NATURE AND ORIGIN OF THE ROOT OF THE SIERRA NEVADA

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ABSTRACT. The Sierra Nevada is underlain by a thick crustal root that coincides in plan view with the Sierra Nevada batholith, with an elongate region of uplift, with abnormally low heat flow, and with depressed upper-mantle P-wave velocities. Data from field relations, xenoliths carried to the surface in Cenozoic volcanics, tectonic considerations, and geophysical measurements provide a basis for interpreting the nature and origin of the root. The exposed granitoid and associated low-grade metamorphic rocks and an underlying lens of meta-igneous hornblende-rich rocks, which thins toward the margins of the batholith, compose the upper half of the crust. A series of mafic-ultramafic rocks that intrude granulite-grade feldspathic metamorphic rocks at higher levels and more mafic granulite at deeper levels compose the lower half of the crust. A down-dragged slab of oceanic crust, recrystallized at high pressure to eclogite, underlies the deepest part of the root, and, in turn, is underlain by olivine-rich ultramafic rocks at greater mantle depths.

We believe that the crustal root originated chiefly in the Mesozoic, contemporaneous with generation and emplacement of granitoid plutons, but that minor additions occurred during the Cenozoic coincident with volcanism. We attribute the Late Cenozoic uplift of the Sierra Nevada to conversion of upper mantle lithosphere to lower density asthenosphere (thermal isostasy) concurrently with extension across the Basin and Range Province to the east. The down-dragged slab of oceanic crust shields the batholith and subjacent lower crust from upward flow of heat and explains the low heat flow within the batholith.

INTRODUCTION

Interest in the deep structure beneath the Sierra Nevada was first aroused in 1936 when A. C. Lawson published a paper in which he used average crustal and upper-mantle densities and isostatic principles to estimate a crustal thickness of about 88 km in the vicinity of Mount Whitney (Lawson, 1936). In a comment on this paper, Byerly (1938) confirmed the existence of a crustal root from delay in the arrival times at stations east of the range of earthquake waves that originated west and northwest of the range. Since these pioneering studies of Lawson and Byerly, many other studies have been made that provide information that bears on the shape, composition, and age of the root. As used here, the root refers to the downward projection of crust with P-wave velocities of less than 7 km/sec into upper mantle with velocities greater than 7.5 km/sec. The root coincides in plan view with the Mesozoic Sierra Nevada batholith, with a strongly elongate region of major Cenozoic uplift, with low upper-mantle P-wave velocities of 7.9 km/sec, and with the lowest heat flow in the western United States (fig. 1).
Fig. 1. Generalized geologic map of the Sierra Nevada showing locations of seismic refraction sections A-A', B-B', and C-C' used in the construction of figure 2; topographic cross section D-D'; xenolith localities; and gravity anomaly and heat-flow boundaries.
Interpretations have been based on a variety of data including (1) seismic refraction (Eaton 1963, 1966; Bateman and Eaton, 1967; Carder, Qamar, and McEvilly, 1970; Carder, 1973; Crough and Thompson, 1977; Pakiser and Brune, 1980; Mavko and Thompson, 1983), (2) gravity (Oliver, Pakiser, and Kane, 1961; Oliver and Mabey, 1963; Oliver, 1977, (3) tectonic considerations (Christensen, 1966; Hay, 1976), and (4) petrologic studies of xenoliths from Tertiary volcanic necks and flows (Domenick and others, 1983; Dodge, 1986: Dodge, Calk, and Kistler, 1986). Two interpretations have received substantial support: (1) The root formed during the Mesozoic when the batholith was emplaced and is essentially the downward continuation of the batholith: and (2) it began to form in the Late Cenozoic and is continuing to form as the Sierra Nevada is tilted westward and uplifted as the result of tectonic and (or) magmatic processes. We briefly summarize the information now available, present new data bearing on the composition of the root, consider the merits of previous interpretations, and present our interpretation. Rapidly accumulating geophysical data and continuing study of xenoliths brought to the surface in Cenozoic volcanics can be expected to result in at least some revision of our interpretation.

SHAPE AND ORIENTATION

Seismic and gravity studies provide the principal evidence for the shape and orientation of the root. The fence diagram (fig. 2) is constructed from seismic refraction sections published by Eaton (1963, 1966) and Bateman and Eaton (1967). It is diagrammatic, and details may be incorrect, but it is the best approximation available of the gross seismic structure beneath the Sierra Nevada. The principal control is longitudinal section A-A', which closely follows the Sierran crest and parallels the gross structure (Eaton, 1966). This section is based on reversed measurements along the profile of refracted waves originating in chemical explosions at Shasta Lake, just north of the area shown in figure 1, at Mono Lake, near the center of the section, and at China Lake, at its south end. Transverse sections B-B' and C-C' were constructed with reference to this section from additional seismic measurements, including two transverse refraction profiles, one of which coincides with section B-B'.

The diagram shows the Moho is depressed beneath the high eastern Sierra Nevada to a depth of a little less than 50 km at the latitude of Lake Tahoe and to a little more than 50 km at the latitude of Bishop, and that the width of the root at a depth of 45 km ranges between 70 and 75 km. The dashed lines on the map (fig. 1) connecting depths of 45 km on sections B-B' and C-C' show that in the northern half of the Sierra Nevada the root trends about N 30° W and that the axis closely follows the eastern escarpment of the Sierra Nevada. In this construction, the western half of the root below 45 km underlies the eastern part of the
Fig. 2 Fence diagram showing the seismic structure beneath the Sierra Nevada. Constructed from seismic refraction profiles published by Eaton (1966) and Bateman and Eaton (1967). Location shown in figure 1. 2X vertical exaggeration.
Sierra Nevada, but the eastern half underlies Owens Valley and other
down-faulted blocks east of the Sierra Nevada.

Carder (1973) and Carder, Qamar, and McEvilly (1970) have
questioned this configuration of the root. They interpreted two trans-
verse seismic refraction profiles with shot points east of the Sierra
Nevada to indicate that the root lies east of the Sierra Nevada and that
the depth to the Moho beneath the Sierra Nevada is less than 30 km.
However, Pakiser and Brune (1980) published additional seismic refra-
tion and reflection data that confirm Eaton's interpretation of the depth
and general position of the root. Their reinterpretation of the data of
Carder (1973) and Carder, Qamat, and McEvilly (1970) shows the root
to be more strongly asymmetric than was indicated by Eaton's data and
the eastern flank to rise steeply immediately east of the Sierra Nevada.
This modification is shown in profile C-C' of figure 2 and probably also
applies to section B-B'. A suggestion by Oliver (1977), based on study of
gravity data, that the deepest part of the root lies 30 km farther west
than is shown on profile C-C' is also possible.

The eastern edge of a zone of steeply eastward-decreasing contours
on Bouguer gravity anomalies (Oliver, 1977) runs the length of the
Sierra Nevada (fig. 1) and between the two seismic refraction profiles
coincides with the western boundary of the seismic root at 45 km depth.
The break in slope of gravity contours continues southward about half
way between the eastern and western sides of the Sierra Nevada, and we
assume that it defines the western side of the root in the southern Sierra
Nevada (fig. 1). The Sierran root is depressed about 25 km, on the
average, below the Moho in the flanking areas. Both east and west of the
spans of seismic refraction sections B-B' and C-C' shown on figure 1, the
Moho flattens and is remarkably flat across the Basin and Range
Province (Eaton, 1963; Klemperer and others, 1986).

HEAT FLOW

Heat flow in the Sierra Nevada is extremely low but increases
eastward from less than 0.5 HFU (μcal/cm² sec) in the western foothills
to a little less than 1.5 HFU just west of the crest of the range (Roy,
Blackwell, and Decker, 1972; Henyey and Lee, 1976; Lachenbruch,
1968). An abrupt increase occurs along a line that closely follows the
eastern escarpment, and heat-flow values are high and variable (2 to 7+
HFU) farther east across the Basin and Range Province where extension
prevails (fig. 1). Plots of heat flow against heat generation in the granitic
rocks of the batholith indicate about 0.4 HFU at zero heat generation.
This amount of heat is interpreted to represent the mantle contribution
within the Sierra Nevada; higher amounts are postulated to represent
the amount produced in the crust as the result of radioactive decay. The
low mantle contribution has been attributed by Henyey and Lee (1976)
to the presence of a subducted slab of oceanic crust at depth, which has
acted as a heat sink. High and variable heat flow in the Basin and Range
Province is considered to be correlative with tectonic extension accom-
panied by uplift. Upwelling warmer material replaces material that moves laterally in the extending layer and thus preserves isostatic equilibrium. Thus the boundary between crust and mantle (the Moho) in the Basin and Range Province is young and continues to be modified.

**COMPOSITION**

Xenoliths in Late Cenozoic flows and feeders provide direct evidence for the composition of the root. Although not common, xenoliths have been discovered in recent years at several principal and associated minor localities in the central Sierra Nevada. These include the Jackson Butte and nearby Golden Gate Hills dacite domes on the west side; the Oak Creek and associated Waucoba basalt flows on the east side; and the Blue Knob alkali-basalt plug, the Chinese Peak trachyandesite flow, and the Big Creek andesite neck in the interior (fig. 1). The xenoliths recovered at these localities include peridotites, both olivine-bearing and olivine-free pyroxenites, eclogites, several varieties of quartz-free metamorphic rocks, and partially fused gabbroids and granitoids.

The Jackson Butte and nearby Golden Gate Hill dacite domes (Rose, 1959) on the west side and the Oak Creek and associated Waucoba basalt flows (Wilshire, Schwarzman and Trask, 1971) on the east side contain abundant fragments of near-surface country rocks, but they also contain magnesian peridotites (generally hornblende- or spinel-bearing lherzolites). The magnesian peridotites (Cr-diopside ultramafic group of Wilshire and Shirvais, 1975, or Group I of Frey and Prinz, 1978) are representative of the mantle materials under the margins of the batholith where the crust is thin.

Each of the localities in the core of the batholith has yielded a unique assemblage of xenoliths from the lower crust and mantle. The Blue Knob alkali-basalt plug contains peridotite, pyroxenite, and sparse feldspathic granulite (Dodge, 1987: Wilshire and others, in press); the Big Creek andesite pipe contains abundant eclogite and garnet granulite, less abundant peridotite and feldspathic granulite, and scarce pyroxenite (Dodge, Calk, and Lockwood, 1986); and the Chinese Peak trachyandesite flow contains abundant pyroxenite and feldspathic granulite and sparse peridotite (Dodge, Calk, and Lockwood, 1986).

Wilshire and Pike (1975) and Wilshire and others (in press) have suggested that plagioclase-bearing peridotite xenoliths such as those at Blue Knob originated as the result of diapiric rise of Cr-diopside peridotite through the upper mantle and into the crust, where it mingled with crustal melts of varying composition and was concentrated in thin layers. Mingling of peridotite with crustal magmas could explain the broad compositional range of feldspathic and non-feldspathic peridotites, pyroxenites, and gabbroids of the Blue Knob assemblage. Wilshire and others (in press) suggest mingling occurred at the time the alkali basalt at Blue Knob was erupted, which was in the Tertiary,
probably close to the time of eruption of several nearby basalts with isotopic ages of 3.4 to 3.6 Ma (Dalrymple, 1963, 1964; Van Kooten, 1980). However, Carswell and Gibb (1980) have suggested that upper mantle peridotites in western Europe were tectonically interleaved with lower crustal materials during a plate collision event. In the Sierra Nevada, such an event could have occurred during the Mesozoic.

Eclogite xenoliths have been reported previously at only two localities in volcanic rocks in the western United States (Krieger, 1965; Esperanca and Holloway, 1984) and at a few localities in kimberlites. Thus, their presence at Big Creek is highly significant, even more so as grospydite (carbonate-bearing grossular garnet-pyroxene rock) also occurs at this locality. To date, Big Creek is the only North American locality where grospydite has been discovered. The eclogites from Big Creek are chemically similar to eclogites from the glaucophane schist terranes of the Franciscan assemblage of the California Coast Ranges (Coleman and others, 1965), and their protoliths probably also were ocean-floor basalt. Slightly lower contents of silica and soda and apparently higher contents of magnesia and iron oxide than in the Franciscan eclogites may be attributable to the loss of a small amount of partial melt from the xenolithic material. Limestone is the most likely protolith for the grospydite (Dodge, Calk, and Lockwood, 1986). These interpretations are consistent with the inference made from low heat flow, that a cold slab of oceanic crust has been subducted beneath the Sierra Nevada (Henyey and Lee, 1976). A similar slab of oceanic crust, evidenced by eclogite xenoliths in kimberlites, has recently been postulated to underlie the southern African craton in the subcontinental mantle and interpreted to represent the boundary layer between two different thermal regimes (Basu, Ongley, and MacGregor, 1986).

The Chinese Peak xenoliths are a coherent group of fragments of an orthopyroxene-bearing intrusion or series of intrusions and associated quartz-poor granulites (Dodge, Calk, and Kistler, 1986). Rocks closely analogous to the Chinese Peak xenoliths are exposed in the Giles Complex of central Australia (Nesbitt and others, 1970), which consists of several deformed layered mafic and ultramafic intrusions emplaced into a granulite facies terrane. The rare Chinese Peak peridotites, which are significantly richer in iron than associated pyroxenites, are samples of transgressive members of cyclic sequences. The garnet-bearing ultramafic xenoliths yield pressures of 13 kb which correspond to a depth of about 43 km. However, these xenoliths are rare, and the absence of garnet pseudomorphs in most of the ultramafic xenoliths suggests this is a maximum equilibration pressure. The absence of garnet in any of the granulites implies pressures less than about 10 kb (Green and Ringwood, 1967: Ito and Kennedy, 1971). Pressure limits between 5 and 9 kb, or equilibration depths between 17 and 30 km, are inferred by comparison with experimentally determined phase relations for a compositionally similar xenolith from Delegate, Australia (Irving, 1974).
The mafic and ultramafic xenoliths, which we interpret to have come from deep levels at all localities, are overwhelmingly silica- and alumina-undersaturated—that is, they are olivine and diopside normative (fig. 3). These compositions indicate that the Sierra Nevada root and underlying mantle are of mafic-ultramafic composition. In contrast, Sierra Nevada granitoids, representative of shallow levels, are silica oversaturated and alumina saturated.

If the densities of the xenoliths roughly approximate the average densities of the rocks at their sites of origin, the depth of these sites can be estimated by comparing the densities of the xenoliths with densities inferred from P-wave velocities. However, inferences of depth of origin based on density must be used with caution because the seismic data indicate the presence of small-scale reversals of P-wave velocities (Pakiser and Brune, 1980; J. P. Eaton, oral commun., 1986). The densities of some mafic and ultramafic xenoliths have been measured accurately, but it is difficult to determine directly meaningful densities of many xenoliths because of alteration and small sample sizes. Consequently, some densities have been estimated, in part, from their normative or modal compositions (table 1). The difference between the densities of rock in the laboratory and the same rock at depth under load pressure also must be taken into account. With increase of confining pressure from 1 to 10 kb, densities of a variety of rocks increase by about 0.03

Fig. 3. Plot of mutually exclusive normative constituents of xenoliths showing silica and alumina undersaturation. Field of Sierra Nevada granitoids includes more than 90 percent of 499 CI PW norms of Sierra Nevada plutonic rocks from Bateman, Dodge, and Bruggman (1984).
Table 1

Relative rock abundances in xenolith assemblages from principal Sierra Nevada localities and typical densities of xenolith groups

<table>
<thead>
<tr>
<th></th>
<th>JB</th>
<th>BK</th>
<th>BC</th>
<th>CP</th>
<th>OC</th>
<th>Density (g/cm³)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Granite and granodiorite</td>
<td>—</td>
<td>A</td>
<td>A</td>
<td>—</td>
<td>A</td>
<td>2.66</td>
</tr>
<tr>
<td>Phyllite, schist, quartzite</td>
<td>A</td>
<td>C</td>
<td>R</td>
<td>R</td>
<td>—</td>
<td>2.78</td>
</tr>
<tr>
<td>Feldspathic granulite</td>
<td>—</td>
<td>R</td>
<td>C</td>
<td>A</td>
<td>—</td>
<td>2.84</td>
</tr>
<tr>
<td>Gabbro and norite</td>
<td>R</td>
<td>C</td>
<td>C</td>
<td>—</td>
<td>R</td>
<td>2.90</td>
</tr>
<tr>
<td>Amphibolite</td>
<td>—</td>
<td>—</td>
<td>R</td>
<td>—</td>
<td>—</td>
<td>3.00</td>
</tr>
<tr>
<td>Pyroxenite</td>
<td>R</td>
<td>C</td>
<td>R</td>
<td>A</td>
<td>C</td>
<td>3.10</td>
</tr>
<tr>
<td>Peridotite</td>
<td>C</td>
<td>C</td>
<td>C</td>
<td>R</td>
<td>C</td>
<td>3.18</td>
</tr>
<tr>
<td>Garnet granulite and eclogite</td>
<td>—</td>
<td>—</td>
<td>A</td>
<td>—</td>
<td>—</td>
<td>3.54</td>
</tr>
</tbody>
</table>

Locality symbols: JB = Jackson Butte; BK = Blue Knob; BC = Big Creek; CP = Chinese Peak; OC = Oak Creek.
Relative abundance symbols: A = abundant; C = common; R = rare; — = absent.

g/cm³ (Bateman and Eaton, 1967). Table 2 shows approximate densities of rocks as they exist at depth under load pressure relative to laboratory determinations and gives examples of rocks that correspond with these densities. Consideration of the densities of the xenoliths suggests that, as a generalization, granitoid and low-grade metamorphic rocks are from the shallowest depths; gabbro, norite, and amphibolite come from intermediate depths; and pyroxenite, peridotite, garnet, granulite, and eclogite come from the greatest depths.

The mantle is presumed to be the ultimate source of the magnesium peridotites, but they may have been transported in more than one stage. The peridotites from Jackson Butte, where mantle depths are relatively shallow, could have been derived directly from the mantle, but low pyroxene-equilibration temperatures (table 3) suggest that those from the interior of the batholith resided at shallower depths for prolonged intervals or else were re-equilibrated after they were included in the volcanic magma. Low equilibration temperatures also

Table 2

Rocks corresponding to different inferred rock densities, depths, and P-wave velocities

<table>
<thead>
<tr>
<th>Depth (km)</th>
<th>Load pressure (kb)</th>
<th>P-wave velocity (km/sec)</th>
<th>Density (g/cm³)</th>
<th>Rocks</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td></td>
<td></td>
<td>In place</td>
<td>In lab</td>
</tr>
<tr>
<td>7</td>
<td>3</td>
<td>6.0</td>
<td>2.67</td>
<td>2.66</td>
</tr>
<tr>
<td>15</td>
<td>4</td>
<td>6.4</td>
<td>2.83</td>
<td>2.81</td>
</tr>
<tr>
<td>35</td>
<td>10</td>
<td>6.9</td>
<td>3.03</td>
<td>3.00</td>
</tr>
<tr>
<td>55</td>
<td>15</td>
<td>7.9</td>
<td>3.23</td>
<td>3.20</td>
</tr>
</tbody>
</table>
suggest a possible temperature-pressure re-equilibration during crustal residency for the Big Creek peridotites, but an absence of feldspar and the occurrence of garnet indicate somewhat greater depths during residency than for Blue Knob xenoliths.

Isotopic data (Domenick and others, 1983; Dodge, Calk, and Kistler, 1986) suggest that some of the mafic high-grade metamorphic xenoliths, other than eclogites, may represent residues from sources that were partially melted to produce the magma that formed the batholith. These xenoliths probably are polygenetic and include both residual minerals from partial melting and early precipitates.

**Late Cenozoic Uplift and Tilt**

Late Cenozoic uplift and westward tilting of the Sierra Nevada were recognized during the early studies of Whitney (1880), Le Conte (1889), Ransome (1898), Lindgren (1911), and others; and more recent workers, such as Matthes (1930, 1960), Hudson (1960), Christensen (1966), and Huber (1981), have attempted to quantify the amount and timing of tilt by reconstructing and dating stream profiles and erosion surfaces. According to Huber (1981), who has provided the most recent interpretation of the history of uplift, based chiefly on studies of the San Joaquin River drainage, which crosses the central Sierra Nevada, uplift and tilting probably were underway by 25 my ago, but at a relatively low rate. About two-thirds of the total uplift of 3450 m at the Sierran crest has taken place during the last 10 my, and one fourth in the last 3 my, which suggests that uplift is accelerating. Despite this uplift, the Sierra Nevada and adjacent regions are approximately in isostatic equilibrium, and preliminary investigations indicate that if differences in the densities of the exposed rocks were taken into account, the remaining small gravity residuals would be virtually eliminated (Oliver, Moore, and Sikora, 1986).

Relations east of the southern Sierra Nevada and of the central Sierra near Mono Lake (fig. 1) suggest that the Sierra Nevada may actually be the western limb of a broad arch whose eastern limb was broken and the individual blocks rotated eastward during arching (Hopper, 1947; Bateman, 1965). In this interpretation, Owens Valley,
Long Valley (which contains the Long Valley caldera), and the Mono basin are downdropped “keystone” blocks in the crest of the arch. The cross section shown in figure 4 extends eastward across the southern Sierra Nevada (section D-D' in fig. 1) only to Panamint Valley, but the arch continues eastward to Death Valley where bed rock plunges below sealevel. Farther north, at the latitude of Mono Lake, a series of blocks east of the Sierra Nevada to and including the White Mountains have similarly been rotated eastward. However, the existence of an arch in the intervening span and farther north has not been established. Stewart (1980) has shown that the ranges east of the Sierra Nevada can be grouped into domains within which all the ranges and younger Cenozoic deposits are tilted in the same direction. Domains of eastward-tilted ranges meet domains of westward-tilted ranges along northward-trending antiforms (one of which is Owens Valley) and synforms. Latitudinally, the domains terminate at east-trending boundary lines 120 to 150 km apart which are continuous across the Basin and Range Province. Regardless of whether the Sierra Nevada is or is not the western limb of a broken arch, maximum uplift of about 3450 m occurred during the late Cenozoic along or just east of the Sierra Nevada crest line and approximately coincident with the axis of the Sierran root.

**TIME OF ORIGIN**

Christensen (1966) concluded that because the region is in isostatic equilibrium, the root must have originated concurrently with Cenozoic uplift. He argued that the uplift could not have resulted from delayed isostatic adjustments to a Mesozoic root that had lain dormant for at least 50 my while the land was being deeply eroded. He suggested that magma generated at depth caused crustal thickening and resulted in uplift. Hamilton and Myers (1967) concurred with the opinion that the root is of Cenozoic age but postulated that the cause of uplift was radioactive decay in the crust, which retarded cooling and conduction of mantle heat and caused phase changes in the upper mantle and lower crust with consequent enlargement of the Sierran root. Isostatic equilibrium of the region provides the strongest argument that the root originated during the Late Cenozoic uplift.

In contrast with these interpretations of a Cenozoic age, Bateman and Wahrhaftig (1966) and Bateman and Eaton (1967) assumed that the Sierran root originated concurrently with the emplacement of the batholith, during the Mesozoic. Influenced by the then popular tectogene paradigm of Griggs (1939) and Vening-Meinesz (1948), they envisaged the batholith as having developed by crustal melting at the base of a synclinorium. In a later publication, Bateman (1979) postulated that the root consists of the refractory residual material of the magmas that formed the overlying granitic rocks. Dodge, Calk, and Kistler (1986) postulated that development of mafic-ultramafic complexes in the lower crust during generation of the batholith may account for the present day thick crust, and as evidence they cited isotopic data that
Fig. 4. Topographic cross section D-D' across the southern Sierra Nevada to Panamint Valley. Location shown in figure 1.
indicate approximate age contemporaneity between Chinese Peak xenoliths and granitic rocks in the general area.

Schweickert and Cowen (1975), Henyey and Lee (1976), Crough and Thompson (1977), and Chase and Wallace (1986) have also considered the Sierran root to have originated concurrently with the batholith. Hay (1976) suggested that the root originated in the Mesozoic, but that movements along the San Andreas fault during the Late Cenozoic produced northwest-oriented tensional stresses across the Sierra Nevada, which allowed it to rise and still maintain isostatic equilibrium. Chase and Wallace (1986) postulated that isostatic equilibrium was attained only when Tertiary extension of the Basin and Range Province permitted the Sierra Nevada to rise. This interpretation carries the unlikely implication that a 200 mgal anomaly coincident with the present Sierra Nevada existed for at least 80 my.

Crough and Thompson (1977) postulated that the Cenozoic uplift was caused by the conversion of lithospheric mantle to lower density asthenosphere as suggested by abnormally low P-wave velocities of 7.9 km/sec. They compared the Sierra Nevada with the Appalachian Range, which is only about half as high and has a similar crustal thickness and P-wave velocities but normal upper-mantle velocities of about 8.2 km/sec. They suggested that a subducted slab of cold oceanic lithosphere beneath the Sierra Nevada, as postulated by Henyey and Lee (1976), caused the present low heat flow and shielded the Sierra Nevada from a high regional asthenospheric heat flux. Warming subsequent to northward migration of the Mendocino triple junction and the cessation of subduction converted sub-Sierran mantle lithosphere to asthenosphere and raised the Sierra Nevada region.

**OUR INTERPRETATION**

The Sierra Nevada batholith and its underlying crustal rocks are layered. Granitoid and associated greenschist to amphibolite-grade metamorphic rocks exposed in the central Sierra Nevada correspond with a surface seismic-density layer \( (v_p = 6.0 \text{ km/sec}; \rho = 2.67 \text{ g/cm}^3) \). Studies in the southernmost Sierra Nevada, where deeper crustal levels are reported to be exposed (Ross, 1985), indicate that a largely metaigneous assemblage of hornblende-rich gneissic amphibolite- to granulite-grade rocks underlie this layer. These metaigneous rocks form a roughly 10-km-thick lens \( (v_p = 6.4 \text{ km/sec}; \rho = 2.83 \text{ g/cm}^3) \) within the upper crust, which thins toward the margins of the batholith. The lower crust \( (v_p = 6.9 \text{ km/sec}; \rho = 3.03 \text{ g/cm}^3) \) constitutes about half the entire crust. Xenoliths from Tertiary volcanic feeders indicate that in the interior of the batholith the upper part of the lower crust, to a depth of about 40 km, is made up of a series of deformed mafic-ultramafic intrusions. The mafic-ultramafic intrusions cut granulite-grade feldspathic metamorphic rocks. Less feldspathic granulite occurs below this level in the lowest parts of the crust. Beneath the deeper part of the Sierran root, a seismic discontinuity at 55 km may mark downward transition to an easterly-dipping, down-dragged slab of ocean-floor
basalt transformed to eclogite ($v_p = 7.9$ km/sec; $\rho = 3.25$ g/cm$^3$). Westward at shallower depths, the eclogite should grade to basalt, but a transition has not been recognized. Beneath the deepest part of the Sierran root, olivine-rich ultramafic rocks occur at greater mantle depths, but in the margins of the batholith they immediately underlie the Moho. They also occur as diapirs or tectonic interlayers in the lower crust.

Downward increase of mafic minerals within some intrusions (Sawka, 1985; Bateman, in press), isotopic evidence that xenoliths are of approximately the same age as the enclosing granitic rock (Domenick and others, 1983; Dodge, Calk, and Kistler, 1986), and currently popular models for the generation of the batholith are consistent with the root having been formed during the Mesozoic, contemporaneously with and as the downward extension of the batholith. Two models for the origin of the Sierra Nevada batholith are currently in vogue: (1) The source for the batholithic magmas was the lower crust, some of which is at least 1700 my old, and some of which was basalt introduced from the mantle during late Proterozoic and early Paleozoic periods of crustal extension (Kistler and Peterman, 1973; 1978). In this model, the isotopic and many chemical properties of the batholith were inherited from the lower crustal source rocks. As the exposed granitoids are far more silicic overall than the postulated source rocks, a mafic-ultramafic residue must remain at depth, which could correspond to the rocks that now form the root. (2) The batholith originated by the mixing of basaltic magma rising from the mantle with crustal material, and the isotopic and many compositional properties reflect the relative proportions of mantle and crustal material (DePaolo, 1981). In this model, as in model 1, it is to be expected that the ratio of basaltic to felsic crustal material would increase with depth. The two models are not necessarily mutually exclusive: the heat required to mobilize the lower crustal source material postulated in model 1 probably was carried in additional basaltic magma rising from the mantle.

The Cenozoic uplift of the Sierra Nevada appears to be related only indirectly to the existence of the root. Correlation of crustal thickness with terrane elevation in isostatically compensated terranes is poor and in many places requires that the attainment of isostatic equilibrium involve the mantle (thermal isostasy). For example, the Moho apparently is not depressed relative to regional depths beneath either the Cascade Range or the Rocky Mountains, and the crustal thicknesses in the structurally high Basin and Range Province are in the general range of 25 to 30 km as compared with thicknesses of 40 to 45 km under the Colorado Plateau and even greater thicknesses under extensive areas of the relatively low eastern United States. In general, terrane elevations appear to correlate better with variations in P-wave velocities (and deduced densities) in the upper mantle than with crustal thicknesses. Thus the P-wave velocity under the Sierra Nevada is 7.9 km/sec, generally about 7.8 under the structurally high Basin and Range Province, about 8.0 to 8.1 under the structurally lower Colorado Plateau, and more than 8.1 in the relatively low eastern United States.
These considerations lead us to favor the interpretations of Crough and Thompson (1977) and of Mavko and Thompson (1983) that the Late Cenozoic uplift is related to high heat flow and conversion of upper mantle lithosphere to lower density asthenosphere rather than to generation of the Sierran root. The cold subducted plate of oceanic crust that underlies the root shields the Sierra Nevada from the high asthenospheric heat flow that is affecting the Basin and Range Province. However, the high heat flow is converting upper mantle lithosphere beneath the plate to lower density asthenosphere, causing uplift in the Sierra Nevada.

We are also attracted to the suggestion of Hay (1976) that northward movement during the late Cenozoic of the Mendocino triple junction and of active subduction beneath the Sierra Nevada was accompanied by northward migration of uplift and westward tilting of the Sierra Nevada. The presence of both silicic and basaltic volcanism along the eastern edge of the Sierra Nevada, where fracturing is continuous and probably extends to considerable depth, suggests the possibility that a magmatic arc similar to earlier arcs that existed within the Sierra Nevada during the Mesozoic may be developing.

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