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GEOLOGY AND ALTERATION OF THE COSO GEOTHERMAL AREA, INYO COUNTY, CALIFORNIA

By
Jeffrey B. Hulen

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ABSTRACT

Geology and alteration of the Coso geothermal area were mapped in conjunction with geophysical surveys and a deep drill test (CGEH-1) to facilitate selection of a follow-up drill site.

The oldest rocks exposed at Coso are intermediate to mafic metamorphic rocks of uncertain age intruded by dikes and pods of quartz latite porphyry and felsite, and by a small stock of Late Cretaceous (?) granite. These rocks are locally overlain by Late Cenozoic volcanic rocks, which include the domes, flows, and associated pyroclastic deposits of the Coso rhyolite dome field.

Principal structures in the geothermal area are older high-angle faults of uncertain displacement trending northwest, west-northwest, and east-northeast, and younger high-angle faults with a normal component of displacement trending north-northwest, north-northeast, and (subordinately) northeast. Active surface thermal phenomena and hydrothermal alteration are concentrated along the younger northerly-trending faults, especially where these faults intersect older structures. Deep thermal fluid flow at Coso will be controlled entirely by structural permeability developed in otherwise tight and impermeable host rocks. Neither geologic mapping nor deep drilling have revealed potential deep primary aquifers.

Surface alteration at Coso is of three main types: (1) clay-opal-alunite alteration, (2) weak argillic alteration, and (3) stockwork calcite veins and veinlets, which are locally associated with calcareous sinter.
Clay-opal-alunite and weak argillic alteration are typically developed around

active thermal emissions. These are almost entirely restricted in distribution to an east-northeast-trending belt roughly one mile in width and four miles in length. Calcareous alteration is much more widely distributed, but is confined to a broad zone of anomalous geophysical response interpreted as evidence for a concealed geothermal reservoir.

A follow-up drill hole at Coso should be collared near a fault intersection involving young northerly-trending faults within the zone of coincident surface alteration and anomalous geophysical response. The southern end of the Coso Hot Springs fault zone (S. 1/3, Sec. 4, T22S, R39E) satisfies these requirements, and appears to be the most favorable site for discovery of a high-temperature geothermal resource.

INTRODUCTION

The Earth Science Laboratory, at the request of the U.S. Department of Energy (DOE), completed detailed geophysical and geological studies of the Coso geothermal area, situated in the Coso Mountains of southeastern California (Fig. 1), during mid- and late 1977. These studies were carried out concurrently with an initial deep drill test of the system by DOE contractors, and were designed primarily for selection of a follow-up drill site. They included:

1) Geologic and alteration mapping of an area including the site of CGEH-1 and all known surface thermal phenomena and hydrothermal alteration.

2) A detailed dipole-dipole resistivity survey (Fox, 1978a).

3) A low-altitude aeromagnetic survey (Fox, 1978b).

4) Geological and geophysical monitoring and interpretation of DOE's deep drill hole (CGEH-1; Galbraith, 1978).

Results of the geologic and alteration mapping program are discussed and

FIGURE 1
LOCATION MAP

interpreted in the present report.

Thermal phenomea of the Coso geothermal area were first documented by Wheeler in 1876 (Ross and Yates, 1943). Associated low-grade mercury deposits of the Devil's Kitchen and Nicol prospects (Pl. I) were discovered in 1929 and briefly described by Warner (1930) and by Tucker and Sampson (1938). These mercury deposits were subsequently studied by Wilson and Hendry (1943), Fraser, Wilson and Hendry (1943) and Ross and Yates (1943). The U.S. Bureau of Mines (1948) drilled several short holes in each of the three prospects, but failed to discover commercial concentrations of mercury ore.

The potential of the Coso Hot Springs area as a source of geothermal energy was first recognized by Austin and Pringle (1970). Godwin and others (1971) subsequently classified Coso as a Known Geothermal Resource Area (KGRA). This classification led to numerous additional geophysical and geological investigations within and around the geothermal area,[1] including regional geologic mapping by Duffield and Bacon (1976, 1977) and by Roquemore (1978a,b).

Surface geology and alteration of the immediate Coso geothermal area (roughly 15 square miles) were mapped at a scale of 1:24,000 for the present study. To better estimate the resource potential of the geothermal system at depth, the mapping was directed toward determination of the character and extent of near-surface rock permeability and associated thermal fluid flow. Particular emphasis was placed on recording the nature and distribution of

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[1]/Austin, et. al. (1971), Koenig et. al. (1972), Teledyne Geotech (1972) Chapman, et. al. (1973), Furgerson (1973), Babcock and Wise (1973), Babcock (1975), Combs (1975), Combs and Rotstein (1976), Jackson, et. al. (1977), Weaver and Walter (1977). An excellent summary of these investigations prior to 1977 is provided by Combs and Rostein (1976).

active thermal phenomena and hydrothermal alteration. In addition, faults and fault zones--potential secondary or structural aquifers--were examined for extent of associated open-fracture development. The undifferentiated basement complex mapped by Duffield and Bacon (1976, 1977) was also subdivided and searched for potential primary aquifers.

REGIONAL GEOLOGY

The Coso KGRA is situated in the Coso Mountains of the western Basin-Range province of southeastern California, immediately adjacent to and east of the southern Sierra Nevada, and about 45 miles north of the Mojave Desert province, from which the Basin-Range is separated by the generally east-west trending Garlock fault zone.

The western Basin-Range in southeastern California is characterized by northerly-trending fault block mountains separated by deeply alluviated valleys. The ranges are formed of diverse lithologies which vary in age from Precambrian through Holocene.[2] The oldest of these rocks are complexly folded Precambrian through Early Mesozoic marine sedimentary and volcanic rocks, many of which are regionally metamorphosed to corresponding low- to middle-grade metamorphic rock types. This Precambrian-Early Mesozoic sequence is intruded by Jurassic-Late Cretaceous granitic stocks and plugs, which are probably satellites of the southern Sierra Nevada batholith. These intrusives range in composition from gabbro to granite, with quartz monzonite and granodiorite strongly predominant. The intrusives and older rocks are unconformably

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2/For further information on the regional ligholologic setting of the Coso KGRA the interested reader is referred to Hall and MacKevett (1962),, Dibblee (1967), Evernden and Kistler (1970), Austin and others (1971), Stinson (1972), and Duffield and Bacon (1976, 1977).

overlain by Late Cenozonic volvanic rocks of basaltic to rhyolitic composition, with subordinate interbedded terrestrial clastic and lacustrine sedimentary rocks. This Late Cenozoic sequence includes the domes, flows, and pyroclastic deposits of the Pleistocene Coso Mountains rhyolite dome field, along the east-central margin of which the Coso geothermal system is developed. The young rhyolitic rocks of the dome field have been interpreted by numerous workers (Austin, et. al., 1971; Godwin et. al., 1971; Chapman et. al., 1973; Lanphere et. al., 1975) as evidence for a concealed magmatic heat source beneath presently active thermal phenomena.

The rugged horst-and-graben topography of the Western Basin-Range in southeastern California is due primarily to normal displacement along northerly-trending high-angle faults. This portion of the province, however, is also disrupted by major north-northwest-trending high-angle right-lateral strike-slip faults. These faults include the Death Valley-Furnance Creek and Panamint Valley faults east of the Coso geothermal area and the Owens Valley fault to the north (Jennings, 1975), as well as several active right-lateral faults within and extending south of the Coso Mountains (Roquemore, 1978b). The Coso Mountains are also disrupted by a system of high-angle faults striking generally west-northwest: Displacement on these faults may be both dip-slip and left-lateral (Duffield, 1975, after Von Huene 1960).

GEOLOGY AND ALTERATION OF THE COSO GEOTHERMAL AREA

Lithology

The rocks of the Coso geothermal area can be conveniently separated into four distinct groups:

1) An older intermediate to mafic metamorphic sequence of uncertain but pre-Late Cretaceous (?) age.

2) Quartz latite porphyry and felsite of post-metamorphic, but otherwise uncertain age.

3) Late Cretaceous (?) granite and allied intrusive rocks.

4) Late Cenozoic volcanic and subordinate sedimentary rocks.

Metamorphic Rocks

Intermediate to mafic metamorphic rocks of diverse textures and compositions and uncertain age are the oldest exposed in the geothermal area. Rocks of this sequence occur as roof pendants, septa, and xenoliths in granitic rocks in the northern portion of the mapped area, but form a relatively continuous mass in the southern portion (Pl. I). Although locally refolded, schistose rocks in this metamorphic sequence at Coso strike generally northwest to west-northwest, and dip steeply northward. The metamorphics comprise, in approximate decreasing order of abundance in outcrop, biotite schist and gneiss, metadiorite and metadiabase, intermediate metavolcanic rocks, amphibolite, and chlorite schist. Locally associated rock types, in widely scattered outcrops, include probable felsic metavolcanics (both flow rocks and tuffs), possible metachert, granitic gneiss, lit-par-lit injection gneiss, and miscellaneous hybrid rocks along contacts with granitic intrusives. The metamorphic sequence was not differentiated for the present investigation. In general, metadiorites and metadiabases are most common in the northern portion of the mapped area; intermediate metavolcanics are confined to the central portion; amphibolite occurs most frequently in the southern portion; biotite schists and gneisses are ubiquitously distributed. Table I is a petrographic summary of representative major metamorphic rock types exposed in the geothermal area.

Sample Number	Rock Type	MINERALOGY, ESTIMATED VOLUME PER CENT																
		Quartz	Potassium Feldspar	Plagioclase	Hornblende	Fibrous Amphibole	Biotite	Chlorite	Muscovite	Sericite	Epidote	Sphene	Apatite	Calcite	Dark Opaque Minerals	Hematite	Goethite	Leucoxene
C102	Hornblende Biotite Metadiorite	7		45	17		25		tr.	tr.	1	2	1		2	tr.		tr.
CS-6	Porphyritic Biotite Hornblende Metadiorite	5	7	46	25		10	tr.	tr.	2		2	1		1			tr.
C117	Amphibolite				64	20		15			tr.		tr.			1	tr.	
C106	Porphyritic Hornblende Biotite Metadacite	5	7	46	5		10	3	3	10	10	2	1	1	3			tr.
C88	Plagioclase-Hornblende-Biotite Schist	5		48	20		22				tr.	tr.	2		3	tr.	tr.	

Table I. Petrographic summary of selected metamorphic rock samples from the Coso geothermal area.

Quartz Latite Porphyry and Felsite

Quartz latite porphyry dikes cut the older metamorphic sequence in the south-central portion of the mapped area (Pl. I). These dikes, most of which are flow-foliated, generally parallel schistosity in their metamorphic host rocks. They are generally more resistant to weathering than these host rocks, and are therefore easily traceable in outcrop. The northernmost dike consists in thin-section of 5-7% plagioclase phenocrysts and 3-5% biotite phenocrysts embedded in a microcrystalline matrix of plagioclase, orthoclase, and quartz: plagioclase is partially altered to sericite and epidote.

A few light-colored felsite dikes and pods crop out in the same general area as the quartz latite porphyry (Pl. I). Several of the felsite dikes also parallel schistosity, but a few were discordantly injected.

The age relationship of quartz latite porphyry to felsite and of both to granitic rocks exposed to the northeast cannot be established within the mapped area.

Late Cretaceous (?) Granitic Intrusive Rocks

The older metamorphic sequence is intruded west of Coso Hot Springs by an irregular stock, roughly 1-1/2 miles in outcrop diameter, composed dominantly of leucocratic biotite granite (Pl. I). The main body of the stock is flanked to the west and south by marginal plugs of similar composition which may merge with the stock at depth. The absolute age of granitic rocks in the Coso geothermal area is unknown. They are almost certainly genetically related to the composite Mesozoic Sierra Nevada Batholith. Duffield (1975, p. 335; pers. comm. with W. E. Hall, 1974) cites a K-Ar age of 86.7 $\pm$ 2.6 m.y. (Late Cretaceous) for a granitic rock in the west-central Coso Range, but a precise location for the sample is not furnished.

Coarse-crystalline leucocratic biotite granite forms the bulk of the main mass of the stock and also of marginal plugs to the west and north (Pl. I). This granite is also common at depth in drill hole CGEH-1 (Galbraith, 1978). In thin section, the granite is a coarse-crystalline hypidiomorphic-granular aggregate of microcline and orthoclase (35-40%), sodic oligoclase and/or perthite (30-35%), quartz (20-30%), and biotite (<1-3%), with accessory muscovite, magnetite, sphene, and zircon.

The southern portion of the central stock and marginal plugs to the south are generally more finely crystalline than the main mass of the stock and are mapped separately (Pl. I). Several of these marginal plugs appear in the field to be slightly impoverished in quartz and potassium feldspar and enriched in mafic minerals relative to the central stock, and may be quartz monzonitic rather than granitic in composition.

The central granitic stock, marginal plugs, and, to a lesser extent, surrounding metamorphic rocks, are locally intruded by small dikes and pods of aplite, alaskite, and quartz-potash feldspar pegmatite. A few discrete aplite bodies intruding metamorphic rock south of the central stock were included with the undifferentiated fine to medium-crystalline granitic rocks (map unit "gf") on Plate I.

Two small plugs of biotite granite intrusion breccia intrude leucocratic granite about 2000 feet north of the Nicol prospect (Pl. I). The breccia consists of 25-40% angular clasts of the granite and metamorphic rock embedded in a fine- to medium-crystalline granite matrix. The clasts range in dimension from less than one centimeter to two meters. The matrix, which is locally flow-foliated, is composed of sodic oligoclase, microcline, orthoclase, quartz, and biotite, with accessory magnetite, sphene, and zircon.

Late Cenozoic Volcanic and Sedimentary Rocks

Late Cenozoic volcanic rocks exposed in the Coso geothermal area form two main groups--intermediate to basic volcanic rocks and associated sediments of Late Pliocene age, and Pleistocene basalts and rhyolites (Duffield and Bacon, 1977). The latter group includes the domes, flows, and pyroclastic deposits of the Coso rhyolite dome field.

Volcanics of the older sequence crop out along the eastern margin of the mapped area (Pl. I), and include the remnants of a vesicular basalt flow and a pyroxene dacite flow immediately to the south. The basalt is a dark gray aphanitic rock composed of 2-5% olivine phenocrysts in a groundmass of plagioclase, pyroxene, olivine, and dark opaque minerals. The dacite flow, the margins and surface of which are autobrecciated, consists of quartz, plagioclase, pyroxene, and pseudomorphs of amphibole (?) and biotite (?) phenocrysts in a glassy matrix rich in dark opaque minerals: basalt xenoliths are locally present (C.R. Bacon, pers. comm., 1978). The amphibole (?) and biotite (?) pseudomorphs in the sample examined were totally altered to fine-crystalline iron oxide aggregates. Duffield and Bacon (1977) report K-Ar ages for this rock type of 3.42 $\pm$ 0.10 m.y. (biotite) and 2.20 $\pm$ 0.70 m.y. (plagioclase).

The older volcanics are overlain to the north by coarse fanglomerates of the Coso Formation (Pl. I). These fanglomerates consist of subangular pebbles, cobbles, and boulders of granitic and metamorphic rocks in a medium- to coarse-grained arkosic matrix. Air-fall pumice beds interbedded with Coso fanglomerates just east of the mapped area (sec. 11, T22S, R39E; Pl. I) have been dated by K-Ar methods at 2.95 $\pm$ 0.13 m.y. (Duffield and Bacon, 1977).

Two superficially similar basalt flows occur along the eastern margin of the mapped area. One flow forms the southern margin of the mapped area; the other, with an associated cinder cone, is situated south and west of the Wheeler mercury prospect (Pl. I). Both flows consist of olivine and plagioclase phenocrysts (with pyroxene phenocrysts in the northern flow) embedded in a microcrystalline matrix of plagioclase, pyroxene, olivine, and opaque minerals. The northern flow, which overlies the southern flow south of the mapped area, has been dated by K-Ar methods at 234,000 ± 22,000 years (Duffield and Bacon, 1977).

The western half of the mapped area is situated in the central portion of the Coso rhyolite dome field. The domes range in known age from roughly one million years (Duffield, pers. comm., 1978) to 41,000 ± 21,000 years (Lanphere et. al., 1975). According to Duffield (1977; 1978, pers. comm.), a typical dome in the Coso field consists of a dense, stony core of devitrified glass surrounded by an obsidian shell, in turn enclosed by a blocky, chaotically flow-foliated pumiceous to perlitic carapace. Erosion has exposed the core only in older domes: Younger domes have retained their carapaces, which, however, are locally dissected to reveal the subjacent flow-foliated shell of obsidian.

The perlite, pumice, obsidian, and rhyolite of the Coso field generally contain less than 1% phenocrysts. These are mainly sanidine, quartz, and oligoclase in various combinations, but may rarely include hornblende and biotite. Clinopyroxene, orthopyroxene, iron and titanium oxides and fayalite are locally present as accessory minerals (Duffield and Bacon, 1977; Lanphere and others, 1975).

Four domes just northwest of the mapped area, as well as the eroded dome just south of the Devil's Kitchen (Pl. I), are contaminated with xenoliths of porphyritic basalt. Lanphere and others (1975) suggest that microscopic equivalents of these xenoliths may have resulted in apparent K-Ar ages for the four northwestern domes older than their actual ages of crystallization.

Unconsolidated to semi-consolidated air-fall rhyolitic pyroclastic deposits form prominent explosion rings around many of the rhyolite domes. They also form a thin, discontinuous mantle over older rocks throughout the dome field. The pyroclastics consist mainly of variable amounts of ash and lapilli and blocks of pumice and obsidian with a few accidental granitic and metamorphic clasts. The pyroclastic ring around the eroded dome south of the Devil's Kitchen (Pl. I) contains a few porphyritic basalt lapilli which are identical in hand specimen to xenoliths in the rhyolite of the dome. Pyroclastic deposits at Coso commonly show evidence of water-reworking. Cross-bedding and scour-and-fill structures are common in the Devil's Kitchen and Nicol areas, where these features have been preserved by hydrothermal silicification.

Alluvium and Landslide Debris

Surficial deposits mapped as alluvium (Qal; Pl. I) include coarse, bouldery gravels shed from existing highlands into adjacent basins, as well as slope wash and playa deposits which formed in closed depressions of the rhyolite dome field. Older alluvium (Qoal) consists of unconsolidated to semi-consolidated unsorted gravels which have been elevated and partially dissected.

A small landslide has disrupted granitic and metamorphic rocks north of Coso Hot Springs (Pl. I). The landslide consists of jumbled, angular to subangular blocks reaching at least one meter in maximum dimension.

Structure

Principal structures in the central Coso geothermal area are older high-angle faults of uncertain displacement striking northwest to west-northwest and east-northeast, and younger high-angle faults--many with recent normal displacement--striking north-northwest and north-northeast. As noted by Duffield and Bacon (1976), and confirmed by the present investigation, the rocks at Coso are also pervasively fractured into blocks averaging 1/3 to 1 meter on a side.

A prominent high-angle fault trends east-northeast through the Nicol prospect and the deep canyon to the east (Pl. I). This fault parallels and is situated within a 4x1 mile belt which includes all but one of the active thermal emissions of the Coso KGRA (Fig. 2). The surface trace of the fault in granitic rocks at and just east of Nicol is marked by a wide gouge and breccia zone and local silicification. Resistivity studies indicate that the fault may extend west-southwestward beneath surficial cover through and just past the northern end of the Devil's Kitchen (Fox, 1978a). Here and at Nicol, thermal phenomena and hydrothermal alteration are localized on or near the intersection of the east-northeast-trending fault with northerly-trending fault.

A unique low angle fault crops out just northwest of a basaltic cinder cone west of the Wheeler mercury prospect (Pl. I). This fault trends east-northeast and dips 30-40° north-northwest. Its surface trace is clearly marked by a dense calcitic stockwork.

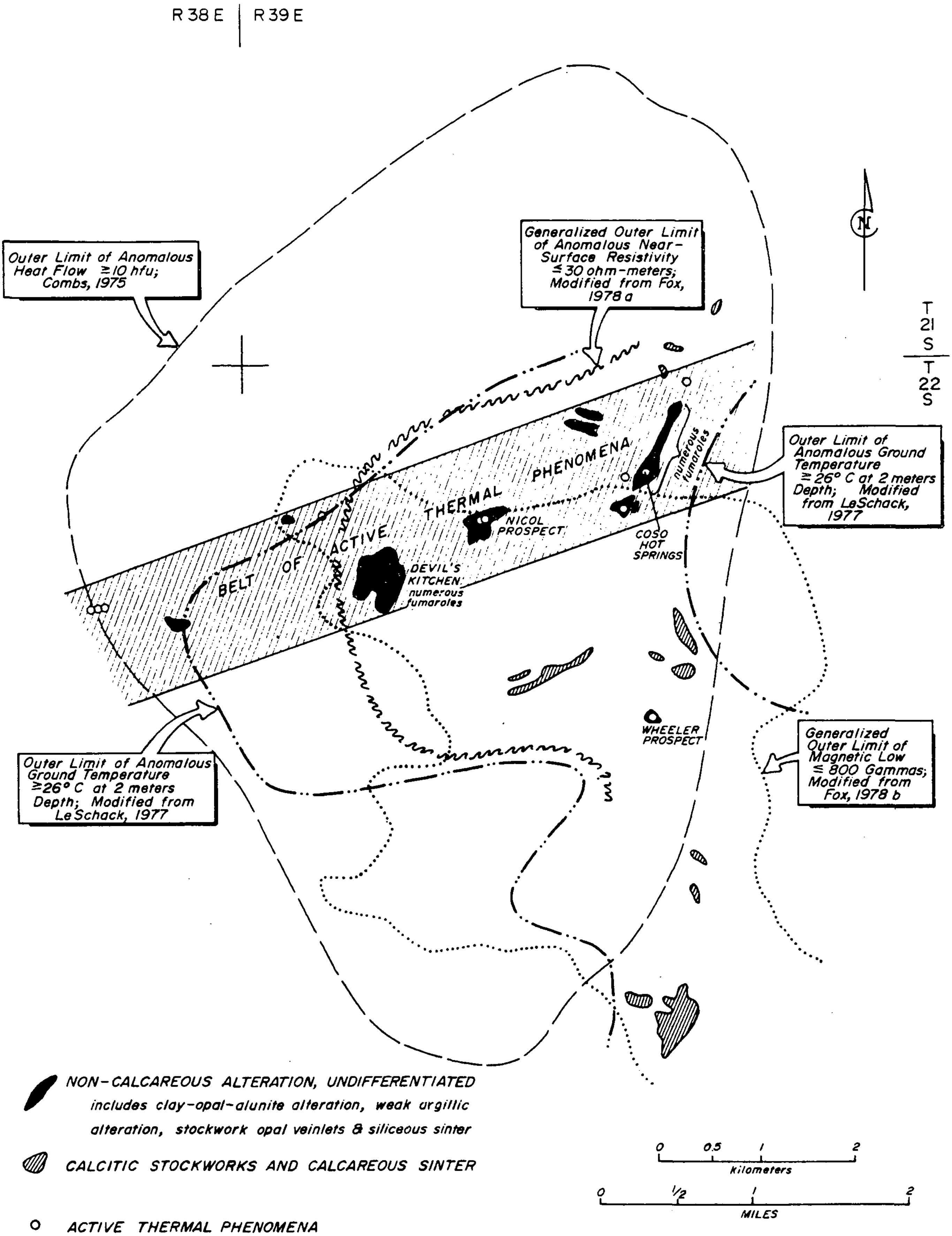

FIGURE 2
GENERALIZED ALTERATION AND GEOPHYSICAL MAP

High-angle faults trending northwest-west-northwest--parallel to the dominant foliation in pre-granitic metamorphic rocks--are common throughout the mapped area (Pl. I). These faults can be assigned to a major regional fault system described by Duffield (1975, after Von Huene, 1960; this report, p. 6). Displacement on the faults is probably both left-lateral and dip-slip. The faults are characterized by wide gouge and breccia zones which in most cases apparently impeded or precluded thermal fluid flow: With few exceptions, they are barren of hydrothermal alteration and active thermal emissions except at or near intersections with younger northerly-trending structures.

North-northwest-, north-northeast-, and (in the southern portion of the mapped area) northeast-trending high-angle faults form a second important fault system disrupting the rocks of the geothermal area. These faults commonly or truncate older northwest-west-northwest and east-northeast-trending faults. Many of these young northerly-trending faults show clear evidence of recent normal displacement: The Coso Hot Springs fault and the eastern range-front fault at the southern end of the mapped area (Pl. I) for instance, have formed scarps in recent alluvial debris. Normal movement along these northerly-trending faults may be in response to local east-west crustal extension, which, according to recent seismic studies by Weaver and Walter (1977), characterizes both the geothermal area and the entire Coso rhyolite field. Roquemore (1978a) suggests that the Coso Hot Springs fault and range-front faults to the north and south may also have undergone right-lateral movement, and that they may be part of a major northerly-trending right-lateral strike-slip fault system (this report, p. 6).

Active surface thermal phenomena and hydrothermal alteration within the mapped area are concentrated along (although not confined to) young northerly-trending faults, particularly at or near the intersections of these faults with older structures. Young northerly-trending faults or fractures also apparently control thermal fluid flow at depth in drill hole CGEH-1: Maximum temperatures in the hole were recorded in a north-northeast-trending fault (or fracture) zone between 1850 and 2725 feet (Galbraith, 1978).

The concentration of thermal phenomena and alteration along young northerly-trending faults at Coso may reflect the origin of these faults, at least in part, in response to active east-west extension (Weaver and Walter, 1977). Such an origin would promote the development of open breccias and fractures along these faults, which would then serve as excellent structural conduits for thermal fluid flow.

Alteration, Mineralization, and Thermal Phenomena

Hydrothermal alteration and active thermal phenomena (fumaroles, steaming boreholes, and "warm ground") in the Coso KGRA are scattered across an irregular eight-square-mile area situated along the east-central margin of the Coso rhyolite dome field (Pl. III). Within this area, nearly all active thermal phenomena are confined to a mile-wide belt roughly four miles in length trending east-northeast from the western slope of Sugarloaf Mountain to Coso Hot Springs (Fig. 2) The single known exception is a small fumarole at the Wheeler mercury prospect, roughly 1-1/4 miles south-southwest of the belt. Most of these thermal phenomena are accompanied by surficial alteration of host rocks (or alluvium) to opal, clay, and alunite in various proportions. Along the eastern range front north and south of Coso Hot Springs, the belt of active thermal emissions is flanked by scattered calcitic stockworks.

Rhyolitic pyroclastic deposits of the Devil's kitchen and the Nicol prospect (Pl. I, III) are altered to porous to dense aggregates dominated by opal, but also including significant amounts of alunite and kaolinite. Granitic rocks of the Nicol prospect are similarly altered, but richer in kaolinite. A variety of hydrous sulfates--as well as native sulfur--are erratically distributed throughout both altered areas as surface encrustations, veinlets, and partial cavity fillings (Austin and Pringle, 1970, p. 5-16). Sulfur-rich encrustations are most common around active fumaroles in the Devil's Kitchen.

Pyrite and cinnabar are locally present in altered rocks of the Devil's Kitchen and the Nicol prospect. Pyrite occurs as small grains and grain aggregates and rare discontinuous thin veinlets. It is most common in lower levels of the Devil's Kitchen. At higher levels, the pyrite is largely oxidized to powdery goethite-hematite mixtures. Cinnabar, commonly admixed with a little powdery hematite, occurs sparingly in both areas as films and crusts lining cavities and open fractures.

Scattered patches of alteration in granitic rocks east of the Nicol prospect and west of Coso Hot Springs (Pl. III) are texturally and mineralogically similar to altered granites at Nicol, but lack active thermal emissions. A few of these alteration patches, including those along west-northwest-trending fault zones just west of Coso Hot Springs (Pl. III) are reported by Koenig et. al. (1972) to possess abnormally high temperatures. Several other similarly altered areas, however, appear to be thermally inactive, and may represent "fossil fumaroles".

The fumaroles, steaming boreholes, and boiling mud pools aligned along the Coso Hot Springs fault form the most dramatic thermal display of the Coso KGRA. Surficial alteration developed around these features, however, is relatively subdued. The alteration is characterized by partial conversion of the host granitic alluvium to a crumbly, commonly hematite-stained clay with residual quartz. The clay is cut by a few scattered calcite and hyalite veinlets, and is locally accompanied by a little alunite and perhaps other hydrous sulfates, as well as chlorite and epidote: the latter two minerals are regional in distribution and probably antedate the geothermal system. A clay concentrate of a sample of the clay collected from the central portion of the altered area (C-122; Pl. III) was shown by X-ray diffraction to be a montmorillonite-kaolinite mixture.

Shallow drill hole Coso #1 (Pl. I, III) penetrated altered alluvium and granitic rock in the northern portion of the Coso Hot Springs fault zone to a depth of 375'. Alteration in this hole is essentially similar to that observed at the surface. (Austin and Pringle, 1970, p. 29-32; Fig. 23; Table 10).

Surficial alteration around active thermal emissions and "fossil fumaroles" at Coso is essentially identical in texture and mineralogy to that observed along range-front faults of the Roosevelt KGRA (Parry, et. al., 1976). At both Coso and Roosevelt, this alteration has almost certainly been effected through interaction of host rocks (and alluvium) with near-surface, sulfuric acid-charged waters. According to Schoen et. al. (1974), the acid is produced primarily through oxidation, by sulfate-reducing bacteria, of H_2S boiled from a subsurface water table. At Coso, it also seems likely that the acid may be partially derived from oxidation of pyrite. The acid combines with condensing water vapor or other moisture and seeps downward and outward, interacting with host rocks to produce a variety of alteration minerals. Progressive neutralization of the acid with distance from its production site results first in the formation of siliceous deposits and residues, then kaolinite-alunite-silica aggregates, and finally marginal montmorillonite at the expense of original rock silicates.

The Wheeler mercury prospect (Pl. I, III) is developed in the only siliceous sinter found within the mapped area. The sinter occurs in two small patches deposited on weakly argillized and silicified quartz monzonite and alluvial debris. It consists mainly of spongy to dense, crudely banded, locally clay and/or hematite-bearing opal. The opal is locally cut by irregular bands, streaks, and patches of translucent chalcedony. Brick red to maroon hematite, some of which contains a little cinnabar, occurs in the sinter as irregular crusts and films on fractures and cavity walls and as an erratically distributed pinkish stain.

Stockwork opal veins and veinlets are exposed in two small patches west of the Devil's Kitchen--one atop Sugarloaf Mountain; the other near a feeble fumarole about one mile to the northeast (Pl. III). The Sugarloaf stockwork is developed in perlite breccia, perlite and obsidian, all of which--except for a tiny (roughly 2x3 feet) clay pod in the breccia--are unaltered. The northeastern stockwork has formed in perlite and partially devitrified spherulitic obsidian, also apparently fresh. The veinlets of both stockworks range in width from less than one millimeter to at least five centimeters, and locally coalesce to form irregular masses up to 20 centimeters in diameter. They consist predominantly of milky white, dense to porous and vuggy, locally hematite-stained opal: Water-clear botryoidal hyalite occurs subordinately as films, crusts and vug linings. In the northeastern stockwork, the opal is altered to chalcedony in rare scattered irregular patches.

Siliceous breccias crop out locally within the mapped area (Pl. III). Most of these breccias are elongate in plan and were doubtless developed along previously existing fault zones. They consist of partially silicified country rock clasts embedded in a matrix of rock flour and silica in various proportions. Two of the breccias, situated immediately east of the Nicol prospect and in the northern third of sec. 9, T22S, R39E, respectively (Pl. III), are heavily impregnated and coated with dark gray manganese oxides. Siliceous breccias northeast of the Wheeler prospect are commonly laced with banded, goethite-bearing calcite veinlets.

Scattered calcitic stockworks are exposed along the eastern range front fault zone for at least four miles south and one-half mile north of the Coso Hot Spring fault (Pl. III). The stockworks are formed of microcrystalline to medium-crystalline, generally limonite-bearing calcite veins and veinlets and crusts on open fractures. The veins range in width from less than one milimeter to at least 20 centimeters (average about three milimeters). They are commonly delicately to coarsely banded--the result of variation in crystal size and form and limonite content. Host rocks are usually bleached to some extent, and are commonly weakly limonite-stained. X-ray diffraction of two bleached rock samples collected from calcitic stockworks south of the Nicol prospect (Pl. III; samples C-10, C-16) detected no clay minerals. This indicates that at least some of the bleaching accompanying the calcitic stockworks is not produced through argillization, but rather through simple leaching of iron from mafic minerals.

Two dissected calcareous sinter deposits rest on calcite-cemented alluvium just east of the range front in section 23, T22S, R39E (Pl. I, III). These deposits, up to two meters in thickness, are banded, limonite-bearing (goethite ± hematite), and essentially identical in texture to the larger veins of the previously described calcitic stockworks. A few such veins, up to at least 15 centimeters in width, cut calcareous alluvium beneath the northern travertine blanket. These veins merge upward into the travertine, and were clearly feeders for its deposition.

With the exception of the eastern range-front calcitic stockworks, the areas north, south and west of the east-northeast-trending belt of active thermal emissions are largely barren of alteration within the mapped area. Calcite is present in trace to minor amounts along the entire length of CGEH-1 (Galbraith, 1978). It occurs most commonly in association with epidote and/or chlorite in intermediate to mafic metamorphic rocks, and probably predates development of the Coso geothermal system. A few small widely scattered patches of calcareous sinter occur west of Sugarloaf Mountain (Pl. I). These small sinter deposits differ from those exposed in the southeastern portion of the mapped area in being cryptocrystalline calcium carbonates devoid of accessory limonite.

Granitic and metamorphic rocks of the geothermal area are ubiquitously but sparingly cut by epidote veinlets and patches of variable size and continuity. The epidote may occur singly or in combination with one or more of the minerals chlorite, calcite, and quartz. The density of these veinlets and patches, in general, varies directly with percentage of mafic minerals in the host rock, but the veinlets seldom account for more than a few per cent of the total rock volume.

A few massive milky quartz veins are also widely scattered in granitic and metamorphic rocks throughout the mapped area. These veins range in width up to an observed maximum 1/3 meter (average less than 10 centimeters), and in length up to 25 meters. A few are weakly mineralized with goethite, malachite, azurite, chrysocolla, and pitch limonite. These quartz veins, as well as the epidote-bearing veinlets and patches described above, are not confined to the immediate geothermal area, but occur in pre-Tertiary rocks on a regional scale. They are probably unrelated to the presently active geothermal system.

DISCUSSION AND CONCLUSIONS

The distribution at Coso of active thermal emissions and surface alteration, including calcitic stockworks and calcareous sinter, falls within the surface expression of a broad composite geophysical anomaly (Fig. 2) which has been interpreted as possible evidence for a concealed geothermal reservoir. Components of this anomaly include high heat flux (greater than 10 hfu; Combs, 1975), high ground temperature (greater than 26°C at two meters; LeSchack, 1977), low subsurface resistivity (Furgerson, 1973; Fox, 1978a) and weak rock magnetization (Fox, 1978b). Low bedrock resistivities in the inferred geothermal reservoir could reflect the combined subsurface presence of hot conductive fluids and locally argillized host rocks (Fox, 1978a). The magnetic low may indicate both magnetite destruction (through hydrothermal alteration) as well as original lithologic differences (Fox, 1978b).

Thermal emissions and associated clay-opal-alunite and weak argillic alteration at Coso are genetically related to the presently active geothermal system. It may be argued, however, that spatially associated calcareous deposits, which are thermally inactive, may not be genetically related. If not, however, their confinement within the zone of anomalous geophysical response suggests that they may reflect the same structural plumbing network controlling thermal fluid flow at depth. They may, in fact, serve as an effective, near-surface cap preventing fluid and heat loss from the geothermal system everywhere but along the east-northeast-trending belt of active thermal emissions west of and including the Coso Hot Springs fault zone.

Deep fluid flow in the inferred Coso geothermal reservoir will probably be wholly structurally controlled. Neither geologic mapping nor deep drilling in CGEH-1 have revealed potential deep primary aquifers. Structural permeability in the reservoir should be best developed along younger northerly trending high-angle faults, especially where these faults intersect older structures.

For maximum discovery potential, therefore, a follow-up drill hole at Coso should be situated near a fault intersection involving young northerly-trending faults within the zone of coincident surface alteration and favorable geophysical response. Such an area exists at the southern end of the Coso Hot Springs fault in the southern one third of Section 4, T22S, R39E (Pl. I). Here, the junction of north-northeast- and north-northwest-trending fault zones may be intersected by the sub-alluvial projection of an older east-northeast-trending structure. The follow-up drill hole should be collared at some distance from this fault intersection (to avoid caving and lost circulation problems), then deflected to penetrate it at an optimum depth for production of high energy geothermal fluids.

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EXPLANATION

CENOZOIC	QUATERNARY	HOLOCENE	Qal	alluvium; includes fan gravels, slope wash and playa deposits
		PLEISTOCENE	Ql	landslide debris
			Qoal	older alluvium; dissected older fan gravels
			r	rhyolitic volcanic rocks undifferentiated; predominantly perlite, pumice, and obsidian with subordinate rhyolite and porphyritic rhyolite
			rp	rhyolitic pyroclastic debris; mostly air-fall and water-reworked accumulations of pumice and obsidian lapilli and ash in various proportions
			bi	intrusive(?) basalt of uncertain age
			b3f / b3p	vesicular olivine-pyroxene basalt < b3p: cinder cone; b3f: flow rock } K-Ar age 234,000 ± 22,000 yrs. (Duffield and Bacon, 1977)
			b2	vesicular porphyritic olivine-pyroxene basalt
			cf	fanglomerate of the Coso formation
	TERTIARY	PLIOCENE	b1	vesicular olivine-pyroxene basalt
			d	vesicular porphyritic pyroxene dacite and dacite flow-breccia K-Ar age 3.42 ± 0.10 m.y.-biotite; 2.20 ± 0.70 m.y.-plagioclase (Duffield and Bacon, 1977)
MESOZOIC	LATE CRETACEOUS-?		gbx	fine-crystalline biotite granite intrusion breccia
			gf	fine to medium-crystalline granite and quartz monzonite, undifferentiated; includes small dikes, plugs and pods of alaskite, aplite and quartz-potassium feldspar pegmatite
			gc	coarse-crystalline leucocratic biotite granite; includes small dikes, plugs, and pods of alaskite, aplite and quartz-potassium feldspar pegmatite
?			f	felsite dikes and pods
			qlp	biotite quartz latite porphyry dikes
			m	intermediate to mafic metamorphic rocks, undifferentiated; includes biotite schist and gneiss, metadiorite and metadiabase, meta-andesite and metadacite, amphibolite (metagabbro ?), and chlorite schist, with very minor sericite schist, felsic metatuff (?), possible metachert, granitic gneiss, lit-par-lit injection gneiss and miscellaneous hybrid rock types along contacts with granitic intrusive rocks

Contact, dashed where approximate - dashed and dotted where gradational

Fault, long dashes where approximate, short dashes where inferred, dotted where concealed. Bar and ball on downthrown block.

Concealed fault inferred from resistivity studies (Fox, 1978a)

50 Strike & dip of beds

45 Strike & dip of flow foliation in volcanic rocks & schistosity in metamorphic rocks

Drill Hole

2000 0 2000 4000

SCALE IN FEET

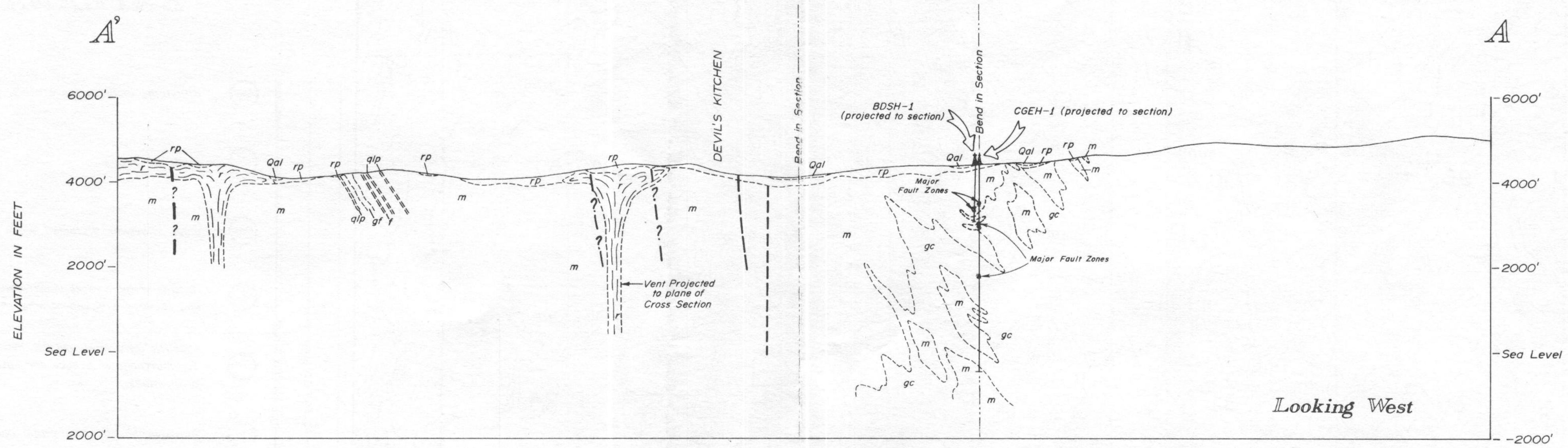
N

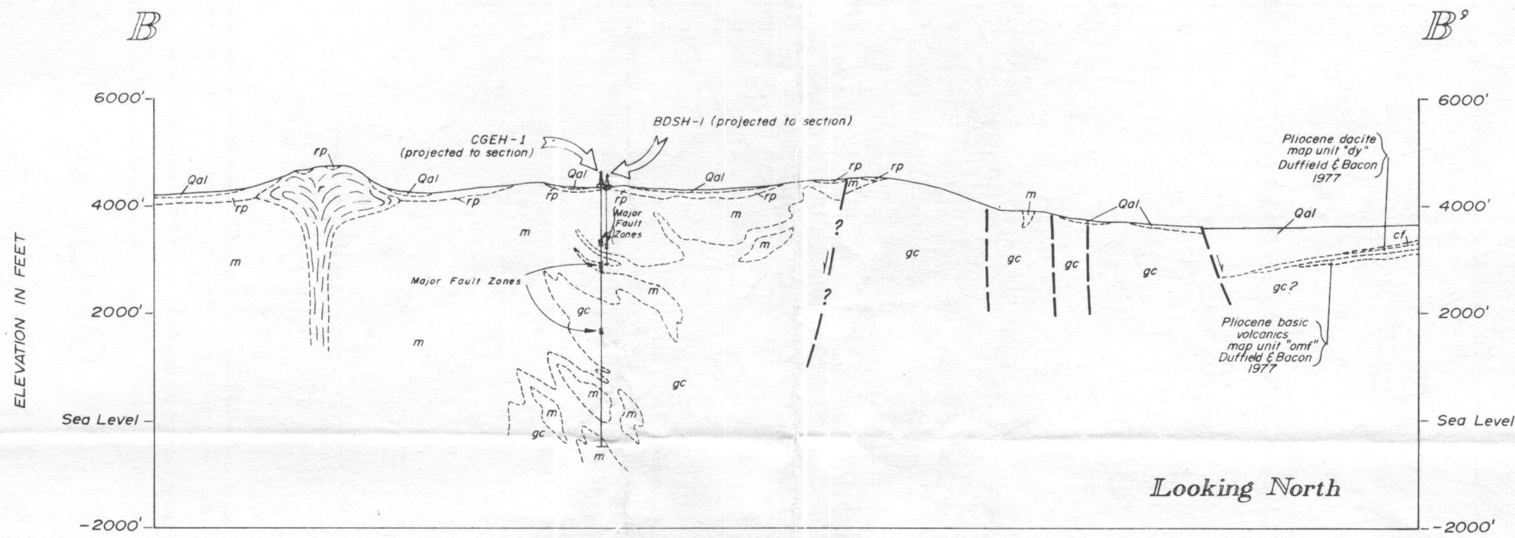
PLATE I

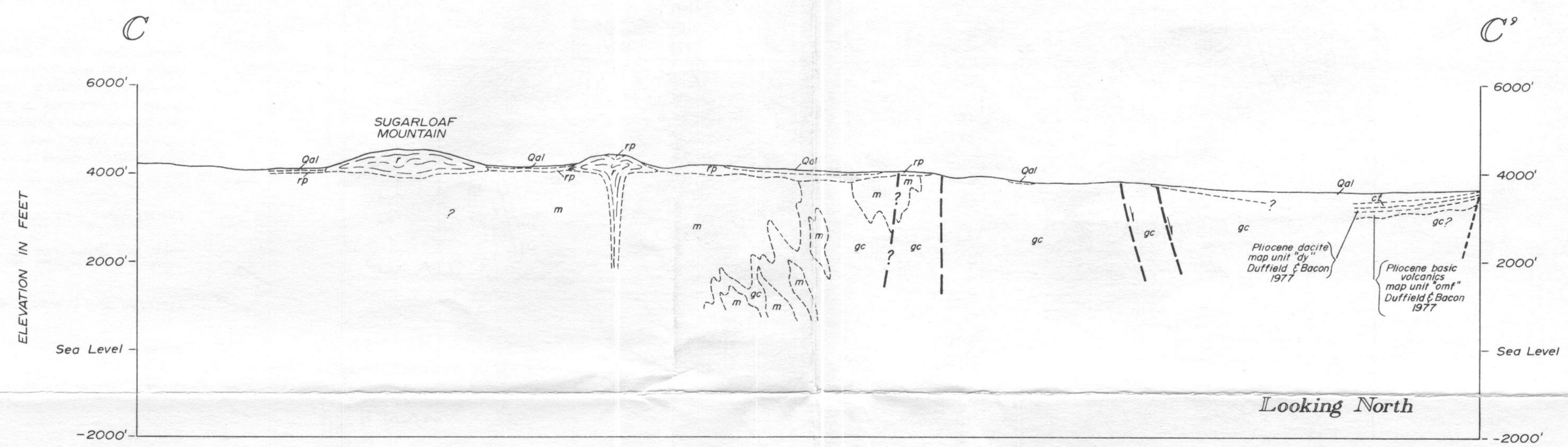
Geologic Map of the Coso Geothermal Area

Data by J. B. Hulen; modified from Duffield & Bacon, 1977

DRAFTING D.CULLEN
MAP NO 8







Refer to Plate 1 for explanation

PLATE 2

Geologic Sections through the Coso Geothermal Area
(to accompany geologic map; plate 1)

Data by J. B. Hulen

DRAFTING D.CULLEN 3-78
MAP NO 10

CGEH-1 data modified from Galbraith, 1978
BDSH-1 data modified from field log by J. Hyde and R. Galbraith, 1977

PLATE 2

EXPLANATION

Opal-alunite-kaolinite alteration. These three minerals in various proportions with native sulfur and miscellaneous hydrous sulfates locally present

Argillic alteration along the Coso Hot Springs Fault. Characterized by partial to complete conversion of alluvium to montmorillonite ± kaolinite, locally accompanied by opal, alunite and calcite and probably miscellaneous hydrous sulfates, as above.

Stockwork opal veinlets. Dense to porous opal, rarely altered to chalcedony in irregular patches. Density of veinlets averages >10 per linear meter where mapped. Scattered opal films and veinlets averaging 1–3 per linear meter occur throughout most of the rhyolite domes.

Siliceous sinter. Banded, subhorizontal deposits of dense to porous opal — locally altered to chalcedony in irregular bands and patches. Commonly stained and coated with hematite, some of which contains a little cinnabar. Confined to the Wheeler Prospect.

Silicified fault breccia. Weakly to moderately silicified clasts embedded in a matrix of rock flour and silica.

Stockwork calcite veinlets. Banded veinlets of fine to coarse crystalline calcite, generally with minor goethite ± hematite as a stain in certain bands or as films and crusts separating bands. Commonly accompanied by weak bleaching of the host rocks. Density of veinlets generally greater than 20 per linear meter where mapped. In alluvium, fewer veinlets, but pervasive calcite flooding of matrix.

Weak calcitic alteration and bleaching. Original rock feldspars and mafic minerals partially altered to calcite. Mafic minerals also commonly bleached. Minor montmorillonite locally present. Calcite veinlets, as above, sparsely distributed.

Calcareous Sinter or Travertine. Banded, subhorizontal deposits of banded calcite, identical in texture to the stockwork calcite veinlets which are described above.

Fumarole

Steaming shallow borehole

Alteration sample

Drill Hole

2000 0 2000 4000
SCALE IN FEET

PLATE 3

Surface Alteration in the Coso Geothermal Area (overlay for geologic map)

Data by J.B. Hulen

DRAFTING D CULLEN 3-78
MAP NO 9