Stable Isotope Geochemistry: A Tribute to Samuel Epstein
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Oxygen isotope studies of Jurassic fossil hydrothermal systems, Mojave Desert, southeastern California*

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Abstract—Whole-rock oxygen isotope analyses of 66 Jurassic plutonic and subvolcanic granodiorites and monzogranites from the Rodman-Ord Mountains (ROM) area in the Mojave Desert range from $\delta^{18}O = -3.2$ to $+9.4$. These data define an elongate WNW–ESE zone of ^{18}O depletion, where intrusive igneous rocks with original $\delta^{18}O$ values of +7.5 to +9 have been partially altered and veined by epidote, chlorite, and sericite, and depleted in ^{18}O by two to ten per mil over an area of more than 1000 km^2. These effects were produced by exchange with heated low-^{18}O meteoric ground waters in association with a series of volcanic centers. These centers are identified by ovoid-shaped areas of extreme ^{18}O depletion where $\delta^{18}O < +2$. Earlier Triassic plutons (4 samples) and later Cretaceous plutons (10 samples) from the ROM area do not display any analogous ^{18}O depletions, indicating that the identifiable hydrothermal events are confined to the Jurassic igneous episode, which clearly had to be epizonal in nature. Reconnaissance $^{18}O/^{16}O$ analyses of another 20 early Mesozoic granodiorites and monzogranites elsewhere in Southern California demonstrate that the ROM-type low-^{18}O effects extend well to the southeast along the major Jurassic rift zone and associated calderas proposed by BUSBY-SPERA (1988). This graben depression extends from Yerington, Nevada (where the associated Jurassic hydrothermal waters were higher in ^{18}O and probably marine in origin) southeastward across a Jurassic coastline and through the subaerial ROM area (where the hydrothermal fluids were continental meteoric in origin); the low-^{18}O rift-zone continues across southeastern California and then into southern Arizona where only scattered oxygen isotope data are available. In the ROM area the low-^{18}O patterns are truncated by the Cretaceous plutons and they are also offset by displacements along NW-trending late Cenozoic strike-slip faults. The $\delta^{18}O$ systematics can be used to map offsets on these faults, confirming that they are relatively small. For example, the right-lateral offset on the Camp Rock Fault is constrained by the $^{18}O/^{16}O$ patterns to be only 5 ± 2 km.

INTRODUCTION

THIS PAPER IS part of a series of studies by us of the oxygen isotope geochemistry of plutonic igneous rocks of the Transverse Ranges and Mojave Desert regions of Southern California. These studies were undertaken mainly to map the primary $\delta^{18}O$ values of Mesozoic plutons in this region, in order to expand on and supplement the data of TAYLOR and SILVER (1978) and MASI *et al.* (1981) on the Peninsular Ranges and Sierra Nevada batholiths. However, it soon became apparent that in contrast to the Cretaceous-age plutons, many of the Jurassic-age plutons of this broad region constituted a special case, in that their original $^{18}O/^{16}O$ ratios had been shifted down to lower values as a result of meteoric-hydrothermal alteration. We learned that we would have to "look through" and understand this low-^{18}O overprint if we were going to be able to map the primary $\delta^{18}O$ values of the original magmas.

This paper reports on reconnaissance isotope studies throughout the Mojave Desert region, but it particularly focuses on detailed studies of what appears to be the largest and most accessible of these Jurassic hydrothermal centers, namely the Rodman-Ord Mountains (ROM) area in the vicinity of Stoddard Valley and Lucerne Valley, north of the San Bernardino Mountains, east of the town of Victorville, and south of the town of Barstow (Fig. 1). This area exhibits the sorts of $^{18}O/^{16}O$ relationships that are characteristic of most fossil meteoric-hydrothermal systems throughout the world, such as are found in Tertiary volcanic centers like the Comstock Lode described in this volume (CRISS and CHAMPION, 1991) or the Eocene parts of the Idaho Batholith (TAYLOR and MAGARITZ, 1978; CRISS and TAYLOR, 1983).

A detailed sampling program involving analyses of whole-rock $\delta^{18}O$ in 80 intrusive igneous rocks was undertaken in the ROM study area for the reasons listed above, but also: (1) to define the size and characteristics of this area of altered rocks, inasmuch as no major $^{18}O/^{16}O$ study of such a large fossil meteoric-hydrothermal system has yet been carried out in Southern California; and (2) to test the possible usefulness of $^{18}O/^{16}O$ studies in determining offset along late Cenozoic faults in the area, by defining the limits of hydrothermal exchange and then

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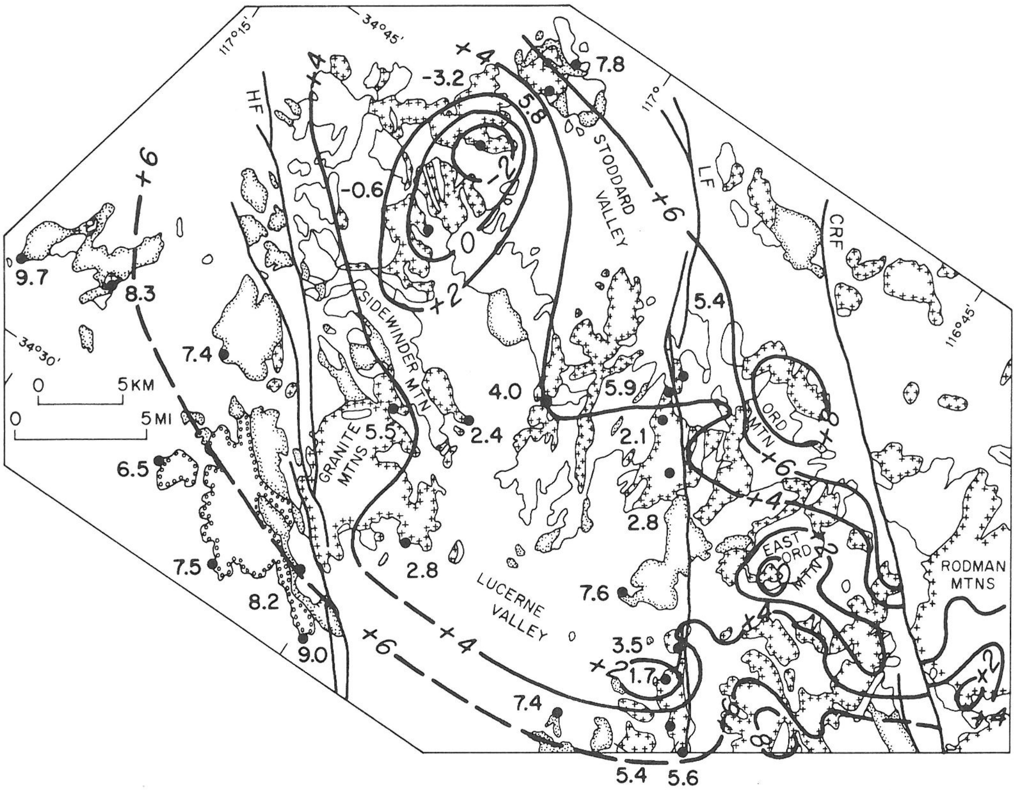

FIG. 1. Geologic map of the ROM area, showing Mesozoic batholithic rocks, pre-batholithic country rocks, late Cenozoic strike-slip faults, and whole-rock $\delta^{18}O$ contours on Jurassic intrusive rocks (geology after BISHOP, 1963; and BORTUGNO and SPITTLER, 1986). The $\delta^{18}O$ contours are based on the whole-rock $\delta^{18}O$ values given in Table 1 and plotted on this figure and on Fig. 2 (sample locations indicated by solid circles). The $\delta^{18}O$ values southwest of the Lenwood Fault (LF) are shown on this figure, but for rocks northeast of LF they are shown on Fig. 2. Mesozoic batholithic rocks are indicated according to age of emplacement by different symbols along inside margins of map units: (1) Triassic plutons are shown by small circle patterns; (2) Jurassic plutons are shown by cross patterns; and (3) late Cretaceous plutons are indicated by stippled patterns. Unlabeled outcrops on the map are the pre-batholithic country rocks, and include early Mesozoic silicic pyroclastic units and volcanic flows, Mesozoic sedimentary rocks, and Precambrian crystalline basement. HF = Helendale Fault; CRF = Camp Rock Fault.

mapping any fault displacements of the regional $\delta^{18}O$ contours.

GEOLOGICAL RELATIONSHIPS

Mesozoic plutonism in the Mojave Desert is characterized by at least three separate magmatic episodes: (1) sparsely outcropping Permo-Triassic monzonite and granodiorite; (2) relatively abundant epizonal Jurassic granodiorite and monzogranite; and (3) very widespread late Cretaceous granodiorite and monzogranite (BURCHFIEL and DAVIS, 1981; MILLER, 1978; JOHN, 1981). The Jurassic plutons commonly show intense hydrothermal alteration, and in places are mineralized. They are typically emplaced into volcanic rocks, and many probably represent exhumed volcanic centers. Late Cretaceous plutonism in the Mojave Desert was locally accompanied by emplacement of muscovite-bearing granites, and in places developed pegmatitic facies. No volcanic carapace has been mapped for the Cretaceous episode of magmatism, and in general that plutonic episode appears to have been relatively deep-seated.

The tectonic processes responsible for the immense mobility of upper plate rocks in latest Cretaceous time eventually culminated in the formation of mid-Tertiary metamorphic core complexes throughout the Cordillera, including parts of the Mojave Desert (CONEY, 1980). Miocene volcanism and related hypabyssal plutonism are known to occur within the study area, as part of a northwest-trending belt that extends throughout the Mojave region. However, these features post-date the igneous and hydrothermal events of concern in this paper, and they are not discussed further. The late Cenozoic strike-slip faulting, which resulted in displacements of the Jurassic crystalline basement within the study area, is of interest and is discussed in more detail below.

Figure 1 is a generalized geologic map of the Rodman-

Ord Mountains (ROM) area. Figure 2 shows the geology of the eastern portion of this area at a larger scale. This eastern region between the Lenwood Fault and Camp Rock Fault was studied in more detail because an initial reconnaissance revealed that this was a principal area of "disturbed" $^{18}O/^{16}O$ ratios.

The ROM area was geologically mapped by DIBBLEE (1960a,b,c; 1964a,b,c; 1967), MILLER (1978), MILLER and CARR (1978), and MILLER and CAMERON (1982). The area is underlain by Mesozoic plutonic rocks intrusive into Precambrian crystalline basement, PermoTriassic(?) volcanic rocks, and Paleozoic and Mesozoic metasediments and volcanics. The Mesozoic plutonism began in Triassic time with the intrusion of alkalic plutons, but it is dominated by hydrothermally altered Jurassic granodiorites that appear to be associated with a number of propylitized ring zones that are aligned along a major northwest-trending lineament. A prominent late-Jurassic(?) latite dike swarm is oriented sub-parallel to this lineament, and cuts the Jurassic plutons and their associated volcanic country rocks. Late Cretaceous plutons cross-cut the area, but are not affected by either hydrothermal alteration or by the main group of latite dikes, although several large felsic dike-like bodies may be late Cretaceous in age.

Crystalline rocks of probable Precambrian age crop out between Stoddard Ridge and Ord Mountain, and consist of quartz dioritic gneiss, granitic gneiss, and hornblende-biotite schist. DIBBLEE (1964c) describes these units as being generally similar to, and presumably correlative with, Precambrian(?) gneissic rocks of the San Bernardino Mountains (Baldwin Gneiss).

The ROM area was the site of late Precambrian to Paleozoic miogeoclinal sedimentation. STEWART and POOLE (1975) proposed that the Paleozoic section at Quartzite Mountain near Victorville is correlative with strata elsewhere in the southern Great Basin. MILLER and CAMERON (1982) review the Paleozoic geology, and suggest that the lack of Ordovician through lower Devonian strata in the Sidewinder Mountains probably indicates a transition from miogeoclinal to cratonal sedimentation.

During early Mesozoic plutonism, the Paleozoic rocks were multiply deformed and metamorphosed. The Triassic(?) alkalic pluton on the east side of Apple Valley in the Granite Mountains appears to have been intruded at this time. Mesozoic sedimentary and volcanic rocks were unconformably deposited on the Paleozoic section. These consist of shallow marine quartzites interbedded with latite prophyry flows and tuffs. The quartzitic rocks are lithologically correlative with the early Jurassic Aztec Sandstone in the eastern part of the Rodman Mountains area. The volcanic rocks are known locally as the Sidewinder Volcanics, and consist mainly of latite porphyry and latite porphyry breccia ranging in composition from quartz latite to andesite. Hydrothermal alteration is conspicuous throughout the volcanic country rocks, with chlorite and sericite replacing groundmass minerals, and epidote filling fractures and vesicles.

The main episode of Mesozoic plutonism in the ROM area involved the intrusion of Jurassic hypabyssal biotite- and hornblende-bearing granodiorites and less abundant quartz monzonites (=monzogranite) and granitic stocks. These plutons are typically medium-grained, and most are affected by hydrothermal alteration to varying degrees. Chlorite, epidote, and sericite are the common alteration minerals; in places these impart a greenish cast to the rock where feldspar has been pervasively altered. Epidote-filled fractures are common.

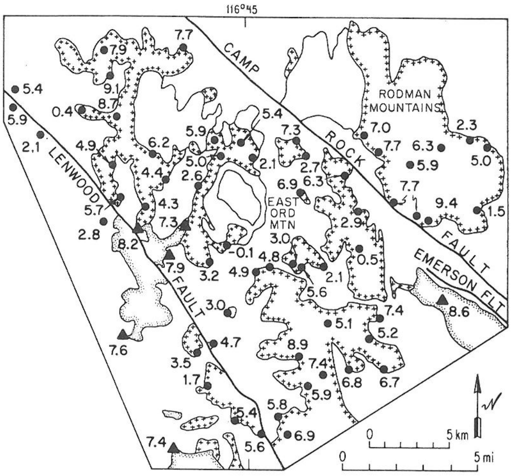

FIG. 2. Geologic map of the northeastern portion of the ROM area, showing Jurassic and Cretaceous granitic plutons, early Mesozoic volcanic units, and $^{18}O/^{16}O$ sample localities with whole-rock $\delta^{18}O$ values lettered in (geology after DIBBLEE, 1964a,b). The geologic map units and $^{18}O/^{16}O$ sample symbols are the same as those listed above for Fig. 1, except that the late Cretaceous sampling localities are shown on this figure by solid triangles.

On the west flank of Ord Mountain, molybdenum veinlets are locally abundant in intensely altered rocks. Surrounding the flanks of East Ord Mountain is a fine-grained, buff-colored, aplitic quartz monzonite whose outcrop pattern distinctly resembles a "ring structure" about four to five km in diameter (see Fig. 2). This pluton has abundant miarolitic cavities and a myrmekitic texture in thin section, clearly indicating a shallow depth of emplacement.

The final pulse of Mesozoic batholithic activity was the intrusion of late Cretaceous plutons. Throughout the ROM area, isolated late Cretaceous plutons intrude the hydrothermally altered Jurassic rocks, but are not themselves hydrothermally altered except in areas of silicification associated with aplitic-facies rocks. The late Cretaceous quartz monzonites (monzogranites) are medium-grained, mostly equigranular rocks whose main accessory mineral is biotite. These rocks weather in a friable manner by breaking down to separate grains around mounds of outcrop, serving to readily distinguish them from the Jurassic plutons, which are generally made up of much tougher rocks (mainly because of the effects of hydrothermal alteration).

The ages of the Jurassic plutons in the ROM area are not well known. For the northern and western portions of the area, minimum K-Ar ages obtained by MILLER and MORTON (1980) on hornblende are 163 to 186 Ma, and for biotite the ages are between 68 and 134 Ma. Where hornblende and biotite from the same sample are dated, the hornblende shows older ages than the biotite, with most biotites clustering between 70 and 80 Ma. Clearly, the late Cretaceous thermal event was important in imprinting biotite K-Ar ages on the Jurassic rocks.

The cluster of biotite ages probably gives a minimum age for the late Cretaceous plutonism, and with dates between 70 and 80 Ma, this event appears to be essentially synchronous with the late Cretaceous plutonism in the San Bernardino Mountains just to the south. Because the latitic dikes cut the Jurassic granodiorites, the age of dike emplacement must be younger than 163 Ma but earlier than 70 to 80 Ma. The dike swarm may correlate in age with the Independence Dike Swarm of the Owens Valley, which has been dated at around 142 Ma (L. T. SILVER, pers. comm.; CHEN and MOORE, 1982).

The major late Cenozoic strike-slip faults are, from west to east, the Helendale, Lenwood, Johnson Valley, and Camp Rock. The Emerson Fault forms the southeastern extension of the Camp Rock Fault, which dies out near Iron Ridge. These faults are part of the major group of strike-slip faults that have absorbed most of the late Cenozoic deformation in the Mojave Block (DOKKA, 1983). DOKKA (1983) places the timing of movement along the faults as mainly between the early Miocene and Pleistocene.

Figure 2 shows the locations of the Camp Rock and Lenwood faults relative to the detailed $^{18}O/^{16}O$ sampling grid. Previous estimates of offset for the Camp Rock Fault range anywhere from 1.5 to 10 km, and estimates for the Lenwood Fault range from 1.5 to 20 km (HAWKINS, 1975; GARFUNKEL, 1974; DOKKA, 1983). There is a wide disparity between these various estimates, because of the uncertain nature of geologic contacts in the post-Mesozoic volcanic terranes in the region, and because no tightly constrained piercing points have been found in the pre-Tertiary crystalline basement. Knowledge of the actual displacements would be extremely useful in reconstructing the late Cenozoic deformation of the Mojave Region.

ISOTOPIC RELATIONSHIPS

Rodman-Ord Mountains area

Figure 1 shows the sample locations and $^{18}O/^{16}O$ data for the western part of the ROM area, and Fig. 2 shows similar data for the more densely sampled eastern part of the area, at a somewhat larger scale. These isotopic analyses and exact locations of all Triassic, Jurassic, and Cretaceous samples studied from the ROM area are given in Table 1.

Triassic rocks crop out in the Granite Mountains and at Pitzer Butte; three of these samples have whole-rock $\delta^{18}O$ values of +6.5 to +8.0, and one sample from the southern edge of a dike-like extension of the major Granite Mountains pluton has a $\delta^{18}O$ = +9.0. None of these rocks show obvious mineralogic signs of hydrothermal alteration, and it is assumed that these $\delta^{18}O$ values are primary, magmatic values. We simply note the general similarity of the $\delta^{18}O$ of these Triassic rocks to the values obtained for the Lowe Granodiorite complex (+6.8 to +7.8), a composite pluton of similar age in the San Gabriel Mountains (SOLOMON, 1989).

Late Cretaceous plutons occur as scattered outcrops across the area but are overshadowed volumetrically by the Jurassic rocks. The Cretaceous rocks do not show any signs of widespread ^{18}O depletion attributable to hydrothermal alteration; except for the most westerly sample near Victorville, which has an anomalously high $\delta^{18}O$ = +9.7, they have whole-rock $\delta^{18}O$ values between +7.3 and +8.6. Generalized contours of the primary whole-rock $\delta^{18}O$ values of these Cretaceous plutons are not shown on any of the figures in this paper, but they in fact fit in well with the regional patterns established by SOLOMON (1989) for the San Gabriel and San Bernardino Mountains; the pattern of primary magmatic Cretaceous $\delta^{18}O$ contours in the ROM area is characterized in a general way by an eastwardly decreasing $\delta^{18}O$, from +9.7 in the west to values as low as +7.3 and +7.4 in the east. In addition, as was found for all the other areas in Southern California, the higher-^{18}O plutons are generally located adjacent to outcrops of Paleozoic miogeoclinal sediments, while the lower-^{18}O plutons occur near Precambrian cratonal basement. The eastward decrease in $\delta^{18}O$ correlates with the appearance of a predominantly cratonic basement around West Ord Mountain.

The Jurassic plutons in the ROM area are associated with volcanic rocks that grade downward into hypabyssal stocks (DIBBLEE, 1964a,b). Figures 1 and 3 show contours of whole-rock $\delta^{18}O$ for these plutons. The zone of ^{18}O-depletion is approximately 60 km in the east-west dimension, and 15 to 30 km in the north-south dimension. The low-^{18}O zone is broadest in the north and west, and becomes narrower to the south and east. In detail, the contours define several oval-shaped, "ring-like" patterns within a broad, west-northwest trending zone in which the $\delta^{18}O$ values are all less than +4.0. Within the elliptical ring zones defined by the +2.0 per mil contours, the rocks are extremely variable in $\delta^{18}O$, as low as 0.0 or lower. The lowest value, −3.2, was observed just north of Stoddard Ridge in a sericitized dike-like body that intrudes the Sidewinder Volcanics.

Whole-rock $\delta^{18}O$ values of +7.7 to +9.4 are observed in some of the least altered Jurassic-age samples in the study area (see Figs. 1 and 2); these values are similar to those observed in other Jurassic-age plutons from analogous geologic settings elsewhere in the North American Cordillera, and we conclude that this range very likely represents the original $\delta^{18}O$ values of these plutons prior to hydrothermal alteration. Thus, an area more than 1000 km^2 in size has undergone an ^{18}O depletion of between two and ten per mil. The individual volcanic centers scattered along this zone correspond to the ovoid-shaped areas with $\delta^{18}O < +2$; the latter represent whole-rock ^{18}O depletions of at least five per mil, and together in the ROM area they aggregate about 100 km^2.

The overall size of the ROM ^{18}O-depleted zone and the magnitude of the ^{18}O-depletions are both nearly as large as those discovered by TAYLOR and MAGARITZ (1978) and CRISS and TAYLOR (1983) surrounding Eocene batholiths emplaced into the Cretaceous Idaho Batholith. The $^{18}O/^{16}O$ effects in the ROM area are spread over a much larger area than those reported for similar systems by TAYLOR (1974), LARSON and TAYLOR (1986), or FORESTER and TAYLOR (1976, 1977). The $\delta^{18}O$ contour patterns in these other areas have all been proven to be the result of sub-solidus interaction between the plutons and low-$\delta^{18}O$ heated meteoric waters within a hydrothermal circulation system. Therefore, a similar model undoubtedly also applies to the ROM area.

All of these meteoric-hydrothermal systems characteristically require that extremely large quantities of water must flow through highly fractured, permeable rocks, fed from surface recharge in a convection pattern around the plutonic heat source (*e.g.*, see CRISS and TAYLOR, 1986). The low-^{18}O fluids exchange oxygen isotopes with the rocks, producing higher-^{18}O fluid and, by material-balance, an ^{18}O-depleted rock. The actual magnitude of the effect depends on the initial $\delta^{18}O$ of the water, the $^{18}O/^{16}O$ fractionation factors between minerals and the fluids (which are a function of temperature), and on the overall mass of water that flowed through the system at temperatures where reaction kinetics promote exchange. The grain size of the rocks can also play a role in the exchange kinetics, but this is not a factor in the present study because we are comparing data on similar samples that are all relatively uniform, medium-grained plutonic rocks. All of the $\delta^{18}O$ contours on Figs. 1, 2, and 3 are based on intrusive samples; none of the isotope analyses are from fine-grained or aphanitic volcanic country rocks.

Cretaceous plutons in the area cross-cut the altered Jurassic plutons, but the Cretaceous rocks do not exhibit any ^{18}O-depletions; therefore, it is clear that the hydrothermal systems responsible for ^{18}O-depletion in the ROM area must have been older than the late Cretaceous plutonism, but either younger or synchronous with the Jurassic plutonism. These rocks thus represent some of the oldest and largest low-^{18}O hydrothermal systems yet documented in the Cordillera of North America. This hydrothermal activity in the ROM area was sandwiched in time between the emplacement of the unaltered Triassic plutons and the emplacement of unaltered Cretaceous plutons. Clearly, there must have been a dramatic shift in the tectonic style of igneous activity in this area between the Triassic and Jurassic and also between the Jurassic and the Cretaceous.

The ROM low-^{18}O zone is coincident with, and subparallel to, a major late-Jurassic dike swarm. This low-^{18}O zone very likely continues to the northwest of the map area shown in Fig. 1, because there is no indication that the zone is narrowing in that direction. Indeed, BUSBY-SPERA (1988) has recently suggested that the ROM area is just one of a series of mid-Jurassic volcanic centers and calderas that occupied a continuous graben depression, more than 1000 km long, that extended from the central Sierra Nevada batholith at least as far as the Baboquivari Mountains in southern Arizona (see below).

It is therefore tempting to speculate that we may be looking at a very large rift-zone feature that may have been responsible for a whole series of overlapping meteoric-hydrothermal systems, and one which might conceivably be traced much farther to the northwest, as well as to the southeast. We know that the most important deep-seated hydrothermal systems on Earth today are all associated with such rift systems, notably Iceland, Yellowstone, and the mid-ocean ridge spreading centers (*e.g.*, see TAYLOR, 1988, 1990). Extensional tectonics provide the open fractures and permeability necessary for deep circulation of surface waters, as well as providing the necessary heat energy by allowing upward access for magmas from depth. It would be most interesting to extend our $^{18}O/^{16}O$ studies, and try to follow the ROM low-^{18}O zone in detail along strike to the northwest or to the southeast; in particular, it is important to see whether or not these $^{18}O/^{16}O$ effects correlate with the emplacement of the $\sim$142 Ma Independence Dike Swarm in the Sierra Nevada region (CHEN and MOORE, 1982). The regional implications of these oxygen isotopic results are discussed more thoroughly below.

The existence of such low-^{18}O fossil hydrothermal systems in Jurassic rocks of the Mojave Desert region has interesting paleogeographic implications. Meteoric waters derived from rainfall or snowfall become increasingly ^{18}O-depleted with decreases in the atmospheric temperature, either as a result of increasing elevation or latitude, or both. Thus, in North America there is a general correlation with distance from the Pacific Coast, because oceanic water vapor, which is the ultimate source of the atmospheric meteoric water, becomes steadily depleted in ^{18}O as the air mass moves to the east and north (*e.g.*, see SHEPPARD, 1986). Because of this fractionation process, inland regions have relatively lower-^{18}O surface waters (*e.g.*, $\delta^{18}O < -10.0$), particularly the high, mountainous regions that have

Table 1. Locations and oxygen isotope analyses of plutonic and subvolcanic igneous rocks from the Rodman-Ord Mountains Area, Southern California

Samp. no.	Rock type	$\delta^{18}O$*	Remarks	34°N latitude	116°W longitude
Jurassic-Age Plutons					
158	BGrd	+2.8	Granite Mtns. Pluton, powerline Rd.	31.89′	58.27′
159	BHGrd[e,c]	+5.5	Sidewinder Mtn. Pluton	35.34′	01.65′ †
160	BHMzG[e,c]	+2.4	Sidewinder Mtn. Pluton, Barstow Rd.	36.21′	58.76′
161	BMzG[e,c]	+4.0	Barstow Rd. Pluton, Barstow Rd.	38.27′	56.75′
163	BHGrd[e,c]	+5.8	Stoddard Valley Pluton, Stoddard Wells Rd.	46.62′	03.49′ †
164	GPorph[e,s]	−3.2	Stoddard Wells Pluton, Stoddard Wells Rd.	43.96′	04.53′ †
165	GPorph[e,s]	−0.6	Stoddard Wells Pluton, Stoddard Wells Rd.	40.69′	04.40′ †
167	MiarG	+2.7	East Ord Mtn. Pluton	40.17′	33.06′
168	BHGrd[e,c]	+4.9	Fry Mtns. Pluton, Camp Rock Rd.	36.14′	44.83′
268	BHGrd[e,c]	+5.4	Eastern Lucerne Valley Pluton	32.02′	45.89′
272	BHGrd	+5.6	Eastern Lucerne Valley Pluton, powerline rd.	31.39′	44.69′
274	BHGrd[e,c]	+5.8	Fry Mtns. Pluton, powerline rd.	31.55′	43.99′
275	BHGrd[e,c]	+5.9	Fry Mtns. Pluton, powerline rd.	32.59′	42.59′
276	BHGrd	+7.4	Fry Mtns. Pluton, powerline rd.	32.89′	41.86′
277	BHGrd[e,a]	+6.8	Fry Mtns. Pluton, powerline rd.	33.34′	41.24′
278	BHGrd[e,a]	+5.2	Fry Mtns. Pluton, powerline rd.	33.98′	40.43′
280	BMzG[e,s]	+0.5	Fry Mtns. Pluton, powerline rd.	36.88′	40.72′
281	BMzG[e,s]	+2.1	Fry Mtns. Pluton, powerline rd.	36.39′	42.47′
282	BHGrd[e,c]	+5.6	Fry Mtns. Pluton, powerline rd.	36.43′	43.21′
283	BMzG[e,s]	+3.0	Fry Mtns. Pluton, powerline rd.	36.43′	43.33′
284	BHGrd[e,c]	+4.8	Fry Mtns. Pluton, powerline rd.	36.32′	44.26′
285	BHGrd[e,c]	+3.0	Fry Mtns. Pluton, Camp Rock Rd.	35.09′	45.83′
287	BHGrd[e,c]	+1.7	Eastern Lucerne Valley Pluton	33.15′	47.68′
288	BHGrd[e,c]	+3.5	Eastern Lucerne Valley Pluton	34.17′	47.14′
289	BHGrd[e,c]	+4.7	Fry Mtns. Pluton, Camp Rock Rd.	34.06′	46.62′
292	BHGrd[e,c]	+5.7	Ord Mtn. Pluton, Tyler Valley Rd.	38.65′	50.08′
293	BHGrd[e,c]	+4.9	Ord Mtn. Pluton, Tyler Valley Rd.	39.74′	50.27′
294	BHGrd[e,c]	+4.3	Ord Mtn. Pluton, base of Ord Mtn.	38.77′	49.28′
296	BGorph[e,c]	+5.9	Ord Mtn. Pluton, Ord Valley Rd.	40.25′	46.50′
325	BHGrd[e,c]	+3.2	East Ord Mtn. Pluton	36.58′	46.51′
328	GPorph[e,c]	−0.1	East Ord Mtn. Pluton, near mine	37.24′	45.66′
329	BMzG[b,ac,e]	+6.9	Fry Mtns. Pluton, Camp Rock Rd.	38.58′	43.03′
331	BMzG[b,c]	+6.3	Fry Mtns. Pluton, dirt road	39.29′	41.21′
332	BMzG[b,k,Cu]	+2.9	Fry Mtns. Pluton, dirt road	37.97′	40.76′
333	MiarG[s]	+7.3	East Ord Mtn. Pluton, Daggett Rd.	40.43′	43.04′
334	BGrd[e,c]	+2.1	East Ord Mtn. Pluton, dirt road	39.76′	44.76′
335	BHGrd[e,c]	+5.4	East Ord Mtn. Pluton, dirt road	40.36′	45.25′
336	BHGrd[e,c]	+5.0	East Ord Mtn. Pluton, dirt road	39.95′	46.16′
337	GPorph[e,s]	+2.6	East Ord Mtn. Pluton, dirt road	38.92′	45.66′
338	BHGrd[e,b,mo]	+6.2	Ord Mtn. Pluton	40.21′	49.14′
340	BHGrd[e,c]	+4.4	Ord Mtn. Pluton	39.01′	48.72′
342	BHGrd[e,c]	+6.9	Fry Mtns. Pluton, dirt road	31.04′	43.94′
347	BHGrd	+7.4	Fry Mtns. Pluton, powerline rd.	34.62′	40.08′
348	BMzG[a]	+6.7	Fry Mtns. Pluton, powerline rd.	33.16′	40.23′
349	BHGrd	+8.9	Fry Mtns. Pluton, powerline rd.	33.46′	43.33′
350	G[e,c,s]	+2.8	Ord Mtn. Pluton, dirt road	38.52′	51.26′
351	BHGrd[e,c]	+2.1	Ord Mtn. Pluton, dirt road	39.65′	52.52′
352	BHGrd[e,c]	+5.9	Ord Mtn. Pluton, dirt road	40.56′	53.04′
353	BHGrd[e,c]	+5.4	Ord Mtn. Pluton, dirt road	41.07′	52.87′
354	BHGrd[e,c]	+0.4	Ord Mtn. Pluton, dirt road	41.47′	51.26′
355	BHGrd	+8.7	Ord Mtn. Pluton, W side of Ord Mtn.	41.12′	39.89′
356	BHGrd	+9.1	Ord Mtn. Pluton, Tyler Valley Rd.	42.58′	50.30′
357	BHGrd	+7.9	Ord Mtn. Pluton	43.62′	50.57′
359	BHGrd[e,c]	+7.7	Ord Mtn. Pluton	43.39′	47.58′
506	BHGrd[e,c]	+5.1	Fry Mtns. Pluton	34.89′	42.01′
507	BHGrd	+7.7	Rodman Mtns. Pluton	37.79′	38.51′
508	BHGrd	+9.4	Rodman Mtns. Pluton	37.69′	38.12′
509	BHGrd[e,c]	+1.5	Rodman Mtns. Pluton	38.06′	36.04′
510	BHGrd[e,c]	+5.0	Rodman Mtns. Pluton, dirt road	40.00′	35.71′

Table 1. (Continued)

Samp. no.	Rock type	$\delta^{18}O$*	Remarks	34°N latitude	116°W longitude
Jurassic-Age Plutons					
511	BMzG[e,c]	+2.3	Rodman Mtns. Pluton, dirt road	40.38′	36.43′
512	BMzG[e,c]	+6.3	Rodman Mtns. Pluton, dirt road	39.84′	37.53′
513	BHGrd[e,c]	+5.9	Rodman Mtns. Pluton, dirt road	39.57′	38.70′
514	BMzG	+7.7	Rodman Mtns. Pluton, near Camp Rock Mine	40.00′	40.00′
515	BMzG[e]	+7.0	Rodman Mtns. Pluton, near Camp Rock Mine	40.64′	40.29′
516	BMzG	+7.7	Rodman Mtns. Pluton	38.33′	39.28′
152	HT	+8.3	Bell Mtn. Pluton, road cut	33.24′	13.56′ †
Triassic-Age Plutons					
112	LSy	+9.0	Granite Mtns. Pluton, Rabbit Dry Lake	27.24′	59.59′
154	HMz	+6.5	Granite Mtns. Pluton, Hwy 18	29.31′	08.25′ †
155	HMz	+7.5	Granite Mtns. Pluton, Hwy 18	27.48′	04.03′ †
156	HMz	+8.0	Pitzer Butte Pluton	25.34′	57.94′
Cretaceous-Age Plutons					
111	BMzG	+9.7	Granite of Mojave River Wash, Hwy 18	32.34′	17.18′ †
153	BMzG	+7.4	Fairview Valley Pluton	33.55′	08.62′ †
157	BMzG	+8.2	Granite Mtns. Pluton	29.24′	01.11′ †
162	BMzG	+7.8	Stoddard Valley Pluton, Stoddard Wells Rd.	48.07′	03.33′ †
166	BMzG	+7.6	Ord Mtns. Pluton, powerline rd.	34.62′	50.06′
269	BMzG	+7.4	Eastern Lucerne Valley Pluton, powerline rd.	30.01′	49.48′
279	BMzG	+8.6	Fry Mtns. Pluton, powerline rd.	35.11′	37.02′
290	BMzG	+7.9	Ord Mtns. Pluton, Ord Valley Rd.	36.39′	48.33′
295	BMzG	+8.2	Ord Mtns. Pluton	37.85′	49.37′
326	BMzG	+7.3	Ord Mtns. Pluton	37.69′	47.25′

Abbreviations: BGrd = Biotite Granodiorite; BHGrd = Biotite-Hornblende Granodiorite; BMzG = Biotite Monzogranite; BHMzG = Biotite-Hornblende Monzogranite; GPorph = Granite Porphyry; MiarG = Miarolitic Granite; G = Granite; LSy = Leucocratic Syenite; HMz = Hornblende Monzonite; HT = Hornblende Tonalite.

Brackets indicate that the sample is hydrothermally altered, and contains the hydrothermal minerals e = epidote; c = chlorite; a = albite; s = sericite; mo = molybenite; b = biotite; k = k feldspar; ac = actinolite; Cu = copper minerals.

* The $\delta^{18}O$ analyses were obtained by conventional fluorination techniques (TAYLOR and EPSTEIN, 1962) and are reported relative to SMOW (Standard Mean Ocean Water). In our laboratories, NBS-28 has a $\delta^{18}O$ = +9.60 on this scale.

† 117° West Longitude.

low atmospheric temperatures (*e.g.*, Sierra Nevada region, Rocky Mountains).

The feldspar-H_2O $^{18}O/^{16}O$ fractionation data of O'NEIL and TAYLOR (1967) allow some simple comparative calculations to be made. Between 300 and 400°C, which are likely hydrothermal temperatures, the equilibrium fractionation factors between An30 plagioclase and water are estimated at +4.8 (300°C), +3.5 (350°C), and +2.55 (400°C). Even if we conservatively assume an infinite water/rock ratio, the observed $\delta^{18}O$ value of −3.2 in the most ^{18}O-depleted sample would *require* an initial $\delta^{18}O$ at least as low as −8.0 to −5.8 for the hydrothermal fluid. Also, assuming a temperature of about 350°C, a plausible closed-system material-balance water-rock ratio of about unity (see CRISS and TAYLOR, 1986) for the ovoid areas with $\delta^{18}O$ < +2, and using an initial $\delta^{18}O$ rock = +8, these data *require* that the initial $\delta^{18}O$ of the water must have been lower than −7.5. The actual $\delta^{18}O$ values of the surface waters in this region during Jurassic time therefore must be at least this low, and were probably as low as −10 or lower. However, studies of the Mesozoic sedimentary rocks near Fairview Valley suggest that the environment was coastal in nature during the Jurassic (BURCHFIEL and DAVIS, 1981; MILLER, 1978; MILLER and CARR, 1978), as does the map shown in Fig. 5 (BUSBY-SPERA, 1988). If true, the Jurassic edge of the continent must have been a rather high mountainous region somewhat similar to the present-day geographic environment, in order to produce meteoric waters having $\delta^{18}O$ values as low as −10. To give a more specific comparison, this area could not possibly have had a

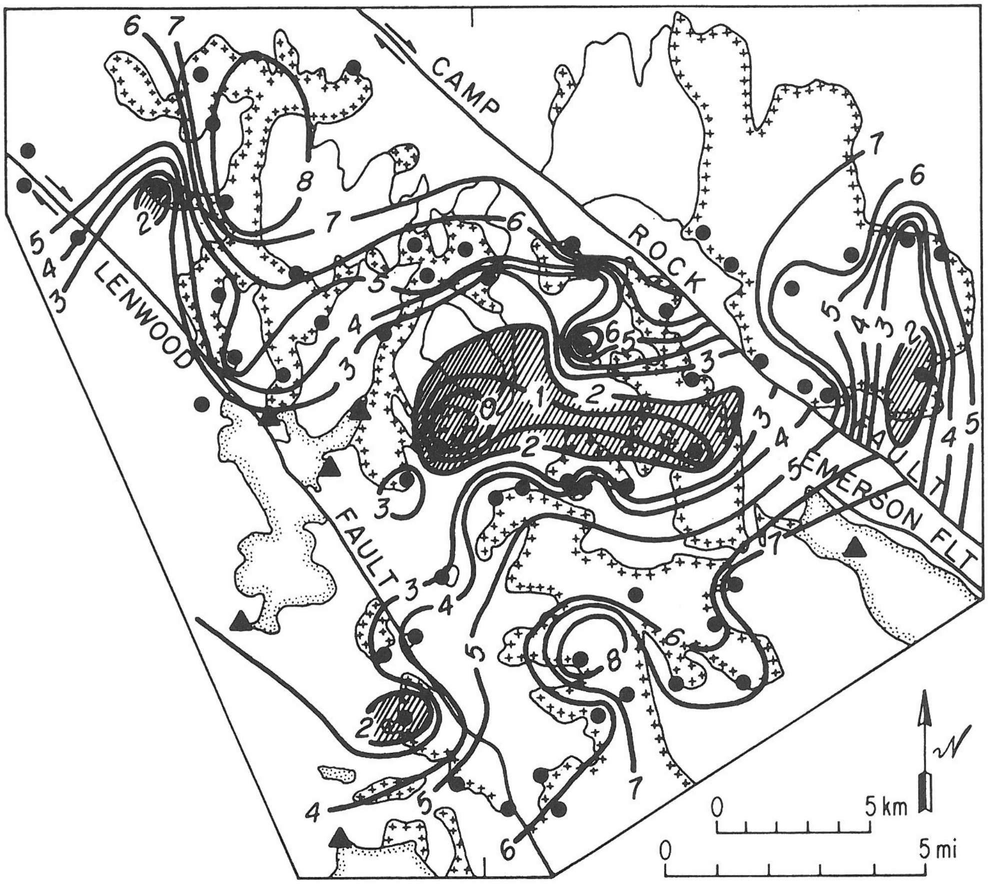

FIG. 3. Generalized geologic map of the northeastern portion of the ROM area (geology after DIBBLEE, 1964a,b), showing Jurassic whole-rock $\delta^{18}O$ contours based on $^{18}O/^{16}O$ data in Fig. 2. The Jurassic sample localities are shown with solid circles; late Cretaceous sample localities are shown with solid triangles. Symbolism for geologic map units is the same as in Fig. 2. The diagonal line pattern indicates areas where whole-rock $\delta^{18}O$ values are less than +2. Right-lateral offset of $\delta^{18}O$ contours (< +3) along the Camp Rock Fault is approximately four km (see discussion in text).

climate or a topography similar to that in the Gulf Coastal Region of the U.S.A. today. The fossil hydrothermal systems in this area clearly deserve more detailed study than was possible in this reconnaissance whole-rock investigation.

Late Cenozoic fault offsets

Late Cenozoic faults cut through and offset the plutons that were affected by the Jurassic hydrothermal circulation systems. DOKKA (1983) comments upon the disparate estimates for the magnitudes of offset along these faults (*e.g.*, GARFUNKEL, 1974; HAWKINS, 1975). In order to see if $\delta^{18}O$ contours could be of use in unraveling fault offsets, the area around East Ord Mountain and the Rodman Mountains was studied in somewhat more detail than the rest of the area. It is clear that the primary igneous $\delta^{18}O$ values in the late Cretaceous plutonic rocks do not have a large enough variation to be used for detailed local contouring. However, it was hoped that more closely spaced sampling of the Jurassic rocks would give sufficient contour resolution to detect any offsets of these fossil hydrothermal circulation centers along the Lenwood and Camp Rock faults.

Figure 3 is a map showing a more detailed set of $\delta^{18}O$ contours for the Jurassic plutons in the vicinity of these faults, which are known to exhibit right-lateral offsets (DOKKA, 1983). From the contours in Fig. 3 it is not possible to accurately determine offset along the Lenwood Fault, but it is probably very small (<5 km), as there is no obvious offset of the major trend of the regional low-^{18}O zone shown in Fig. 1. As one crosses over to the east side of the Lenwood Fault, this broad zone of low-^{18}O rocks (Fig. 1) narrows abruptly, but there are simply not enough outcrops of altered Jurassic plutons to establish detailed contouring. The low-^{18}O zone continues to narrow eastward, however, and on Fig. 3 it can be seen that the Camp Rock Fault truncates a much narrower, better defined, more prominent set of low-^{18}O contours. Surrounding East Ord Mountain, and extending with its long axis in an easterly direction, is an ovoid contour pattern defined by rocks with $\delta^{18}O < +3.0$. The low-^{18}O ovoid zone abruptly terminates on its eastern end, against the Camp Rock Fault, and these low-^{18}O rocks are juxtaposed against a Jurassic pluton whose $\delta^{18}O$ values are all higher than +7.7 (Figs. 2 and 3).

Contouring of $\delta^{18}O$ values in the Rodman Mountains to the east of the fault reveals another zone where $\delta^{18}O$ values are less than +3.0. If the $\delta^{18}O$ contours that define these two zones are extended to intersect the Camp Rock Fault (as shown in Fig. 3), then the magnitude of apparent right-lateral offset on the combined Emerson and Camp Rock faults is seen to be approximately 5 ± 2 km. Considering the errors involved, this compares well with the estimate of 1.6 to 4.0 km by DOKKA (1983) which is based upon offset of an early Miocene structural horizon, but it compares less well with the estimate of HAWKINS (1975). We note, however, that our minimum suggested displacement of about 3.0 km seems to be very tightly constrained by three closely spaced samples with $\delta^{18}O$ = +7.7 to +9.4 collected just northeast of the Camp Rock Fault. The $^{18}O/^{16}O$ data thus corroborate, at least on the Camp Rock Fault, Dokka's hypothesis that offsets along these strike-slip faults in the ROM area are relatively small, and therefore that no large Cenozoic displacements have occurred in this portion of the Mojave Block.

Pre-Cretaceous igneous rocks elsewhere in Southern California

Figure 4 shows contours of whole-rock $\delta^{18}O$ values and a few initial $^{87}Sr/^{86}Sr$ values for Triassic and Jurassic plutons studied elsewhere in southeastern California (termed the SECA area). Most of these plutons have emplacement ages older than 160 Ma. The $\delta^{18}O$ contours on Fig. 4 are compiled from the more detailed $\delta^{18}O$ maps shown in SOLOMON (1989), but they are mainly based on the data shown in Table 2. This map for the early Mesozoic plutons (Fig. 4) does not have anywhere near the resolution of the $^{18}O/^{16}O$ maps we have made for the Cretaceous plutons (SOLOMON and TAYLOR, 1989; SOLOMON, 1989), both because the extent of outcrop is less for the older plutons, and also because there is less areal geochemical coverage for the older plutons. In addition, many of these older rocks exhibit "disturbed" $\delta^{18}O$ values (and $^{87}Sr/^{86}Sr$ ratios?) as a result of hydrothermal alteration. Nonetheless, several observations may be made regarding the older set of plutons.

In the northwestern part of the SECA area, the plutons have presumably "primary" $\delta^{18}O$ values > +8.0, with some indication of a slight decrease to the west to values lower than +7.0. There is a very clear indication of a broad decrease to characteristic regional values of about +6.5 to +7.5 in the eastern Mojave Desert. FOX (1988) analyzed K feldspars from the Jurassic plutons in the Bristol Mountains (BM-HC on Fig. 4) and found that primary $\delta^{18}O$ values were between +6.5 and +7.4; this indicates that primary whole-rock $\delta^{18}O$ for these rocks is likely to be near +7.8, after one takes into account the fact that $\delta^{18}O$ quartz will add about +0.4 per mil to the whole-rock mixture. The $\delta^{18}O$ contours have a northwesterly strike that roughly parallels the regional strike exhibited by the Jurassic magmatic arc as a whole. However, as was shown above, in the large Rodman-Ord Mountains (ROM) hydrothermal center the primary $\delta^{18}O$ patterns are almost totally obliterated. This is also true to a lesser extent in the other areas of hydrothermal alteration shown by the hatchured patterns on Fig. 4.

When we view the $^{18}O/^{16}O$ ratios in Jurassic hydrothermal centers on a regional basis within a zone extending from western Nevada southeast to southern Arizona and Sonora, some remarkable patterns emerge. The Jurassic hydrothermal centers in SECA make up the central portion of the northwest-trending, 1000 km-long graben depression proposed by BUSBY-SPERA (1988) for the early Mesozoic continental arc (Fig. 5). Whole-rock $\delta^{18}O$ values are available, at least in reconnaissance fashion, for several of the major Jurassic hydrothermal centers along the strike of this proposed graben (Fig. 4; Table 2). These centers are from northwest to southeast: (1) the Yerington District, western Nevada (YN; +5.7 to +7.8; 0.7039 to 0.7045; DILLES *et al.*, 1991; SOLOMON *et al.*, 1983); (2) the Rodman-Ord Mountains (ROM; −3.2 to +9.0; this work); (3) Devil's Playground (DP; +4.2; this work); (4) Bristol Mountains (BM; ~ +1.7 to ~ +7.8; FOX, 1988); (5) Copper Mountain and Dale Mining District (CM and DMD; +5.7 to +7.1; this work); (6) Palen Mountains (PM; +2.6; this work); (7) Big Maria Mountains (BMM; +6.7; this work); and (8) Brownell and Comobabi Mountains, south-central

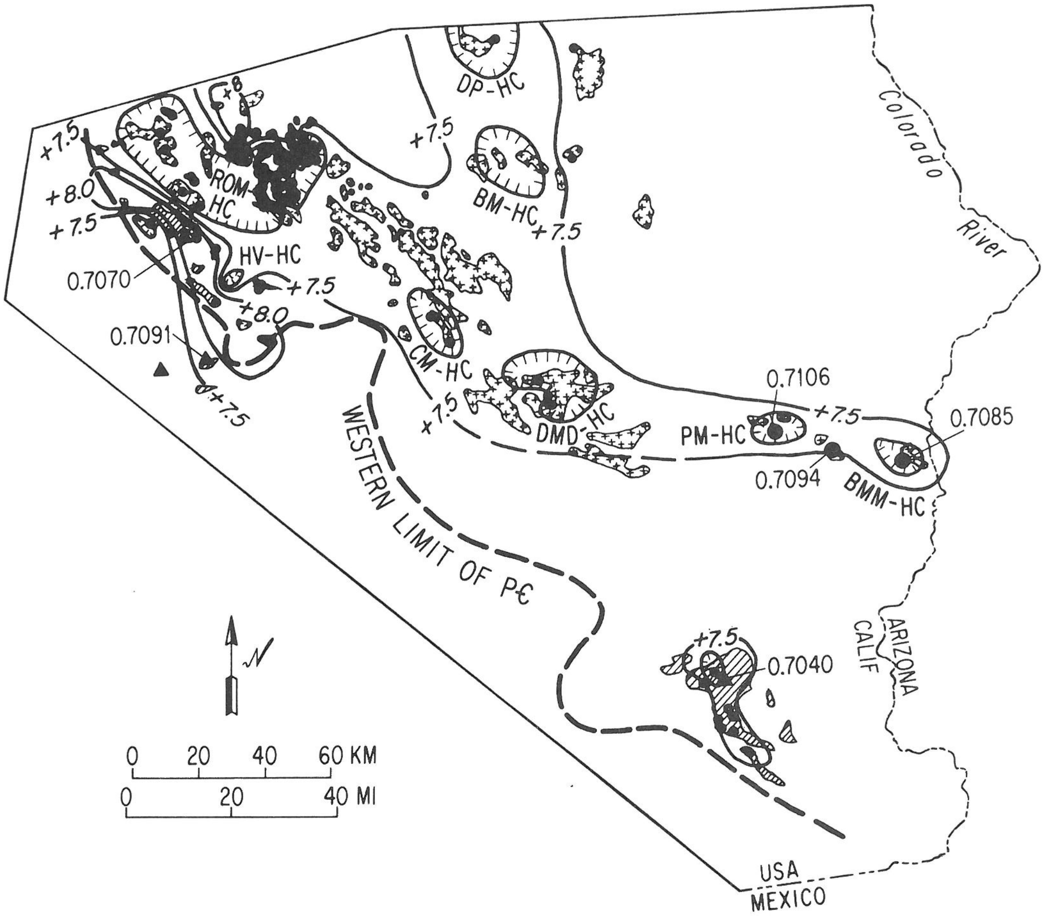

FIG. 4. Reconstructed geologic map of southeastern California (SECA), showing Jurassic and Triassic plutons and the locations of Jurassic hydrothermal centers defined by whole-rock $\delta^{18}O$ contours (based on data given in Table 2, and in Figs. 1 and 2). The hatchured contours enclose samples with $\delta^{18}O < +7$. Also shown are the sample localities where initial $^{87}Sr/^{86}Sr$ data are available (from sources reported in SOLOMON, 1989). Restoration of strike-slip displacements along late Cenozoic faults is discussed in SOLOMON (1989). Jurassic plutons have crosses along the inside margins of map unit, and Triassic plutons are indicated by diagonal lines inside map unit. Heavy dashed line indicates the western limit of mapped Precambrian crystalline basement rocks. The San Gabriel Mountains (SGM) terrane has been restored to its position prior to late-Cenozoic displacement along the San Andreas Fault using the reconstruction of POWELL (1982). Jurassic hydrothermal centers (HC) are: (1) ROM—Rodman-Ord Mountains; (2) DP—Devil's Playground; (3) BM—Bristol Mountains; (4) HV—Holcomb Valley; (5) CM—Copper Mountain; (6) DMD—Dale Mining District; (7) PM—Palen Mountains; (8) BMM—Big Maria Mountains.

Arizona (BM and CM; +6.7 to +9.2; SOLOMON, 1989).

BUSBY-SPERA (1988) proposes that this major graben structure was occupied by calderas, which in places were flooded by lakes or marine embayments, as evidenced by thick sequences of ignimbrites intercalated with fluvial, lake, or marine sedimentary deposits. Our $^{18}O/^{16}O$ data coincide nicely with Busby-Spera's boundary separating marine-type sedimentary sequences on the northwest from predominantly continental-type strata on the southeast (see Fig. 5). The centers to the southeast, or continental side of the boundary, such as ROM, contain Jurassic plutons that were clearly hydrothermally altered by heated, low-$\delta^{18}O$ meteoric waters. In the case of the ROM area, these waters must have initially had $\delta^{18}O$ values as low as -10, indicating a relatively high, cool, mountainous terrane capable of fractionating coastal precipitation sufficiently to produce low-^{18}O rain and snow (*e.g.*, see

Table 2. Locations and oxygen isotope analyses of probable Jurassic-age samples from elsewhere in Southern California.

Samp. no.	Rock type	$\delta^{18}O$	Remarks	Latitude	Longitude
San Bernardino Mountains					
51	BHGrd	+7.7	Cushenberry Grade Pluton, Hwy 18	34°19.93′	116°49.68′
52	BHGrd	+7.8	Cushenberry Grade Pluton, Hwy 18	34°20.05	116°49.82′
106	BGrd	+7.8	Johnson Valley Pluton, Johnson Valley Rd.	34°20.24′	116°30.12′
107	BGrd	+7.9	SE part of Big Horn Mtns.	34°16.38′	116°29.92′
127	M (Triassic?)	+8.4	Mill Creek Pluton, Mill Creek	34°05.31′	116°56.58′
130	BHGrd	+8.4	Cienaga Seca Pluton, Hwy 38	34°10.24′	116°47.06′
Little San Bernardino Mountains					
98	BGrd	+6.7	Older Granite, Joshua Tree Monument	33°59.89′	116°03.70′
194	BMzG	+7.2	Older Granite, Joshua Tree Monument	34°06.83′	116°03.29′
198	BMzG	+6.1	Older Granite, Joshua Tree Monument	34°04.07′	116°00.62′
199	HBGd[e,c]	+6.5	Copper Mtn. Pluton	34°13.03′	116°15.00′
201	HBGrd[e,c]	+6.4	Copper Mtn. Pluton	34°08.76′	116°11.13′
202	HBGrd[e,c]	+7.1	Dale Mining District H. C.	34°04.07′	115°45.25′
205	HBGrd[e,c]	+5.7	Dale Mining District H. C.	34°01.83′	115°44.59′
206	HBGrd[e,c]	+7.1	Dale Mining District H. C.	34°00.07′	115°42.20′
Southeastern Mojave Region					
391	BHMd	+6.7	Big Maria Mtns. H.C. H808M372b K. Howard	34°48.95′	114°52.07′
394	BHGrd	+7.5	Little Maria Pluton H80LM374 K. Howard	33°51.03′	114°52.07′
402	BMzG[e,c]	+4.2	Palen Mtns. H.C. H80Pa189 K. Howard	33°55.17′	115°02.25′
409	BHGrd	+7.6	Providence Mtns. KH78-1 K. Howard	34°55.65′	115°36.13′
395	BMzG	+7.6	Marble Mtns. Pluton H80MM232 K. Howard	34°58.90′	115°36.88′
403	BMzG[e,c]	+4.2	Devil's Playground H.C. Providence Mtns. H80DP220 K. Howard	34°58.57′	115°51.17′

Abbreviations: Same as in Table 1, except M = Monzonite; BHMd = Biotite Hornblende Monzodiorite; H. C. = Hydrothermal Center.

TAYLOR, 1974). Farther southeast, in Arizona, there is no indication of such strongly ^{18}O-depleted meteoric waters, but $^{18}O/^{16}O$ studies in that region are very sparse, and more work is required.

The only center for which we have $^{18}O/^{16}O$ data northwest of Busby-Spera's proposed marine/continental boundary is at Yerington, Nevada, where $\delta^{18}O$ values are relatively high (+5.7 to +7.8). One point worth mentioning is that granitic rocks at the Yerington center with $\delta^{18}O = +5.7$ are as intensely hydrothermally altered mineralogically as those with $\delta^{18}O$ between −3.2 and +2.0 at the ROM center. Both areas contain granodiorites and quartz monzonites with intense propylitic epidote-chlorite veining, and albitic replacement of K-feldspars. In some cases, hand specimens from both areas look identical to one another, but, as indicated by whole-rock $\delta^{18}O$ values, the type of water involved in the alteration is clearly different between the two areas. At Yerington, DILLES *et al.* (1991) and SOLOMON *et al.* (1983) demonstrated that waters with initial $\delta^{18}O$ of around 0.0 were responsible for propylitic alteration, as compared with much lighter water (−10 per mil) in the ROM area. Thus, the waters at Yerington were either sea water or some type of connate or formation water; either of these types of waters would fit nicely with the inferences made by BUSBY-SPERA (1988) about the distribution of marine and terrestrial environments surrounding the graben depression shown on Fig. 5.

Another interesting point to make is that the initial $^{87}Sr/^{86}Sr$ values also show the transition from a marine, island arc–type environment on the northwest to a continentally rooted arc to the southeast. Where the arc sat in an oceanic environment, initial $^{87}Sr/^{86}Sr$ values were ~0.7040 (as at Yerington); and along the strike of the arc, to the southeast, much higher ratios are encountered (0.7085 to 0.7106 in SECA; and 0.7070 in southern Arizona; see Fig. 4). This type of effect is very reminiscent of the East Japan–Marianas arc discussed by TAYLOR (1986), where ITO and STERN (1985) showed that $\delta^{18}O$ and initial $^{87}Sr/^{86}Sr$ were elevated at the point where the northern portion of that arc cuts

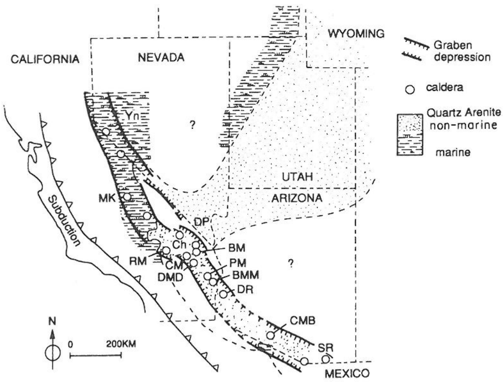

FIG. 5. Map of the southwestern United States showing Jurassic tectonic features, modified after a figure by BUSBY-SPERA (1988). The 1000 km graben depression is indicated by lines with perpendicular hash marks along the inside margins of the graben. The depositional environment for quartz arenitic sandstones associated with Jurassic volcanic centers is mapped by dashed lines, and differentiated according to either marine (horizontal lines within map unit) or non-marine deposition (stippled pattern within map unit). Jurassic hydrothermal centers are indicated by open circles and annotated with the following abbreviations: (1) Yn—Yerington District, NV; (2) MK—Mineral King, CA; (3) RM—Rodman Mountains, CA; (4) Ch—Cowhole Mountains, CA; (5) CM—Copper Mountain, CA; (6) DMD—Dale Mining District, CA; (7) DP—Devil's Playground, CA; (8) BM—Bristol Mountains, CA; (9) PM—Palen Mountains, CA; (10) BMM—Big Maria Mountains, CA; (11) DR—Dome Rock Mountains, AZ; (12) CMB—Comobabi Mountains, AZ; (13) CR—Cobre Ridge, AZ; and (14) SR—Santa Rita Mountains, AZ. Line with thrust-fault symbols indicates approximate location of the axis of a Jurassic subduction zone.

across continental terrane. Clearly, further $^{18}O/^{16}O$ and $^{87}Sr/^{86}Sr$ studies of unsampled portions of the Jurassic plutonic centers within Busby-Spera's regional graben would help refine and elaborate upon our initial reconnaissance observations and better map out these kinds of paleogeographic boundaries.

CONCLUSIONS

In striking contrast to the other Mesozoic plutonic episodes (Triassic and Cretaceous), the Jurassic plutons in Southern California commonly developed extensive meteoric-hydrothermal convection systems which produced characteristic low-^{18}O patterns in the altered intrusive rocks. This is particularly well shown in the Rodman-Ord Mountains area. This requires that the Jurassic plutonic event must have been epizonal and probably associated with extensional tectonics in order to provide the open fractures and necessary hydrologic permeability required. The $^{18}O/^{16}O$ data fit in well with the rift-zone, caldera-emplacement model proposed by BUSBY-SPERA (1988).

We suggest that $^{18}O/^{16}O$ analyses may be a good way to search for such fossil rift zones in areas where the geological relationships are complex. An analogous example of this is given in the paper by TAYLOR *et al.* (1991) in this volume. It would be interesting to carry out $^{18}O/^{16}O$ analyses of the Independence Dike Swarm to see if this can be shown to be an extension of the Rodman-Ord Mountains hydrothermal activity.

We have also shown that the regional $\delta^{18}O$ patterns produced during Jurassic hydrothermal activity have been offset and truncated by the later-stage, deeper-seated Cretaceous plutons. In addition, in more recent geological times, late Cenozoic faulting has also offset these Jurassic-age $^{18}O/^{16}O$ patterns, and we have been able to use our $^{18}O/^{16}O$ data to measure these offsets, confirming the conclusions of DOKKA (1983) that the displacements along these faults in the Mojave Block are all relatively small (<5 km).

Acknowledgements—We wish to take this opportunity to salute Samuel Epstein as he continues to build upon and expand his life-long contributions to the field of stable isotope geochemistry. He has taught us both a great deal over the years. We also wish to thank Keith A. Howard, Leon T. Silver, Robert E. Powell, John H. Dilles, and Robert E. Criss for helpful discussions and for their aid in obtaining some of the samples studied in this work. Financial support for this research was provided by the National Science Foundation, Grants No. EAR-83-13106, EAR-88-16413, and EAR-90-19190.

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