water during the rainy season. At least three vents beneath Cobb Mountain could allow meteoric water to percolate deep into the Franciscan basement. Other volcanic vents present within and adjacent to the vapor-dominated part of the steam field include vents beneath small volumes of olivine basalt at Caldwell Pines, a small rhyolite dome southeast of

Castle Rock Springs (Pine Mountain), and possibly the vents beneath small dacite and rhyolite intrusions (Pilot Knob) adjacent to Mount St. Helena. In the region northeast of the Collayomi fault zone, extensive Quaternary volcanic flows and domes are underlain by numerous vents, and thus significantly larger volumes of water may recharge this part of the hydrothermal system (Goff and others, 1977). This larger potential recharge area may be significant in limiting the extent of the vapor-dominated geothermal system.

At least some recharge to the reservoir probably takes place along segments of steeply dipping extensional faults. Some additional downward percolation may occur along the Mercuryville and Collayomi fault zones, especially where the faults transect or coincide with major drainages or where large volumes of water are trapped along extensional warps or along contacts between different rock units.
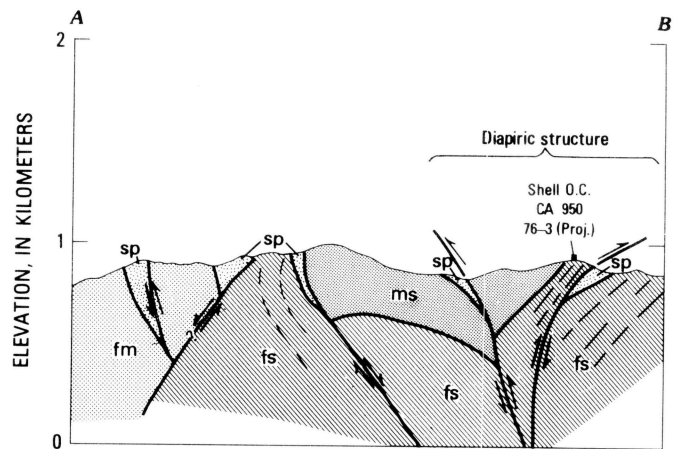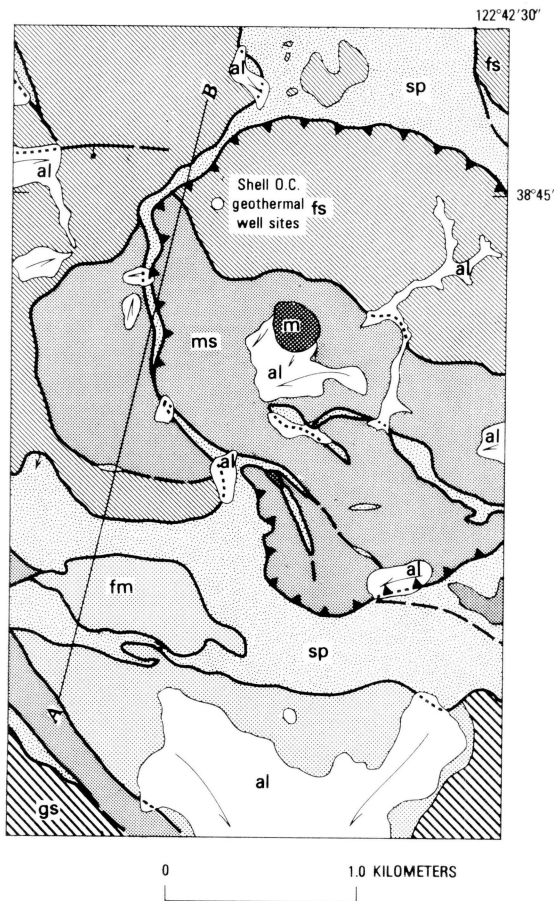
EXPLANATION

| al | Surficial deposits—*Arrows show direction of movement of unconsolidated material* |

| sp | Serpentinite |

Franciscan assemblage

| fm | Melange, undivided |

| fs | Graywacke |

| ms | Lawsonitic metagraywacke |

| m | High-grade blueschist |

| gs | Greenstone |

———— Contact

Fault—*Dashed where approximate; dotted where concealed; queried where uncertain. Bar and ball on downthrown side; on map, arrow on fault indicates direction of dip; in cross section, arrows indicate relative direction of movement*

Thrust fault—*Dotted where concealed. Sawteeth on upper plate*

FIGURE 12.—A diapiric structure associated with unproductive exploratory wells in the Geysers steam field.

CONCLUSIONS

Major vapor-dominated geothermal systems such as the one in the Geysers-Clear Lake area are rare, and its presence perhaps is due to the complex tectonics of the northern Coast Ranges.

The structural stacking of permeable and impermeable rocks in the Geysers steam reservoir and the penetrative shear deformation characteristic of Franciscan melanges and broken formations are thought to be the consequence of deformation associated with the formation of melanges and subduction. The pattern of distribution and orientation of fracture networks within the steam reservoir are largely controlled by this early episode of penetrative deformation that preceded propagation of the San Andreas fault system.

Considerable evidence indicates that extension associated with the San Andreas fault system provided deep zones of weakness along which magma was emplaced into the crust beneath the Geysers-Clear Lake area. Late Tertiary and Quaternary volcanism apparently closely followed the termination of subduction and initiation of strike-slip faulting. Furthermore, several of the present depositional basins in the northern Coast Ranges, including Clear Lake basin, appear to be the result of east-southeast extension within the broad zone of right-lateral shear created since passage of the Mendocino triple junction and initiation of the San Andreas fault system.

The present pattern of regional stress may be the principal factor determining which fracture networks control permeability in the steam reservoir. First-motion studies of earthquakes predict that maximum horizontal extension should occur along north- to northeast-oriented vertical fractures. Significant vertical extension may occur along upwarps in subhorizontal fractures and partings. Permeability provided by vertical extension may be particularly significant along the axes of anticlinal or horstlike structures, especially where subhorizontal fractures are intersected by the north- to northeast-oriented vertical fractures. Local bends or warps in northwest-oriented strike-slip faults may also produce significant horizontal extension.

Several specific structures described in this paper are of unproven importance to steam production at The Geysers. However, depletion of the Geysers steam reservoir is increasing as a result of exploration and development activity. Geothermal developers may soon find it necessary to consider the economic advantages of preferential exploitation of specific structures in the older more depleted areas of the steam field.

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