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Seismic Models of the Root of the Sierra Nevada

L. C. Pakiser and James N. Brune

The deep crustal structure of the root of the Sierra Nevada in California has been studied periodically since 1936. At that time Lawson (*1*) used average crustal and upper-mantle densities and isostatic principles to estimate that the Sierran root extends downward into the mantle to reach a total crustal thickness of 68 kilometers in the vicinity of Mount Whitney. At Lawson's request, Byerly (*2*) in 1937 reviewed seismic evidence bearing on the Sierran root. Byerly demonstrated that seismic waves from earthquakes in northern and central California, as recorded at seismograph stations in Owens Valley, just east of the Sierra Nevada, arrived late when compared with seismic waves recorded at the same stations from earthquakes in Nevada and southern California. He concluded that these delays in travel times supported Lawson's findings.

Byerly assumed that the P_n seismic waves, which travel in the uppermost mantle and arrived at seismograph stations at Tinemaha and Haiwee from earthquakes to the west and northwest, emerged from a sharp western edge of the Sierran root. He further assumed that they were delayed by propagation through the low-density rocks of the Sierra Nevada batholith, in which seismic wave velocity is low. On the basis of these assumptions, the observed delays, and P-wave velocities through the crust and upper mantle of 5.6 and 8.0 kilometers per second, respectively, he calculated that the maximum width of the root is 70 km and that the minimum is 40 km. Byerly made no estimate of the depth of the Sierran root because, according to his assumptions, Owens Valley would lie in a "shadow" of the batholith in which waves emerging from the bottom of the root would not be observed as first arrivals.

In 1939, Byerly (*3*) elaborated on his earlier study and concluded that seismic waves arriving at Santa Barbara from an earthquake in Nevada could have been delayed as much as 1.2 seconds, owing to diffraction under the root. From this he calculated that the maximum crustal thickness beneath the Sierra Nevada could be as much as 71 km.

Recent Evidence Confirms, and Denies, the Existence of a Sierran Root

In the early 1960's, the U.S. Geological Survey conducted an extensive seismic-refraction study of crustal structure in the western United States (*4*). Eaton (*5*) interpreted a profile of that study recorded across the Sierra Nevada between explosion sites near San Francisco, and Fallon, Nevada. His analysis of travel times of waves generated by the explosions indicated that the Mohorovicic (Moho) discontinuity at the base of the crust descends to a depth of at least 40 km beneath the Sierra Nevada. Eaton later interpreted two seismic-refraction profiles based on explosions at Shasta Lake, Mono Lake, and China Lake, California, and concluded that the high southern part of the Sierra Nevada is underlain by a crust about 54 km thick. Oliver (*6*) demonstrated that gravity data in the Sierra Nevada are consistent with Eaton's crustal model. Prodehl (*7*) reinterpreted the profiles originally analyzed

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Summary. Seismic waves generated by earthquakes or explosions show a delay in travel times as they propagate across the Sierra Nevada from all directions except that of the Nevada test site. Early arriving waves from the test site can be explained if they emerge through a rock layer with high seismic velocity from the sharp eastern edge of the Sierran root. Such a layer could be formed by the subducted ophiolite slab that crops out in the western Sierra Nevada foothills. A synthesis of all seismic data indicates that the Sierran root projects downward into the mantle to a depth of about 55 kilometers beneath the high Sierra.

by Eaton and some previously uninterpreted profiles. He concluded that the crustal thickness beneath the Sierra Nevada is 42 km.

Press and Biehler (*8*) reported that delays in the arrivals of P waves at seismograph stations at Tinemeha and Reno, relative to Pasadena, were about 0.8 second. The models they derived to explain these data and gravity anomaly data had crustal thicknesses under the Sierra of about 45 km, as well as a velocity reversal in the crust, that is, a zone in which the velocity of P waves is lower than in zones immediately above and below. These data tend to confirm the existence of the Sierran root, but there are a number of assumptions implicit in their P-wave delay model that need to be independently verified (for example, that the mantle structure is the same under Tinemeha and Pasadena and that the relation of velocity to density is known).

Thus far, all investigations of crustal structure in the Sierra Nevada supported the existence of the Sierran root (*9*). However, Carder and his co-workers (*10*) recorded seismic waves from nuclear explosions at the Nevada test site arriving at portable stations between the California-Nevada border and San Francisco Bay, and they observed that waves identified by them as P_n arrived early in the Sierra Nevada. They concluded that crustal layers beneath the Sierra Nevada have a total thickness of only about 30 km, whereas the crust beneath Owens Valley and the White Mountains to the east is 35 to 40 km thick, suggesting a Sierran "antiroot" or thinning of the crust.

Later, Carder (*11*) recorded two seismic profiles between Death Valley and Monterey Bay from nuclear explosions at the Nevada test site. During the recording expedition, a magnitude 5 earthquake in Monterey Bay in August 1970 provided a partial reversal of one profile. The waves arriving first in the Sierra Nevada from explosions at the Nevada test site arrived early as before, suggesting crustal thinning to as little as 25 km beneath the Sierran crest. However, seismic waves from the earthquake in Monterey Bay arrived progressively later at portable stations in the Sierra Nevada and at Tinemaha as they propagated eastward. These delays were similar to those observed by Byerly in 1937 which led him to conclude that the Sierra Nevada is underlain by a deep root. Carder concluded that the late arrivals from the Monterey Bay earthquake could be attributed, in large part, to relatively low (7.64 km/sec) wave velocities in the rocks of the upper mantle beneath the Sierra Nevada, rather than to the presence of a Sierran root. He devised a crustal model with a thin crust and a low-velocity upper mantle beneath the Sierra Nevada that is compatible with the travel-time data of waves from both the Nevada test site and Monterey Bay.

The Profile down the Backbone of the Sierra Reveals a Root

A magnitude 6.5 earthquake (*12*) occurred in the vicinity of Truckee, California, on 12 September 1966 (Fig. 1). Seismic waves generated by the aftershocks of the quake were recorded by the California Institute of Technology (Caltech) at five portable stations (TLM, GCK, SHC, MKG, and NEL) located along the axis of the Sierra Nevada as a part of a cooperative project with the University of Nevada. The recording units, mounted in trailers, were equipped with horizontal seismometers with 1-second natural periods and 70-millimeter film recorders. They were oriented at angles of 45° along lines to the source in order to detect primarily shear waves. For our study, we analyzed only the first-arriving compressional waves (P_n) that were critically refracted in the upper mantle. In addition to data from the portable stations, we used P-wave data from the Tinemaha (TIN), Woody (WDY), Isabella (ISA), and China Lake (CLC) stations of the Caltech seismograph network (Fig. 1) to calculate crustal thicknesses.

The use of seismic waves from earthquake sources to calculate crustal thicknesses requires accurate location of hypocenters and reliable determinations of times of origin. The University of Nevada and the U.S. Geological Survey quickly placed networks of portable stations in the vicinity of the main-shock epicenter to locate aftershocks of the Truckee earthquake. We recomputed the main shock location by obtaining the difference in location between the main shock of 12 September and an aftershock of 22 September as determined by Ryall *et al*. (*12*) and by relating that difference to the location of the 22 September aftershock as determined by Greensfelder (*13*). Our revised coordinates and time of origin of the main shock are: latitude, 39°26.91′; longitude, 120°8.75′; focal depth, 8.9 km; and time of origin, 16

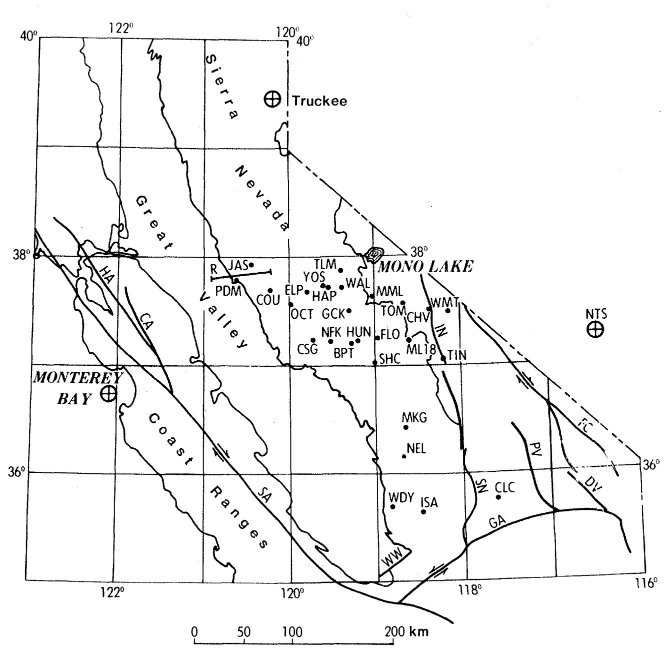

Fig. 1. Map of a portion of California showing major geologic features and locations of seismic sources (circles with crosses), seismograph stations (solid dots with three-letter identifications), and reflection profile (solid bar between stations *JAS* and *PDM*). Faults shown are the San Andreas (*SA*), Hayward (*HA*), Calaveras (*CA*), White Wolf (*WW*), Garlock (*GA*), Sierra Nevada (*SN*), Inyo (*IN*), Panamint Valley (*PV*), Death Valley (*DV*), and Furnace Creek (*FC*). Nevada test site is designated *NTS*.

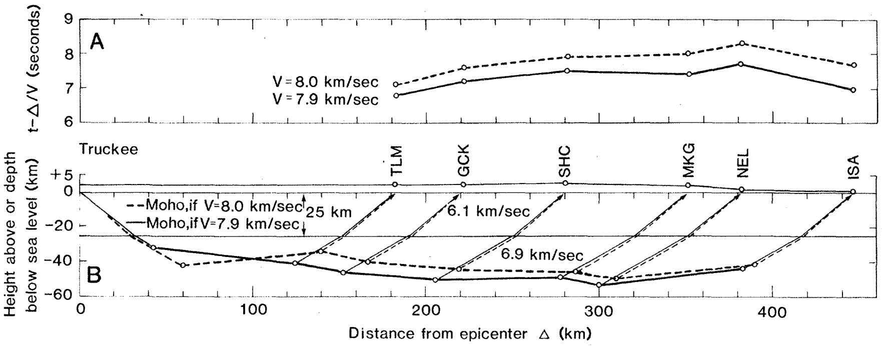

Fig. 2. Interpretation of recordings from September 1966 Truckee earthquake and aftershocks. (A) Reduced travel times or total delay times from sea-level focus based on P_n velocities of 7.9 and 8.0 km/sec. (B) Crustal models based on both P_n velocities and velocities in the crust as shown.

hours, 41 minutes, 02.6 seconds, Greenwich civil time, 12 September 1966.

In addition to the main shock, we used travel times from two aftershocks that occurred on 14 September and another that occurred on 22 September. These aftershocks all had magnitudes of about 4.5. All travel times were calculated from adjusted times of origin referred to sea level.

Stations WDY, ISA, and CLC lie approximately on the arc of a circle 450 km south of Truckee (Fig. 1). The arrival of P_n waves at ISA was delayed by 0.8 to 0.9 second with respect to stations WDY and CLC, suggesting that the crust is 11 to 13 km thicker at ISA than at WDY and CLC, if the velocity of the waves in the lower crust is 6.9 km/sec (*14*). The arrival of P_n waves at NEL was delayed by 1.4 to 1.6 seconds, suggesting that the crust is 19 to 23 km thicker at NEL than at WDY and CLC. Arrivals of P_n waves were also delayed at TLM, GCK, SHC, and MKG.

The apparent velocity of P_n waves arriving between stations TLM and NEL (Fig. 2) is 7.7 km/sec. If the true P_n velocity is 7.9 km/sec, as determined by Eaton (*5*), then the Moho dips down to the south about 2° and the crust is about 12 to 13 km thicker beneath NEL than beneath TLM. The apparent velocity of P_n waves arriving between NEL and ISA is 8.6 km/sec, indicating that the Moho dips up to the south about 5° toward ISA and suggesting that the crust is about 10 km thinner beneath ISA than beneath NEL. These results are compatible with those deduced from stations WDY, ISA, and CLC.

Prodehl (*7*) determined that the depth to the Moho is about 31 km below sea level at CLC, so we conclude tentatively that the depth to the Moho is about 50 km beneath the high mountains of the southern Sierra Nevada. This result supports a preliminary analysis of travel times from aftershocks of the Truckee earthquake by Brune and Charles Archambeau; their interpretation yielded a model with a total crustal thickness of 47 km. This result also supports the work of Eaton (*5*), but it is incompatible with that of Carder and his co-workers (*10, 11*).

We are thus faced with a seeming contradiction. The P_n waves emerging from the base of the crust beneath the Sierra Nevada are delayed if they have propagated along the axis of the Sierra Nevada or come from sources to the west and northwest, but P_n waves propagating westward across the Sierra Nevada from sources at the Nevada test site arrive early. The primary purpose of our analysis is to resolve this apparent contradiction.

Thick Sierran Crust Confirmed

To interpret the data from the Truckee earthquake of 12 September 1966 (Fig. 2), we have assumed that a horizontal boundary at a depth of 25 km below sea level separates the upper crust, where seismic velocities are 6.1 km/sec, from the lower crust, where velocities are 6.9 km/sec. This assumption is consistent with Eaton's model (*5*). In reality, the boundary is probably neither horizontal nor sharp, but departures from the assumed velocities would not significantly affect computations of depths to the Moho.

From the crustal model of Prodehl (*7*), we estimated that the delay time (*15*) for P_n waves arriving at station CLC was 3.1 seconds. Because we know the differences in delay times between CLC and the stations that recorded P_n waves propagating along the axis of the Sierra Nevada from the Truckee earthquake aftershocks, we can determine the total delay times for P_n waves at each of these stations by simply adding 3.1 seconds to the delay-time differences. We computed delay times for each station from assumed P_n velocities of 7.9 and 8.0 km/sec. The reduced travel times for these assumed velocities (Fig. 2) are the sums of the delay times at each station for emerging P_n waves and the delay times for sea-level focuses at the Truckee earthquake epicenter for descending P_n waves. Thus we can compute the delay times at Truckee for P_n waves with velocities of 7.9 and 8.0 km/sec by sub-

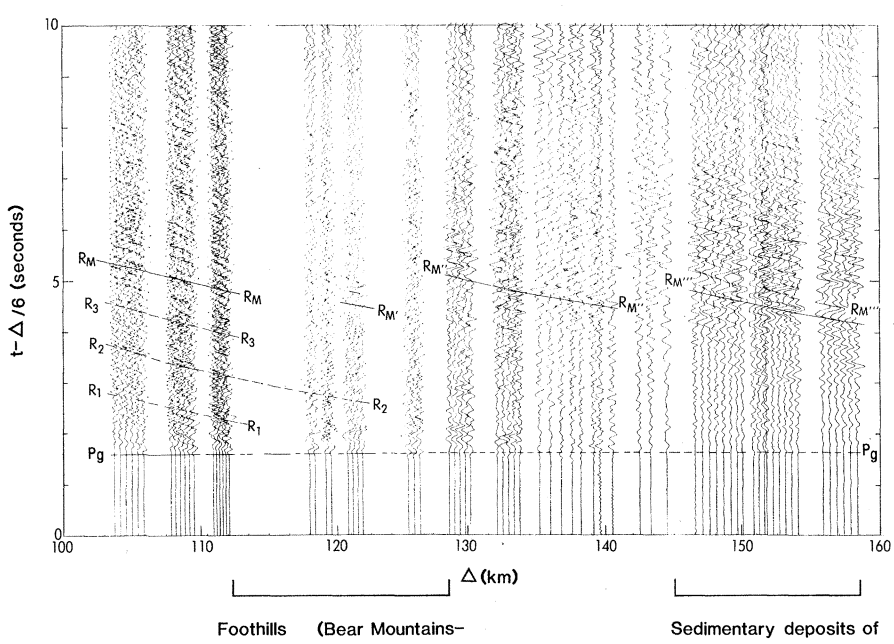

Fig. 3. Record section from recordings of the explosions in Mono Lake; R_M to $R_{M'''}$ are onsets of reflections with the largest bursts of energy; R_1 to R_3 are reflections from crustal layers; Δ is the distance from the site of the explosions in Mono Lake, increasing to right; *t* is time; P_g is the velocity of seismic waves in the upper crust.

tracting the P_n delay times from the reduced travel times (Fig. 2).

The resulting delay times at Truckee are 3.1 and 3.9 seconds for P_n velocities of 7.9 and 8.0 km/sec, respectively, leading to a calculated crustal thickness at Truckee of 32.1 km if the P_n velocity is 7.9 km/sec, and 42.7 km if the P_n velocity is 8.0 km/sec (Fig. 2). A crustal thickness of 32.1 km at Truckee gives a more reasonable Moho configuration from an isostatic perspective, suggesting that 7.9 km/sec is a better estimate of the P_n velocity than 8.0 km/sec.

Crustal thicknesses computed for P_n waves with velocities of 7.9 km/sec that emerge along the axis of the Sierra Nevada range from 40.6 km at TLM to 53.3 km at NEL (Fig. 2). The crustal thicknesses for these P_n waves at WDY and TIN are 32.1 and 34.9 km, respectively, compared with a crustal thickness of 31 km at CLC.

For P_n waves with velocities of 8.0 km/sec, crustal thicknesses along the axis of the Sierra range from 32.1 km at TLM to 49.5 km at NEL, and crustal thicknesses at WDY and TIN are each 30.4 km. In the above estimates, all crustal thicknesses are given with respect to sea level, and the Moho depth points from which P_n waves emerge to each station are displaced to the north of the stations (Fig. 2).

From this analysis, we conclude that the crustal thickness in the highest mountains of the southern Sierra Nevada is about 50 to 55 km (Fig. 2), and they might be more if P-wave velocities in the crust are greater than 6.9 km/sec above the Moho.

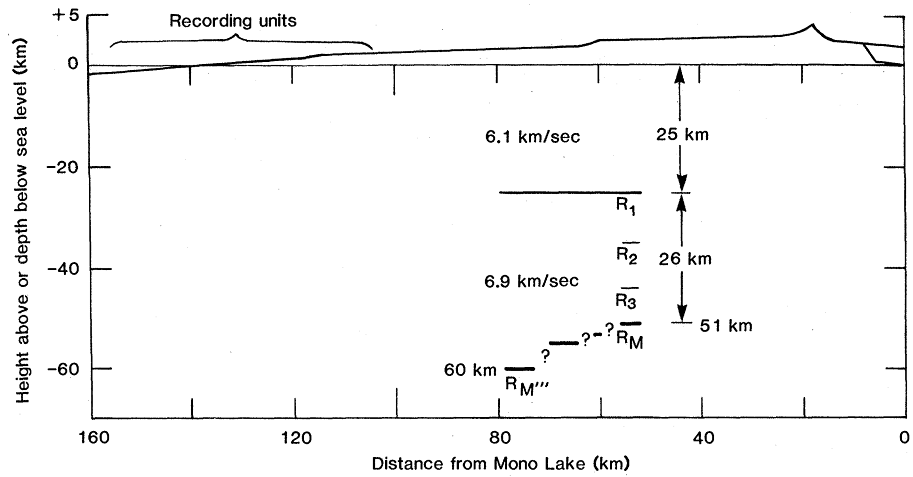

Fig. 4. Locations of reflecting horizons for R_M to R_M''' and R_1 to R_3, based on velocities shown; R_M to R_M''' are related to reflection from the Moho.

Reflections from the Moho

An experiment was conducted by the U.S. Geological Survey in 1970 to determine whether wide-angle reflections could be recorded from the Moho beneath the Sierra Nevada. Chemical explosions weighing 4500 and 5700 kilograms were detonated in Mono Lake on 6 and 8 October 1970, respectively. Recordings of seismic waves generated by the blasts were made on eight-channel seismic systems designed for crustal studies (*16*). The seismic units, mounted on trucks, were equipped with photographic and reel-to-reel analog magnetic-tape recorders and seismometers with 1-second natural periods. Six vertical seismometers per unit were arrayed at intervals of 0.5 km and oriented approximately toward the explosion sources in Mono Lake. Radial and transverse horizontal motions were recorded on horizontal seismometers at the location of a vertical seismometer near the center of each spread of detectors. The recording units were located in the border zone between the Sierra Nevada and the Great Valley at distances ranging from 100 to 160 km from the explosions (Fig. 1).

A record section with data from each vertical seismometer was prepared from the magnetic-tape recordings (Fig. 3). The amplitudes of each trace on the record section were normalized to permit easy correlation of the recorded waves.

After making several attempts to correlate phases that might represent reflections from the Moho, we decided to identify the onset of waves with the largest bursts of energy in each identifiable segment of the record section (R_M to R_M''' in Fig. 3). This procedure results in a somewhat gentler slope for R_M than would be deduced from phase correlation. In addition, we identified three reflections from crustal boundaries in the portion of the record section nearest the sites of the explosions (R_1 to R_3 in Fig. 3). Depths to the (assumed horizontal) boundaries from which these waves were reflected were computed from the velocities adopted for the analysis of the Truckee aftershock recordings (Fig. 2). The average velocity in the crust was estimated to be 6.5 km/sec from the assumed velocities (Fig. 4) and 6.7 km/sec from the travel times of R_M, R_M'', and R_M''' (*17*). The depths computed to the boundaries from which R_M to R_M''' were reflected ranged from 51 to 60 km for an average velocity in the crust of 6.5 km/sec (Fig. 4). The greater depths to the boundaries of R_M'' and R_M''' may be apparent depths caused by delays as the emerging waves propagated through the Foothills (Bear Mountains-Melones) fault zone and the sedimentary deposits of the Sacramento Valley (Fig. 3). The delay in the arrival of R_M''' with respect to R_M'' can readily be accounted for by the low-velocity sedimentary deposits on which the recording units were placed (Figs. 1 and 4). Other possible explanations for the discontinuities in R_M to R_M''' portion of the record section are that the discontinuities are portions of a wave group reflected from a complex zone where a transition in wave velocity occurs or that the Moho is structurally irregular in this area.

We conclude from this analysis that waves identified as R_M to R_M''' were reflected from the Moho or a zone of velocity transition between the lower crust and upper mantle, and that the depth to the Moho below sea level at a distance of about 65 km west of Mono Lake is about 55 km (Fig. 4). Wave R_1 was reflected from a boundary about 25 km below sea level, the assumed depth of the boundary between the upper crust in which wave velocities are 6.1 km/sec and the lower crust in which velocities are 6.9 km/sec. Reflections R_2 and R_3 suggest that the lower crust is layered.

Shadow Zone of the Sierran Root

Carder and his co-workers (*10, 11*) identified the early arriving waves recorded in the Sierra Nevada from sources at the Nevada test site as P_n waves and concluded that they were evidence for crustal thinning. However, the evidence presented here of late P_n arrivals in the high Sierra from the Truckee earthquake and aftershocks and the evidence of a thick crust from reflection data require that we seek alternative interpretations of Carder's data. To find such interpretations, we reexamined key portions of Carder's profiles [WMT to PDM from the 1970 profile (*10*) and TIN to CSG from the 1973 profiles (*11*)] (Fig. 1).

A hint for identifying other paths for the early arriving waves from the Nevada test site comes from Byerly's suggestion (*3*) that "the root projects downward into the mantle sufficiently to keep Tinemaha and Haiwee in its shadow from coastal shocks." Although Byerly's explanation for late arrivals in Owens Valley from sources to the west now seems inappropriate, the concept of a shadow zone may be appropriate as an explanation for early arrivals in the Sierra Nevada from sources to the east.

If the root of the Sierra Nevada is asymmetrical, as is the physiographic Sierra, which has a steep eastern slope and a relatively gentle western slope, P_n waves propagating westward from the Nevada test site might never appear as first arrivals at stations in the Sierra Nevada. As Byerly noted, stations in the Sierra might lie in the shadow of the Sierran root. If the crust beneath the Sierra Nevada is about 55 km thick, as proposed by Eaton (*5*) and confirmed by us, waves emerging from the sharp eastern edge of the root from sources at the Nevada test site would be recorded as early first arrivals, provided that crustal rocks in which velocities are high rise to within a few kilometers of the surface in the high Sierra (Figs. 5 and 6). We propose two models for the high-velocity layer. One (Figs. 5A and 6A) has a finite thickness of 5 km, and the other (Figs. 5B and 6B) extends down to the Moho. For both models, stations in the high Sierra (MML to OCT in Fig. 5 and ML18 to NFK in Fig. 6) would lie in the shadow of the root. The P_n waves would reappear as first arrivals beyond the shadow zone (COU in Fig. 5 and CSG in Fig. 6). The high-velocity layer forms a wave guide in model A, which is thus referred to as the wave-guide model. The P_n waves from the Nevada test site are diffracted from the sharp eastern edge of the root in model B, which is referred to as the "diffraction" model.

In our reinterpretation of the data of Carder *et al.* (*10*), the ray paths for waves emerging from the eastern edge of the root and recorded at stations MML to OCT have travel times for both models (Fig. 5, A and B) that would match those observed within ± 0.1 second. Calculated and observed travel times for P_n waves west of the shadow zone are equally accurate. The wave guide, 5 km thick, rises to within 6.4 km of sea level in model A (Fig. 5); the layer in which velocities are 6.9 km/sec is 13.4 km deep and horizontal beneath the high Sierra in model B.

In our reinterpretation of Carder's 1973 data (*11*), the travel times require that the wave guide (6.9 km/sec) rise to the surface in the western Sierra Nevada if the eastern edge of the root is defined by the wave emerging at station TIN (model A, Fig. 6). For model B (Fig. 6), we assumed that a recording was made at a station midway between TIN and ML18 with the same delay in the crust as at TIN. The travel times for that assumption would yield an irregular boundary between the upper crust and the lower crust, that could be represented approximately by a horizontal boundary at a depth of 10 km. Carder (*11*) noted that "two chemical explosions fired in Mono Lake by the U.S. Geological Survey in early October 1970 and recorded by NFK, BLP, and FLO may be satisfied, although not uniquely, by a structure consisting of 10 km of a 6.0-km/sec layer overlying a 6.7-km/sec medium."

Arrivals of P_n waves from the explosion source in Monterey Bay, recorded at stations NFK, HUN, and TIN,

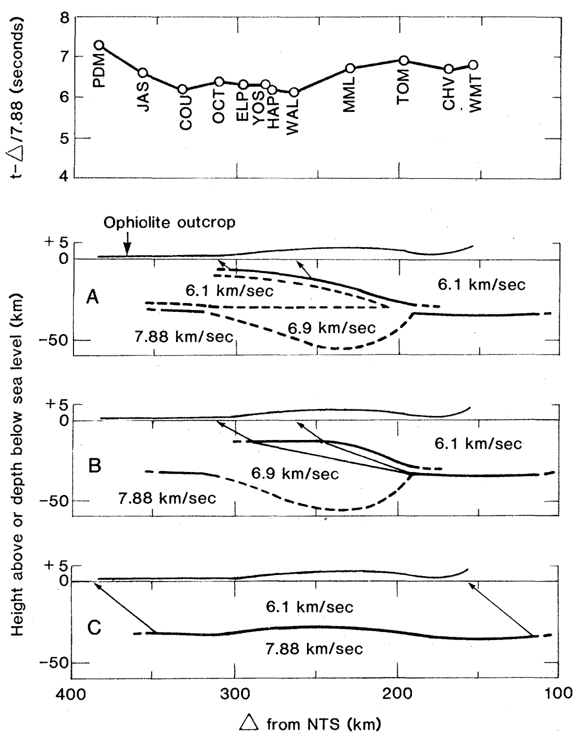

Fig. 5. Reinterpretation of 1970 profile of Carder *et al.* (*10*). (Top) Reduced travel times or total delay times from Nevada test site (*NTS*). (A) Wave-guide model. (B) Diffraction model. (C) Recomputation of model of Carder *et al.* Note approximate location of outcrop of the ophiolite belt in the western foothills in model A. Dashes indicate assumed boundaries. The depth of the root in models A and B was estimated from Truckee earthquake recordings, reflection profile, and Eaton's (*5*) model.

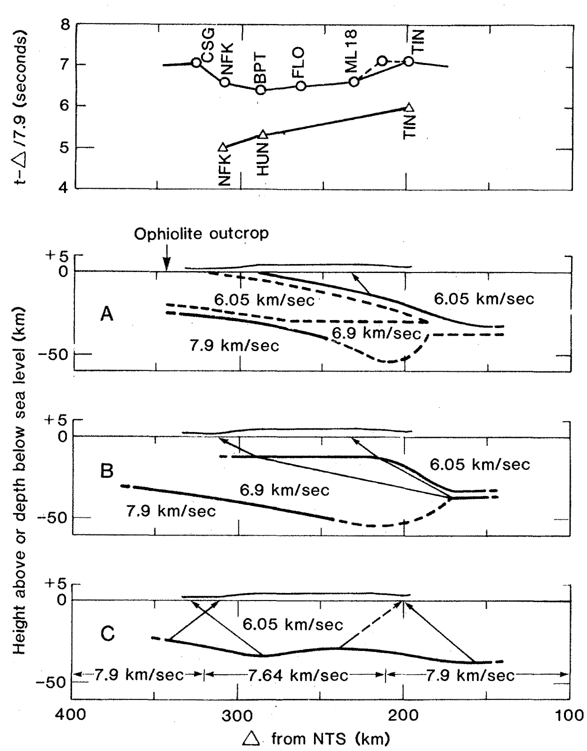

Fig. 6. Reinterpretation of 1973 profile of Carder (*11*). (Top) Reduced travel times or total delay times for source. Circles are travel times from Nevada test site (*NTS*). Triangles are travel times from Monterey Bay earthquake, adjusted to agree with delay times of crustal model. (A) Wave-guide model. (B) Diffraction model. (C) Recomputation of Carder model. Approximate location of outcrop of western foothills ophiolite belt shown for model A. Dashes indicate assumed boundaries. The depth of the root in models A and B was estimated from Truckee earthquake recordings, reflection profile, and Eaton's (*5*) model.

were progressively delayed as P_n waves propagated eastward (Fig. 6). We have interpreted these delays as indicating crustal thickening toward the east rather than the presence of upper-mantle material in which velocities are 7.64 km/sec, as suggested by Carder. For comparison, we have recomputed the models of Carder and his co-workers (Figs. 5C and 6C). Ray paths for those models also have travel times compatible with those observed, but, as we have shown, they are incompatible with the travel times for P_n waves recorded in the Sierra Nevada from the sources of the Truckee earthquake and aftershocks and the reflection data.

Our models, based on emergence of waves propagated in a wave guide (Figs. 5A and 6A) or waves diffracted from the eastern edge of the root of the Sierra Nevada (Figs. 5B and 6B), are compatible with the Truckee earthquake and reflection data, with Eaton's model for the southern Sierra Nevada, and with earlier studies dating back to Byerly and Lawson.

Limitations of the Data

The seismic data presented and interpreted in this study allow us confidently to draw the following conclusions.

1) From the recordings of the Truckee earthquake and aftershocks and the reflection data, we conclude that the crustal root beneath the high mountains of the Sierra Nevada projects downward 20 km or more into the mantle, in relation to the crust beneath the Great Basin to the east and the Great Valley to the west, to reach a depth of about 55 km.

2) From the recordings of Carder and his co-workers (*10, 11*) of the Nevada test site explosions and the Monterey Bay earthquake, we conclude that the Sierran root is asymmetrical, with the Moho dipping steeply on the east and relatively gently on the west.

3) From the recordings of the Nevada test site explosions, we conclude that high-velocity crustal material rises to within a few kilometers of the surface and perhaps to the surface in the western Sierra Nevada.

The recordings of Nevada test site explosions in the eastern Sierra Nevada are widely separated, so the exact location of the sharp eastern edge of the Sierran root is uncertain. The early P_n wave arrivals at TIN and CLC after the Truckee earthquake indicate that the edge lies along or near the eastern face of the Sierra.

Neither the velocity of P_n waves nor the velocities in the crust at depths greater than a few kilometers have been determined precisely because the profiles on which these velocities are based were not truly reversed. However, it is unlikely that these velocities differ by more than ± 0.2 km/sec from those used in this study.

We have assumed that the surfaces are smooth between crustal layers and the Moho. This is unlikely in reality. The reflection data (Figs. 3 and 4) suggest an irregular Moho. The scatter in the data of Carder and his co-workers is large and cannot be readily accounted for by near-surface variations in velocity alone, also suggesting an irregular Moho, structural complexities in the crust, or both.

Our models A and B suggest that the velocities of the first (refracted) waves to arrive in the recordings of the explosions in Mono Lake should be about 6.9 km/sec, whereas they were observed to average only 6.0 km/sec (P_g in the record section, Fig. 3). The lower velocity is compatible with probable delays in the fractured rocks in the Foothills fault zone and in the sedimentary deposits of the Sacramento Valley. The delays of R_M' to R_M''' are also compatible with this observation. The high apparent velocities of the first arrivals (and reflections) between 103 and 112 km are related to near-surface variations in velocity that could suggest a series of thrust sheets under the western foothills.

We have presented three seismic models of the Sierran root (A, B, and C in Figs. 5 and 6). Model A is generally compatible with the gravity low of the Sierra Nevada and with isostasy (*6, 18*); model B is not, unless the density in the layer in which velocities are 6.9 km/sec is laterally inhomogeneous, decreasing to the west. To the contrary, the intrusive rocks of the Sierran crust are increasingly more mafic and dense to the west. Models A and B are both compatible with the heat flow, which increases gradually from west to east in the Sierra Nevada as the thickness of the presumably highly radiogenic upper crust above the high-velocity layer increases (*18*). Model C (Carder's model) is incompatible with the Truckee earthquake and aftershock recordings and with the reflection data. We therefore select model A as our preferred model, because it is the only one that is compatible with all the evidence cited above.

Discussion

If model A or (acknowledging the margin of ambiguity in the data) a model similar to it is the correct one, then the layer in which velocities are 6.9 km/sec rises westward from the sharp eastern edge of the Sierran root to emerge approximately at the location of an ophiolite belt in the western foothills of the Sierra Nevada (Figs. 5 and 6). (Ophiolite is a jumbled mixture of deep-sea sedimentary rocks, submarine lavas, and ultramafic rocks formed along plate margins during subduction.)

Saleeby (*19*) concluded that the Carboniferous mafic-to-ultramafic ophiolite slab was tectonically emplaced by subduction just before Middle Jurassic time. Following the initial subduction, the plate juncture of the subduction zone migrated westward in Middle and Late Jurassic time. The plutonic rocks of the western Sierra and the Sierra Nevada batholith were emplaced in Late Jurassic to Late Cretaceous times, presumably disrupting the subducted ophiolite slab in places.

Saleeby's models suggest that the subducted ophiolite slab was essentially destroyed by the tectonic and magmatic processes that followed its emplacement. It seems more probable to us that the wave guide in model A represents the remnants of the essentially intact subducted ophiolite belt, although other interpretations (for example, a mafic sill injected from the east) are possible. Model A (Figs. 5 and 6) implies that low-velocity crustal rocks are present beneath the subducted slab. These low-velocity rocks could represent in part a mélange of crustal rocks formed as the plate juncture of the subduction zone migrated westward and in part plutonic rocks derived from fusion of the lower crust and upper mantle.

The present position of the ophiolite belt, as represented by the healed Kings-Kaweah suture of Saleeby (*19*), dips steeply eastward, whereas the wave guide in our model A dips more gently. However, our data provide no convincing evidence for the dip of the slab near the surface. It could well dip steeply near the surface and more gently at greater depths.

Our suggestion that low-velocity material underlies a high-velocity slab is similar to the suggestion by Press and Biehler (*8*) of a velocity reversal in a fairly thick (about 45 km) Sierran crust. Their result was based on comparison of the gravity anomaly with the observed P-wave delay at Tinemeha, relative to Pasadena, and an assumed density/velocity ratio of 0.3 gram per cubic centimeter per kilometer per second. They suggested a thermal explanation for the existence of the velocity reversal in the crust. Although the

P-wave delay method is based on a number of assumptions and cannot resolve details in the velocity-depth profile, it does lend support to the type of interpretation we have presented. For example, the Carder model (with a 30-km crust in which velocities are 6.1 km/sec), considered in the context of the Press and Biehler study, would be associated with a P-wave delay of at most 0.3 second, relative to Pasadena, whereas the observed delay was 0.8 second.

Of course, many uncertainties about the nature and structure of the crust of the Sierra Nevada remain, but we believe that we have demonstrated that the root of the Sierra Nevada exists and that it projects downward to a depth of about 55 km beneath the highest mountains of the range, as proposed by investigators as far back as Lawson (*1*). Our preferred model of the root of the Sierra Nevada (Figs. 5A and 6A) is compatible with modern principles of plate tectonics.

Most of the remaining ambiguities and uncertainties about the structure of the root of the Sierra Nevada could readily be resolved by analysis of travel times from local and distant earthquakes, by detailed seismic profiling across and along the axis of the range, and by application of the latest techniques of modeling to seismic record sections.

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14. A magnitude 5.8 earthquake occurred along the eastern edge of the Sierra Nevada (near station TOM, in Fig. 1) on 4 October 1978. The P_n waves from that earthquake were delayed 0.74 second at ISA with respect to CLC, in close agreement with the delay at ISA from the Truckee earthquake when differences in distance and azimuth are considered.
15. The delay of time of P_n waves caused by propagation through the crust is the additional time for waves to travel any segment of the P_n path over the time that would be required to travel the horizontal component of that segment at the velocity of P waves in the uppermost mantle. Variations in delay time are directly proportional to variations in the thickness of the crust.
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20. We thank W. H. Jackson, Sedalia, Colo., who supervised the reflection recording and the explosions in Mono Lake; personnel of the U.S. Geological Survey who participated in the field work; personnel of the Seismological Laboratory at California Institute of Technology who helped install and operate the stations for the Sierra profile; A. Ryall, of the University of Nevada, who supervised the recordings of the Truckee earthquake aftershocks; C. Archambeau, of the University of Colorado, who helped in the early stages of the analysis of the Sierra profile; A. Griscom, W. Hamilton, A. Lachenbruch, and H. Oliver, of the U.S. Geological Survey, for valuable discussions of the data and conclusions; and J. Eaton, A. Espinosa, D. Hill, P. Lipman, W. Spence, and D. Warren, of the U.S. Geological Survey, for helpful reviews of the manuscript.

Solar Tracking by Plants

James Ehleringer and Irwin Forseth

Leaf movements in higher plants have been recognized for many years. Perhaps the most widely known examples are rapid leaf closure in *Mimosa* and the circadian sleep movements in beans and other leguminous species in which leaves move from a horizontal to a vertical position at night (*1*). The movements of leaves fall into three categories: nyctinastic (sleep movements), seismonastic (movements in response to shaking), and heliotropic (*1-3*), which is the subject of this article. As the name implies, heliotropism is the movement of leaves following the sun and is of two types: diaheliotropism and paraheliotropism. The movement of blades of diaheliotropic leaves is such that they remain perpendicular to the sun's direct rays throughout the day. The movement of blades of paraheliotropic leaves is such that they remain parallel to the sun's direct rays. In effect then, heliotropic leaves are solar trackers (Fig. 1). The heliotropic leaf movements may be accomplished in several ways. The two most commonly observed means involve petiole twisting and pivotal movement of the pulvinus, a turgor-dependent structure located at the base of the leaf blade (*1, 2*). These leaf movements are rapid and reversible tropic responses and should not be confused with or considered as growth responses.

Physiological aspects of leaf movements and the morphological mechanisms for achieving them have been studied extensively (*1-3*). However, there has been little discussion of the adaptive value of either of these types of leaf movements and the environmental regimes in which natural selection should favor them. In this article, the heliotropic leaf movements in arid land plants, the potential consequences to metabolic activity, and the probable adaptive value to native plants and agronomic species are discussed.

Diaheliotropism will have a tremendous impact on the daily rate of net photosynthesis because it allows a sunlit leaf to experience high solar irradiances and to operate at maximal rates throughout the day (*4*). This trait could be of particular value to ephemeral or annual vegeta-

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