

Seismic Refraction Study of Upper Crustal Structure in the Lassen Peak Area, Northern California

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In September 1982, the U.S. Geological Survey recorded a 125-km-long refraction profile through the Lassen Peak area of the Cascade Range. This profile extended northwestward to the Klamath Mountains and southeastward to the Sierra Nevada foothills. Interpretation of the refraction data determined the upper-crustal structure in this volcanic region of northern California. Near-surface velocities (1.5–5.55 km/s) are consistent with a thickness of 2–4 km for the Cascade volcanic rocks. Between 0.5 km above and 1.8 km below sea level, velocities are about 4.7–5.55 km/s. The highest velocities are modeled below the Devils Kitchen-Terminal Geyser area, possibly indicating hydrothermal alteration of the volcanic rocks. The absence of low velocities (less than about 3–4.5 km/s) deeper than 1 km above sea level suggests that the Cretaceous sedimentary rocks exposed west of Lassen Peak do not underlie the volcano. Southeast of Lassen Peak, at 1.8 km below sea level, a 0.3-km-thick layer with a velocity of 6.1 km/s overlies a lower-velocity (5.7–5.8 km/s) 2.9-km-thick layer. Because these modeled velocities do not change across the boundary between the Sierra Nevada foothills and the Cascade Range, Sierran basement could continue under the Cascade volcanic rocks as far northwest as Lassen Peak. The velocity model does not indicate the presence of a magma chamber larger than 3 km in diameter within the top 8 km of the crust.

1. INTRODUCTION

In 1982, the U.S. Geological Survey carried out an active seismic experiment along the axis of the Cascade Range in northern California. The refraction profile crossed Lassen Peak, which is the southernmost active volcano of the Cascade Range. Figure 1 shows the locations of the three shot points and the refraction stations. The main profile (125 km long) extended northwestward from the Sierra Nevada foothills to the Klamath Mountains. In Lassen Volcanic National Park (LVNP), a small cross profile recorded travel times in the geothermal area south of Lassen Peak (Figure 2). Since the only previous seismic refraction study to cross Lassen Peak and the southernmost Cascade Range [Eaton, 1966; Prodehl, 1979] used a station spacing of 10 km, the detailed structure of the crust beneath the Cascade Range and the nature of the transition to the structure beneath the surrounding provinces, the Sierra Nevada foothills, the Klamath Mountains, and the Great Valley, are not well-understood. We used closely spaced stations concentrated in the Cascade Range to investigate crustal structure. The problems addressed in this study are the thickness of the Cascade volcanic rocks near Lassen Peak, the composition of the basement beneath the Cascade volcanic rocks, and the possibility that Great Valley Cretaceous sedimentary rocks exposed west of Lassen Peak underlie the volcanic rocks.

2. GEOLOGIC SETTING

The Cascade Range includes 17 major volcanos in a chain of volcanic mountains extending 1000 km from the northernmost Sierra Nevada in California to British Columbia. Pliocene to Holocene volcanism built the High Cascade volcanos

of andesite, basalt, and dacite on a platform of contemporaneous basalt to andesite [MacDonald, 1966; McBirney, 1978].

The Klamath Mountains, northwest of Lassen Peak, are a tectonic assemblage of fragments of Mesozoic and Paleozoic island arcs, melange belts, and ophiolite masses, all separated by east-dipping thrust faults. These units are varyingly metamorphosed and intruded by Mesozoic granitic plutons [Irwin, 1981].

Southeast of Lassen Peak are the Sierra Nevada foothills, where rocks similar in age and lithology to those in the Klamath Mountains are exposed [Hietanen, 1981]. Because the Cascade volcanic rocks hide the underlying rocks in the area between the Klamath Mountains and the Sierra Nevada foothills, the relation between these two provinces is unknown. Hietanen [1981] correlated Sierra Nevada structures with Klamath Mountains structures and inferred the continuity of a suture zone from the Sierra Nevada foothills to the Klamath Mountains. From his interpretation of aeromagnetic data, Griscom [1980] speculated that Sierran basement continues under the volcanic rocks at least as far north as a point 25 km south of Lassen Peak, and gravity data suggest it may continue to Lassen Peak (R. C. Jachens, oral communication, 1984). In this paper we examine the basement beneath the volcanic cover and attempt to determine its nature.

Sedimentary rocks of the Great Valley Sequence lie to the west and south of the Cascade Range. The Chico Formation, consisting of sedimentary rocks of Cretaceous age, is exposed in narrow outcrops along the most deeply incised drainages of the Cascade foothills west of Lassen Peak [Haggart and Ward, 1984]. Sedimentary rocks of Cretaceous age also occur northwest of Lassen Peak [Haggart and Ward, 1984], but the extent and thickness of these rocks under the Cascade volcanic rocks are unknown. Late Cretaceous to mid-Tertiary rotation of the Klamath Mountains away from the Sierra Nevada foothills [Griscom, 1973, 1980; Hamilton, 1978; Craig et al., 1981; Frei et al., 1984] could have formed a marine channel, the "Lassen Strait" proposed by Diller [1895; see MacDonald, 1966], extending from southwest or west of

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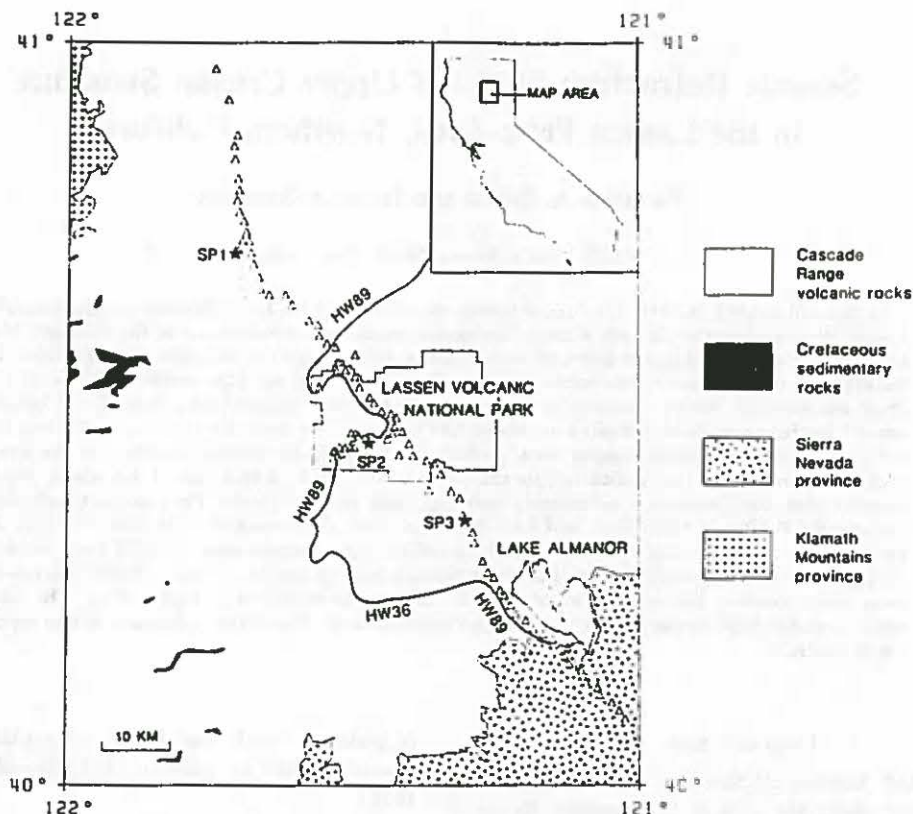


Fig. 1. Generalized geologic map showing location of study area. Stars, shot points; triangles, refraction stations; unshaded area, Cascade volcanic rocks. Geology from Lydon *et al.* [1960]. Lassen Peak is about 4 km northwest of SP2.

present-day Lassen Peak to the east of the Cascade Range. Williams [1932] suggested that the Chico Formation rocks underlie LVNP at about 1.4 km above sea level. In our refraction study we sought to determine whether a layer of sedimentary rocks is present beneath the Cascade volcanic rocks in the LVNP region.

The thickness of the Cascade volcanic rocks in the Lassen area is unknown. The oldest volcanic rocks in the Lassen area make up the Tuscan Formation of late Pliocene age. The Tuscan Formation, which was deposited unconformably on the Sierra Nevada basement complex or on Late Cretaceous and early Tertiary sedimentary rocks [Anderson, 1933; Lydon, 1968; Helley *et al.*, 1981], has an apparent thickness of less than 150 m under the Lassen area [Lydon, 1968]. Overlying the Tuscan Formation is a broad ridge of Quaternary volcanic rocks, primarily pyroxene andesite flows and pyroclastic rocks with subordinate basalt flows, silicic flows, and domes [MacDonald, 1966]. Clyne [1984] reported that the Cascade volcanic rocks pinch out at the edge of the Sierra Nevada foothills and at the southernmost edge of the Klamath Mountains. Using gravity data, Pakiser [1964] estimated that these volcanic rocks could be 6–10 km thick under Lassen Peak. In this paper we use our refraction data to estimate the thickness of the Cascade volcanic rocks.

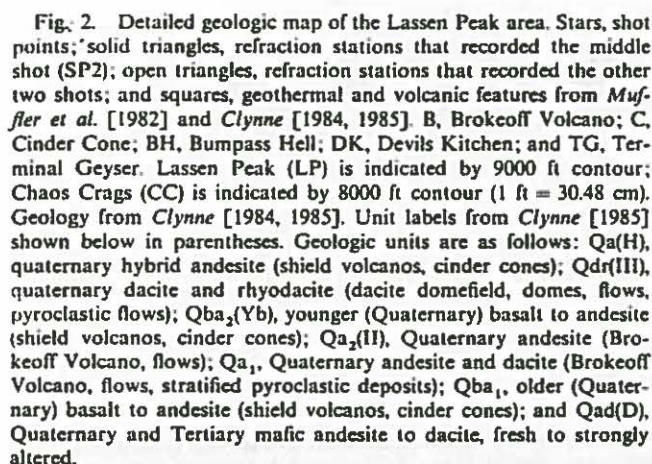
The hydrothermal system at Lassen Peak is presently active [Muffler *et al.*, 1982]. The long history of pyroclastic eruptions in the Lassen dome field and the historical production of magma at two separate vents, Cinder Cone (Figure 2) in 1850–1851 and Lassen Peak in 1915 [Williams, 1932], together with

a major gravity low over the Lassen Peak and Chaos Crags area [Pakiser, 1964; LaFehr, 1965], suggested to Heiken and Eichelberger [Eichelberger, 1979; Heiken and Eichelberger, 1980] that a partially molten magma body lies 9–13 km below the Lassen dome field. However, preliminary analysis of teleseismic data [Monfort, 1980; Berge and Monfort, 1986] and several studies of the seismicity in the Lassen area [Klein, 1979; Monfort, 1982; Walter *et al.*, 1984] were unable to detect a magma chamber.

3. LASSEN REFRACTION EXPERIMENT

Stations along our 125-km-long main profile were spaced an average of 1.5 km apart (Figure 1). The main profile was reversed for 53 km, between the northern and southern shot points. The unreversed E-W cross profile recorded the middle shot for 13 stations spread about 0.5 km apart along two 4-km-long segments around Bumpass Hell (Figure 2). All three shots used 900 kg of explosive detonated in 50-m-deep holes. The refraction experiment used 10 Terratech digital event recorders, 5 Sprengnether DR100 digital recorders, and 90 of the U.S. Geological Survey's portable seismographs, as described by Blank *et al.* [1979] and Healy *et al.* [1982]. (Any use of trade names or trademarks in this paper is for descriptive purposes only and does not constitute endorsement by the U.S. Geological Survey).

The three shot points and 78 stations that successfully recorded data along our main refraction profile (Figure 1) provided higher-resolution velocity data than the previous refraction study in the Lassen area [Eaton, 1966; Prodehl, 1979],



4. METHODS OF MODELING

An interactive ray tracing program (J. Luetgert, written communication, 1984), based on the technique described by Cervený *et al.* [1977], was used to trace rays through models with initially flat-lying layers and linear velocity gradients. Trial-and-error forward modeling was used to change layer

In Figures 4a-6a the seismic signal disappears at distances of 40-60 km from all the shot points. We plotted the data in true amplitude record sections to show that the disappearance of the signal is not due to a high background noise level. We were not able to determine whether poor shot coupling, attenuation, or other factors prevented the signal from carrying to distant stations. Velocity modeling using these data is possible for, at most, the top 8 km of the crust to the southeast of Lassen Peak and the top 4 km to the northwest of Lassen Peak.

With only three shots, the near-surface velocities are not well-constrained in this region of extreme topography, particularly in unreversed sections of the profile (Figures 7a and 7b). For the unreversed region at the southeast edge of the model, rays from both the southern and middle shots were used to constrain the velocities. Although the deeper velocities in this region are not very well-constrained, the relative amplitudes of

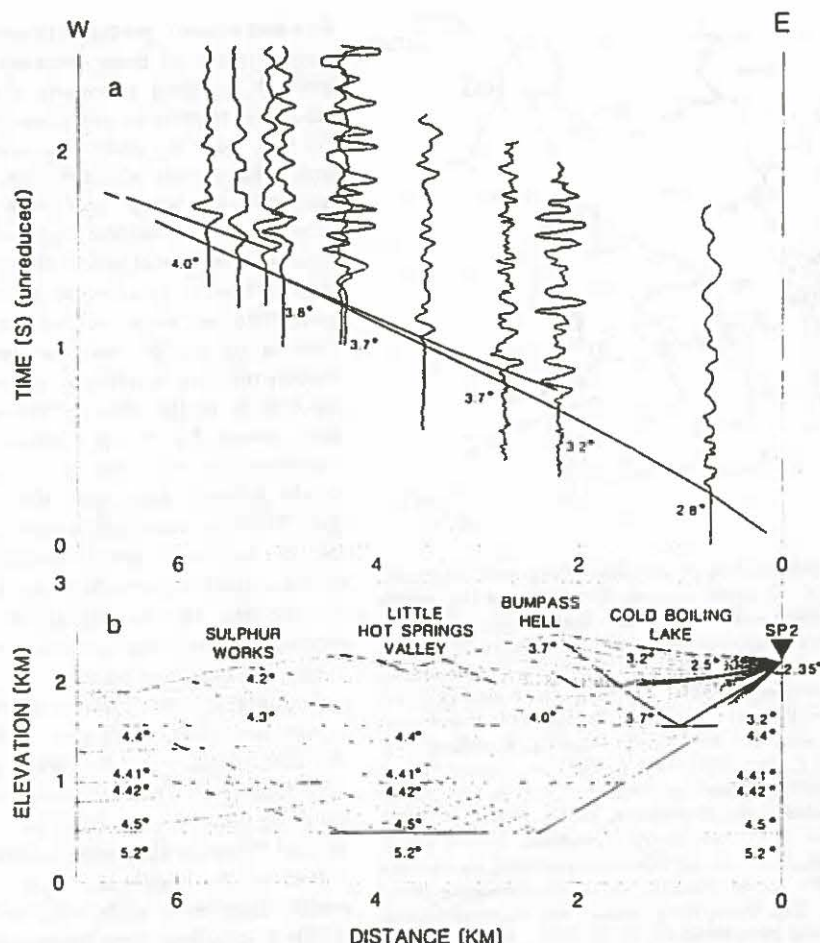


Fig. 3. Data and ray diagram for east-west cross profile. (a) Trace-normalized record section for east-west cross profile through Lassen geothermal area. Apparent velocities (kilometers per second) shown for first arrivals from rays refracting in surface layer; asterisks, unreversed velocity determinations. Line segments indicate arrivals for all refracted and reflected rays shown in Figure 3b. (b) Velocity model for cross profile; no vertical exaggeration.

parallel first and later arrivals indicate the probable presence of a velocity inversion. The region between the middle and northern shot points is well-constrained between 1 km above and 3 km below sea level, where the profile is reversed (Figures 7a and 7b). Instrument timing uncertainties and digitizing problems prevented us from using the data from the unreversed region north of the northern shot point.

The cross profile record section (Figure 3a) shows no large reflection off the steam-water boundary at an elevation of about 1.57 km, the base of the vapor-dominated reservoir that Muffler *et al.* [1982] described for the Lassen hydrothermal system. However, the *P* wave velocity change due to pore pressure variations across the steam-water boundary should be about 0.02 km/s [Ito *et al.*, 1979]. This is too small to be detected in this refraction study. Although we based our velocity model (Figure 3b) on the hydrothermal system model of Muffler *et al.* [1982], we were unable to determine a precise depth to the steam-water boundary and could not contribute additional information to the hydrothermal model. The refraction stations in the geothermal area were mainly useful for constraining the near-surface velocity close to the middle shot point.

5. VELOCITY MODELS

We first examine the near-surface velocities in both the cross profile and main profile models, before discussing the deeper velocity structure of the main profile models. Our cross profile model for the middle shot point (Figure 3b) shows low velocities (2.35–3.7 km/s) near the surface (the top 0.5 km) in the geothermal area south of Lassen Peak. Because this cross profile model is unreversed, velocities in deeper regions and in regions more than a few kilometers west of the middle shot point are not modeled. In the velocity models for the main profile (Figures 7a and 7b), near-surface velocities show great lateral variation, with values of 1.5–4.5 km/s. The shallow velocities in the main and cross-profile models could vary by about ± 0.2 km/s, and the depths to the shallow interfaces could vary by up to about 0.2 km, without changing the fit to observed travel times by more than 0.5 s for most traces. Since this modeling does not resolve any change in near-surface velocities across the boundary between the thin basalt flows at the south edge of the Cascade volcanic rocks (M. A. Clynné, oral communication, 1984) and the fractured metamorphic rocks of the Sierra Nevada foothills, we cannot estimate the

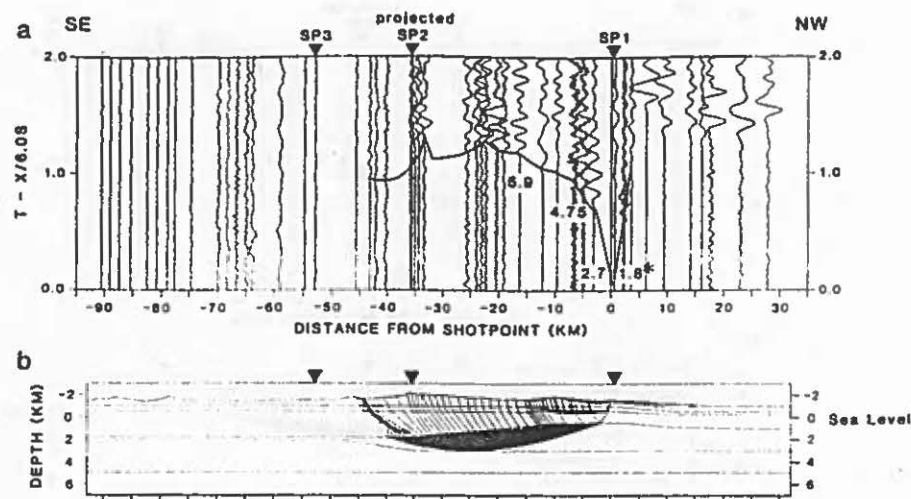


Fig. 4. Data and ray diagram for northern shot point (SP1). (a) Record section showing true amplitude plots. Traces within 17 km of shot point are scaled by true amplitude times $d^{2.5}$, and traces farther than 17 km from shot point are scaled by true amplitude. Solid curves in Figure 4a indicate first arrivals and important later arrivals from rays traced in Figure 4b. Apparent velocities are in kilometers per second; asterisks, unreversed velocity determinations. Off-profile shot points are shown in their projected positions. (b) Rays from shot traced through a model (compare Figure 7a), with 2:1 vertical exaggeration.

thickness of the volcanic rocks at the southeast end of the model.

In deeper layers of the models (Figures 7a and 7b), the velocity-depth structure southeast of Lassen Peak differs considerably from that modeled northwest of Lassen Peak. The basement (about 6 km/s) is much closer to the surface northwest of Lassen Peak, and a velocity inversion is evident in the basement southeast of Lassen Peak. The change in velocity under Lassen Peak evident in all layers deeper than about 0.5 km above sea level may indicate a temperature or structural change, which perhaps controls the location of the volcano. In the following sections we will first discuss the velocities south-

east of Lassen Peak and then the velocities modeled for the region northwest of Lassen Peak.

5.1. Southeastern Region

Southeast of Lassen Peak, at Terminal Geyser between the middle and southern shotpoints, Geyser Steam Company drilled a well through strongly altered volcanic rocks, beginning at an elevation of 1.77 km above sea level [Beall, 1981]. This well ended in the same altered volcanic rocks, at an elevation of 0.55 km above sea level. Our model shows velocities of 4.0–4.5 km/s (± 0.1 km/s) for these volcanic rocks between the surface and a depth of 0.5 km above sea level,

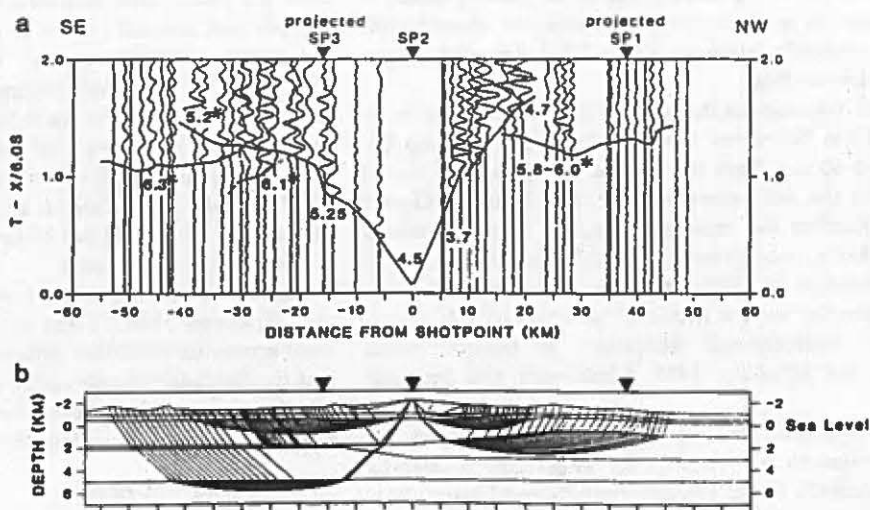


Fig. 5. Data and ray diagram for middle shot point (SP2). (a) Record section showing true amplitude plots. Same conventions as in Figure 4a. (b) Rays from shot traced through a model (compare Figure 7b). Same conventions as in Figure 4b.

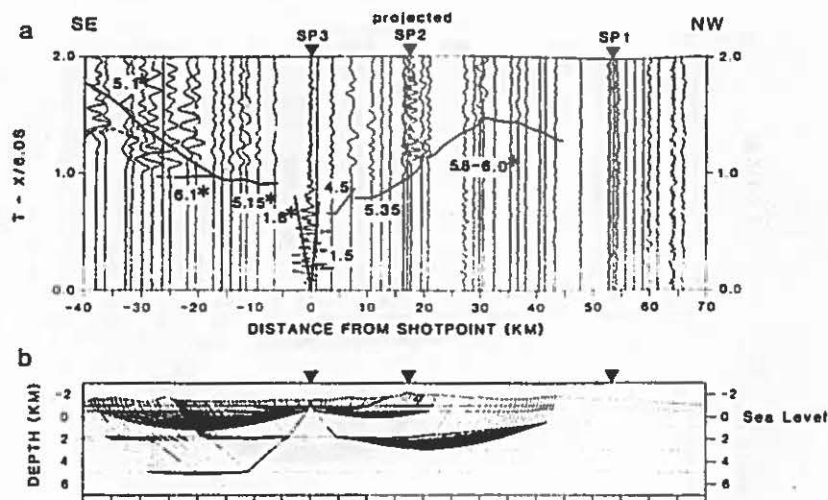


Fig. 6. Data and ray diagram for southern shot point (SP3). (a) Traces within 25 km of shot point are scaled by true amplitude times $d^{1/3}$, and traces farther away are scaled by true amplitude. (b) Rays from shot traced through a model (compare Figure 7a). Same conventions as in Figure 4b.

near the well (Figure 7a). If deeper regions of the models (Figures 7a and 7b) with similar velocities are interpreted to represent the Cascade volcanic rocks, their thickness can be estimated. Velocities of 4.5–5.55 km/s (± 0.1 km/s) are found at depths of from 1 km above to 1.8 km below sea level (± 0.2 km). This is slightly higher than velocities modeled for the near-surface volcanic rocks. This layer may represent volcanic rocks with the same composition but lower porosity, or volcanic rocks with a more mafic composition. Although the 4.5- to 5.55-km/s layer could, alternatively, represent the basement, these velocities are considerably lower than the 5.9–6.3 km/s generally observed for the granitic-metamorphic basement beneath the Sierra Nevada, the Modoc Plateau, and the Cascade Range [Eaton, 1966; Prodehl, 1979; Gortner and Lindh, 1981; Spieth et al., 1981; Leaver et al., 1984; Zucca et al., 1986]. More probably, the 4.5- to 5.55-km/s layer consists of volcanic rocks. Therefore if the top three layers of the velocity model in Figures 7a and 7b represent volcanic rocks, the Cascade volcanic rocks probably compose about 1.2–4 km of the crust southeast of Lassen Peak.

The highest velocities in the presumed volcanic rocks occur at about 1.8 km below sea level, in the reversed region between 50 and 60 km from the southeast edge of the model (Figure 7a) in the geothermal area by the Terminal Geyser and Devils Kitchen hot springs. Here, the velocities are as high as 5.55 km/s, in contrast to 5.15–5.25 km/s to the southeast and an average of 4.75 km/s to the northwest. One possible explanation for such a rise in P wave velocity is that it results from hydrothermal alteration of basaltic rocks [Christensen and Salisbury, 1975; Christensen and Smewing, 1981].

Southeast of Lassen Peak, at 1.8 km below sea level, the velocity increases to 6.1 km/s (± 0.2 km/s) and is laterally uniform between the Sierra Nevada foothills and Lassen Peak. The model shows no low-velocity (less than 4.5 km/s) layers at depths greater than 0.5 km above sea level; thus the Cretaceous sedimentary rocks of the Chico Formation, which are expected to have velocities less than 4 km/s, are not present in

this model. The Chico Formation rocks probably thin to less than a few tenths of a kilometer, below the limit of resolution of our refraction study, or do not underlie the Cascade volcanic rocks in the Lassen area. Therefore the Cascade volcanic rocks probably rest directly on the 6.1-km/s basement rock. The thickness of the 6.1-km/s layer is poorly constrained and could increase by up to 0.4 km if boundaries of overlying layers are moved or shallower velocities are lowered by about 0.2 km/s.

Below this 6.1-km/s layer, at 2.1–5 km below sea level, the data have been modeled with a 2.9-km-thick, 5.7–5.8-km/s (approximately ± 0.5 km, ± 0.3 km/s) layer. This region of the model is unreversed. The velocity and thickness of this layer are poorly constrained, although rays traced from both the middle and southern shot points show a good fit for first and later arrivals (Figures 5a and 6a). The record sections from both the middle and southern shots show the characteristic die out and delayed return of parallel branches of arrivals, indicating a velocity reversal. We model a 6.3-km/s (± 0.2 km/s) layer below the velocity inversion. Although the velocity is poorly constrained in the 6.3-km/s layer, this velocity at a depth of 5 km below sea level generally agrees with the results of the regional models formulated by other workers [Eaton, 1966; Prodehl, 1979; Zucca et al., 1986]. Our results and those of Zucca et al. [1986] are of comparable resolution and are plotted together in Figure 8.

Because the velocity in all layers of the models (Figures 7a and 7b) deeper than 1.8 km below sea level is laterally constant across the boundary between the Sierra Nevada foothills and the Cascade volcanic rocks, we propose that the structure also is constant. Sierran basement apparently continues uninterrupted at least as far northwestward as Lassen Peak.

5.2. Northwestern Region

Northwest of Lassen Peak, the velocities at depths of from 0.5 km above to 0.5 km below sea level are 4.5–4.8 km/s (± 0.1 km/s) (Figures 7a and 7b). These velocities probably represent Cascade volcanic rocks that have not been hydrothermally

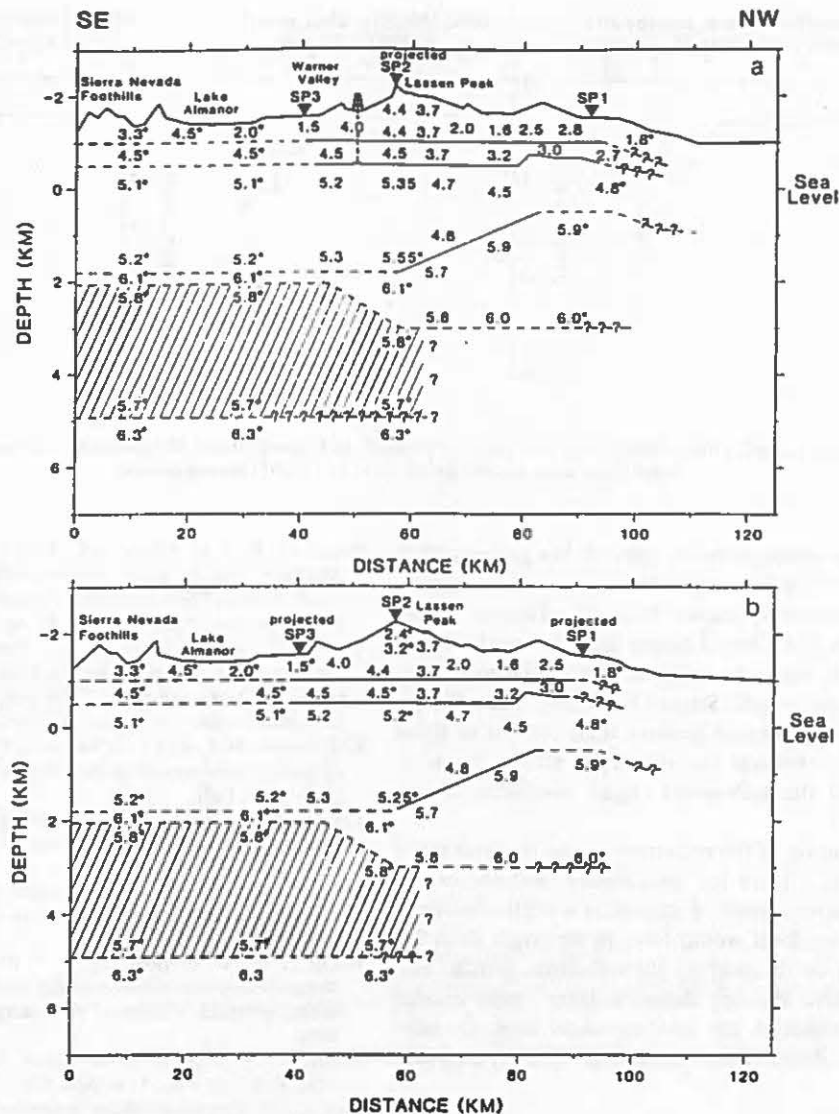


Fig. 7. Velocity models for Lassen refraction profile. (a) Model for shot points 1 and 3. (b) Model for shot point 2 only. Vertical exaggeration, 8:1; asterisks, unreversed velocity determinations. Boundaries are dashed where data are unreversed; shading, velocity inversion. Shot point 2 was off profile; its projected position is shown in Figure 7a, and projected positions of shot points 1 and 3 are shown in Figure 7b. Well symbol (between SP2 and SP3 in Figure 7a) indicates projected position of the Walker "O" No. 1 well at Terminal Geyser, 1.5 km southwest of line through shot points 1 and 3. Devils Kitchen hot springs are 1 km southwest of line through SP1 and SP3; Lassen Peak is 4 km west of main profile.

altered. Therefore we estimate that the Cascade volcanic rocks northwest of Lassen Peak are about 1.2–2 km thick.

In Figures 7a and 7b the 4.5- to 4.8-km/s layer overlies a 5.7- to 6.0-km/s (± 0.2 km/s) basement layer, which rises to within about 2 km of the surface under the northern shot point. Again we see no evidence for a low-velocity layer of Cretaceous sedimentary rocks between the volcanic rocks and the basement. The velocities at a depth of 1.8 km below sea level in the basement layer are slightly lower than those in the Sierra Nevada basement modeled at this depth to the southeast of Lassen Peak. We ended models northwest of Lassen Peak in basement at a depth of 3 km below sea level because seismic signals from rays that traveled through deeper layers disappear within 40–60 km of the shot points. We cannot determine whether the basement northwest of Lassen Peak is Sierran or whether the velocity inversion modeled to the

southeast continues under Lassen Peak and the northern shot point.

6. CONCLUSIONS

In this paper we have addressed the questions of the thickness of the Cascade volcanic rocks in the Lassen area, the composition of the basement beneath the volcanic rocks, and whether the Cretaceous sedimentary rocks exposed west of Lassen Peak underlie the volcanic rocks.

Interpretation of our two-dimensional velocity models indicates that the Cascade volcanic rocks are 1.2–4 km thick to the southeast of Lassen Peak and 1.2–2 km thick to the northwest, and have seismic velocities of about 1.5–5.55 km/s. Rocks at the surface have the lowest of these velocities (1.5–3.7 km/s), and the highest velocities in the volcanic rocks (5.35–5.55 km/s) occur at about 1.8 km below sea level, where the

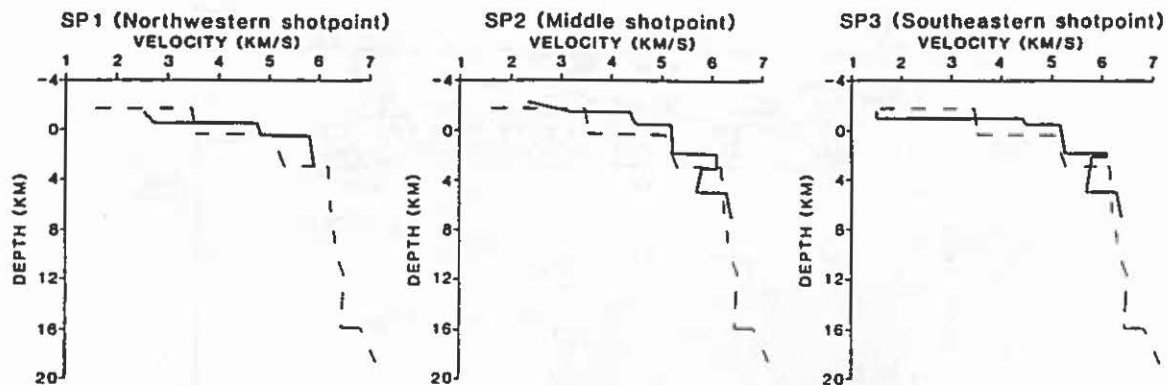


Fig. 8. Velocity-depth plots beneath each shot point as modeled in Figures 7a and 7b (solid curves) compared to velocity depth plots from models by Zucca et al. [1986] (dashed curves).

rocks probably are hydrothermally altered. We propose that Sierran basement (5.7–6.3 km/s) underlies the volcanic rocks at least as far northwest as Lassen Peak. The absence of low velocities (less than 3–4.5 km/s) deeper than 1 km above sea level in our models seems to indicate that Cretaceous sedimentary rocks do not overlie Sierran basement in the Lassen area. If a significant thickness (greater than 300 m) of these sedimentary rocks intersects the refraction profile at all, it would be found in the unreversed region northwest of the northern shot point.

The lateral resolution of the refraction model is about twice the station spacing, 3.0 km for the reversed sections of the main profile. An accumulation of magma at a depth shallower than 6 km below sea level would have to be larger than 3.0 km in diameter to be resolved by the refraction profile. The present velocity data do not detect a large upper-crustal magma chamber, although the velocity model does not continue to the 13-km depth where Eichelberger [1979] expected magma.

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