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Whole-rock $\delta^{18}O$ values have been determined for 155 samples from approximately 140 plutons in the northern 600 km of the Peninsular Ranges batholith (fig. 1). Analyses of tonalites, granodiorites, gabbros and a few quartz monzoni tes are represented in crude proportion to the abundance of these rocks in the batholith. Most samples have been studied also for U-Pb zircon geochronology (Banks and Silver, 1968; Silver and others, 1968); K-Rb-Sr isotope and trace element systematics (Early and Silver, 1973); and rare earth element distributions (Gromet and Silver, 1977). All of these parameters display striking geographic regularities and profound transverse asymmetries related to the NNW-trending plutonic arc (Silver and others, 1975; Silver and Early, 1977).

The major conclusions of this study are as follows:

1. The $\delta^{18}O$ values of the various plutons change systematically from west to east across the batholith, and these differences persist along the length of the batholith for at least 600 km (fig. 1). Except for the gabbros, the $\delta^{18}O$ variations are purely geographic and essentially independent of rock type; the primary $\delta^{18}O$ values of the tonalites and granodiorites systematically increase from about 6.0 to 7.0 in the west to values as high as 12.8 in the east.

2. These $^{18}O/^{16}O$ relationships are virtually identical with the systematic west-to-east $^{87}Sr/^{86}Sr$ variations found in the batholith by Early and Silver (1973); both effects must be a result of the same basic process, as evidenced by the correlation in fig. 2.

3. The $^{18}O/^{16}O$ data show one feature not visible in the $^{87}Sr/^{86}Sr$ results, namely a $\delta^{18}O$ step separating the western and eastern

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portions of the batholith. This δ18O step is shown in figure 1 by the close spacing of the δ18O = 8.5 and 9.0 contours, and it is apparent as a "gap" on figure 2. This remarkably straight 18O discontinuity extends the entire length of the batholith.

4. The 18O boundary approximately coincides with a major geologic boundary which divides the batholith into an epizonal to mesozonal western half characterized by abundant gabbro, inclusion-rich tonalites, and high SiO2 granodiorites (for example, Woodson Mtn. type, > 70 weight-percent SiO2), and a more deep-seated eastern half dominated by sphene-rich tonalites and low-K granodiorites (Larsen, 1948; Gastil, 1975). The discontinuity is also an age boundary, as U-Pb zircon ages range from 105 to 130 m.y. in the west, whereas in the east they range from 80 to 103 m.y. (Silver and others, 1975). Gabbros are sparse and in small masses in the eastern half, which is the locus of the most abundant and largest tonalitic plutons. Because of greater depths of erosion and a thicker crust, the original volume of batholithic rocks in the high-δ18O eastern zone must have far exceeded the volume of lower δ18O rocks in the western zone.

5. The gabbros also show a progressive enrichment in 18O from west-to-east, but to a lesser degree than the quartz-rich rocks, ranging from values as low as 5.3 in the west to values as high as 8.3 in the east. The gabbros also fit the 18O/16O, 87Sr/86Sr correlation pattern, but all of the gabbros plot in the field of the western granitic rocks on Figure 2.

6. Except along a strip at the extreme western edge of the batholith, the δ18O quartz-feldspar fractionations in the granitic rocks all have "normal" values of 1.1 to 2.3, indicating little or no postcrystallization alteration. However, the epizonal, commonly granophyric plutons found along the entire western edge of the batholith suggest that this zone was close to the roof of the batholith in the Early Cretaceous. All along this zone we find exceedingly heterogeneous whole-rock δ18O values and abnormal δ18O quartz-feldspar values. This is clearly the result of strong interactions with convectively circulating hydrothermal fluids in the roof zone of the batholith. However, at least two kinds of H2O are indicated, a low-18O meteoric ground water in the north and a high-18O (marine?) pore fluid in the...
south. In the strip extending from Ensenada north to Riverside, the whole-rock $\delta^{18}O$ values vary by more than 10 permil, from $\delta^{18}O = -5.0$ to $\delta^{18}O = 6.5$, and the more susceptible feldspar has typically been depleted in $^{18}O$ to a much greater degree than the coexisting quartz. Heterogeneous $^{18}O$ variations are also characteristic of the altered country rocks around these plutons. South of Ensenada the alteration produced $^{18}O$ enrichment in the feldspars, and no evidence was found for the above type of low-$^{18}O$ meteoric hydrothermal alteration. Previous studies (Silver and others, 1963; 1975) have suggested that the batholith is the deeper extension of a volcanic arc which extended from a continental margin in southern California into an oceanic island arc in Baja California. The contrasting nature of the $\delta^{18}O$ values in the two types of hydrothermal fluids is compatible with such a transition. The heterogeneous isotopic effects described above do not, however, extend any appreciable distance eastward into the main part of the batholith, indicating that the major $^{18}O$ variations in the batholith are primary characteristics of the original magmas. This is in sharp contrast to the pronounced meteoric-hydrothermal $^{18}O/^{16}O$ and D/H effects observed within the interiors of the more northerly Cordilleran batholiths in Idaho and British Columbia (for example, see Taylor, 1978). This difference can be ascribed to the less complicated intrusive and tectonic history of the Peninsular Ranges batholith, which formed totally in the Cretaceous, whereas the northerly batholiths exhibit a complex multi-episode history extending from the Triassic well into the Tertiary. The slight upturn in the initial $^{87}Sr/^{86}Sr$ ratio found by Early and Silver (1973) along the western edge of the Peninsular Ranges batholith conceivably might reflect such peripheral hydrothermal alteration effects (see fig. 2).

7. As far as primary $\delta^{18}O$ variations are concerned, the only geographic unit of the batholith that clearly deviates from the regional east-west patterns is the San Jacinto-Santa Rosa Mtns. block that lies just northeast of the San Jacinto fault. The tonalite and granodiorite samples in this part of the batholith form a separate population on figure 2, indicating derivation from a distinctive source rock at depth, presumably from a parent material that was slightly lower in $^{18}O$ and higher in $^{87}Sr/^{86}Sr$ than that which dominated most of the eastern half of the batholith. This "reversal" in $\delta^{18}O$ to the northeast might be attributed to involvement of the extreme southwest edge of crystalline basement of the North American craton in the fusion process that produced these magmas. Such an older, high-rank metamorphic complex might be expected to contain more radiogenic strontium and to exhibit $\delta^{18}O$ values of about $+10$ or lower. There is some other evidence that supports this concept, namely slightly higher K-feldspar contents in the granodiorites and the occasional appearance of traces of inherited zircons in a few plutons (L. T. Silver, unpublished data).

8. The simplest explanation of the patterns shown in figures 1 and 2 is that the source materials of the Peninsular Ranges batholith were dominated by two end-members, one with $\delta^{18}O \approx +6.0$ and $^{87}Sr/^{86}Sr \approx .703$, and the other with $\delta^{18}O \approx 13.0$, or higher, and $^{87}Sr/^{86}Sr \approx 0.708$, or higher. Evidence for a less important, third end-member, is present in the rocks northeast of the San Jacinto fault. The low-$^{18}O$, low $^{87}Sr$ end-member that dominates the western part of the batholith appears to be derived from melting of the upper mantle, although it is also possible that this may have involved a two-stage process in which oceanic lithosphere was re-melted in the orogenic environment, perhaps as a consequence of the subduction process. The uniformly low $^{87}Sr/^{86}Sr$ and $\delta^{18}O$ values of all the western plutonic rocks, from gabbro to high-$SiO_2$ granodiorite, clearly imply that the parent magmas of all these rocks were derived from fundamentally the same source material. An important corollary of this statement is that less than a one permil change in $\delta^{18}O$ takes place during "differentiation" of hydrous plutonic granitic magmas in the batholithic environment. This has never before been so clearly demonstrated (for example, see Taylor, 1978).

9. The nature of the high-$^{18}O$, high $^{87}Sr$ end-member(s) is much more problematical. The important contribution of the $^{18}O/^{16}O$ data to this problem is that a large reservoir of rock with such high $\delta^{18}O$ values has been identified only in materials which once resided on or very near the earth's surface (that is, either sedimentary rocks or possibly volcanic rocks that have been intensively altered at very low temperatures). In terms of the $^{18}O$ results alone, the most likely end-member would be a thick section of sedimentary or metasedimentary rocks, as this is the only sufficiently abundant type of rock on Earth with the requisite high $\delta^{18}O$ values. Several samples of the batholithic country rocks were analyzed. Except for one sample of volcanoclastic sediment with $\delta^{18}O = 7.9$, the $\delta^{18}O$ values range from $+10.9$ to $+20.2$, the highest values being recorded in the northwest part of the batholith in the Bedford Canyon and French Valley Formations. Thus, the low-$^{18}O$ plutons in the western belt are surrounded by extremely high-$^{18}O$ metasedimentary rocks, indicating that $^{18}O$ exchange with the adjacent country rocks is not a significant factor in determining the $\delta^{18}O$ values of the plutons. Furthermore, mechanisms involving partial melting of such country rocks do not satisfy some major chemical constraints because these rocks are much too aluminous and potassic to provide the characteristic calcic to calalkaline plutons of the batholith. A possibly more favorable rock type might be a Franciscan-type graywacke, which has extremely
uniform δ18O values of +11 to +14 (Magaritz and Taylor, 1976). However, in order for this type of sedimentary section to satisfy the chemical constraints on magma genesis it would have to contain appreciable amounts of intermixed basaltic greenstones and (or) limestones, and there would have to be remarkably complete chemical homogenization during the melting process. Because of the complexities involved, without further sampling and more chemical data, we cannot at this time more specifically identify the high 18O end-member.

In summary, during the Early Cretaceous the western part of the batholith was generated dominantly from a primitive source material apparently derived from the upper mantle. Eastward migration of the axis of magmatism involved increasing access to heavy 18O reservoirs, probably involving assimilation from or exchange with a thick pile of metasedimentary rocks, or with the extensively altered upper portions of an ancient oceanic lithospheric slab. The principal source of heat energy to drive this gigantic mixing process was probably contributed by mantle-derived magmas analogous to the western series of plutons, because the isotopic contribution of the low-18O end-member is observed throughout the eastern side of the batholith (fig. 2).


