Bulletin of the Seismological Society of America, Vol. 72, No. 3, pp. 901-909, June 1982

A SEISMIC REFRACTION STUDY OF THE SANTA CLARA VALLEY AND SOUTHERN SANTA CRUZ MOUNTAINS, WEST-CENTRAL CALIFORNIA

BY WALTER D. MOONEY AND JAMES H. LUETGERT

ABSTRACT

Two seismic refraction profiles were recorded in the Santa Clara Valley region of central California to determine the upper crustal seismic velocity structure. A reversed, 8-km-long profile was recorded across the valley near Gilroy and an unreversed 38-km-long profile was recorded in the southern Santa Cruz Mountains. The data indicate that the valley is wedge-shaped in cross section with the basement dipping 10° to the east. The alluvial fill of the valley has a maximum thickness of 1.5 km and has an average compressional-wave velocity of 2.3 km/sec. The top of the basement has a velocity of 4.3 km/sec; the velocity reaches 6.0 km/sec at a depth of 2 km. The Calaveras fault zone, located due east of the valley, was crossed by a short, unreversed profile. It appears to be characterized by a low velocity (Vp = 2.7 km/sec) to a depth of ~2.5 km. The southern Santa Cruz Mountain profile indicates a 4.6-km/sec near-surface refractor and a layer with a velocity of 6.1 km/sec at 2-km depth. Thus, considered together, the similarity in velocity structure determined from the two profiles indicates that the Franciscan rocks of the Santa Cruz Mountains continue beneath the valley.

The presence of high compressional-wave velocities (≧6.0 km/sec) at 2-km depth in this Franciscan terrain can best be explained by an abundance of metabasalts (greenstones) at that depth. These seismic observations indicate that an area of at least 120 km^2 is underlain by this high velocity, basaltic material. Therefore, the upper crustal structure in the study area differs dramatically from the Franciscan terrain of the Diablo Range where greywackies and metagreywackies (Vp ≦ 5.4 km/sec) dominate in the uppermost crust.

INTRODUCTION

The Santa Clara Valley and the southern Santa Cruz mountains of west-central California were chosen as the site of a seismic refraction investigation in July 1980 for two reasons. First, the region is of considerable tectonic interest because it constitutes the inner part of the "Y" formed by the bifurcation of the San Andreas fault system south of Hollister (Figure 1). Thus, an understanding of the structure and subsurface composition of crustal materials in the region is important to the reconstruction of the Cenozoic tectonics of central California. Second, the region lies to the west of the portion of the Calaveras fault that ruptured in the magnitude 6.4 Coyote Lake earthquake in August 1979 (Lee *et al.*, 1979; Figure 1). Continuing investigations of foreshocks and aftershocks of that earthquake indicate strong lateral velocity variations in the epicentral region (Figure 1); we provide some details concerning those variations. In addition, five strong ground motion instruments located in the Santa Clara Valley near the city of Gilroy wrote records of the main shock and its aftershocks (Brady *et al.*, 1981). Preliminary interpretation of these accelerograms indicates that the velocity structure of the valley has a significant effect on the seismograms (Spudich and Angstman, 1980). We here describe the shallow structure of the valley in the vicinity of Gilroy, California.

Geologic Setting

The study area is centered around the Santa Clara Valley, which extends for about 60 km from San Jose southeast to Hollister. The valley is only 3 km wide south of San Jose and widens to about 15 km near Hollister. It is flanked to the east by the Diablo Range and to the west by the southern Santa Cruz Mountains, both areas in which late Mesozoic rocks of the Franciscan assemblage and Great Valley

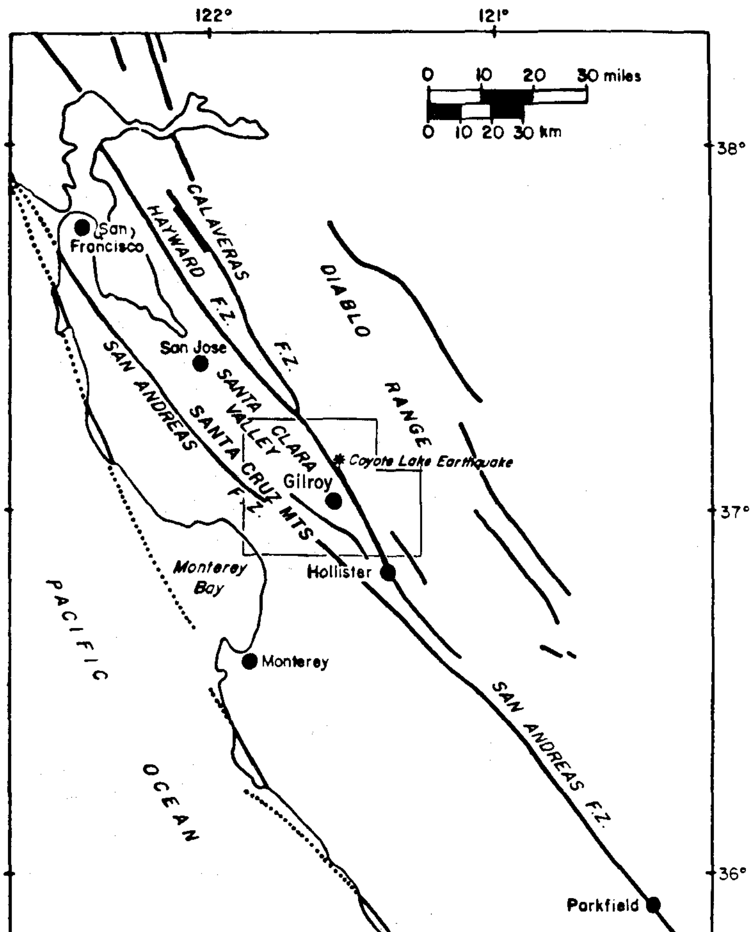

FIG. 1. Principle active faults and geologic regions of the San Francisco Bay region. Area of Figure 2 is in *box*. Coyote Lake earthquake of 6 August 1979, is indicated.

Sequence predominate (Figure 2). The Franciscan assemblage (Bailey *et al.*, 1964) consists mainly of sedimentary, metasedimentary, and altered basaltic rocks, and is largely structurally chaotic. The Great Valley Sequence consists of clastic sedimentary rocks with normal stratiform continuity. The transition from the alluvium of the Santa Clara Valley to the Franciscan rocks of the Diablo Range is through a sequence of Great Valley rocks (Figure 2) which are cut in the seismically active Calaveras fault (Bakun, 1980). Ultramafic and mafic rocks are locally prominent, especially in the Franciscan terrain of the Santa Cruz Mountains. Some of these igneous rocks may be highly dislocated parts of the Coast Range ophiolite (Bailey *et al.*, 1970) which, in normal regional sequence, separates Franciscan rocks from rocks of the overlying Great Valley Sequence. It will be shown here that a portion of the Franciscan terrane of the southern Santa Cruz Mountains has a compressional-wave velocity structure that differs from that previously determined (Stewart, 1968) for the Franciscan terrane of the Diablo Range.

Seismic Refraction Profiles

A northeast-southeast reversed refraction profile was conducted in July 1980 across the Santa Clara Vally south of Gilroy (profile 1NE and 2SW; Figure 2).

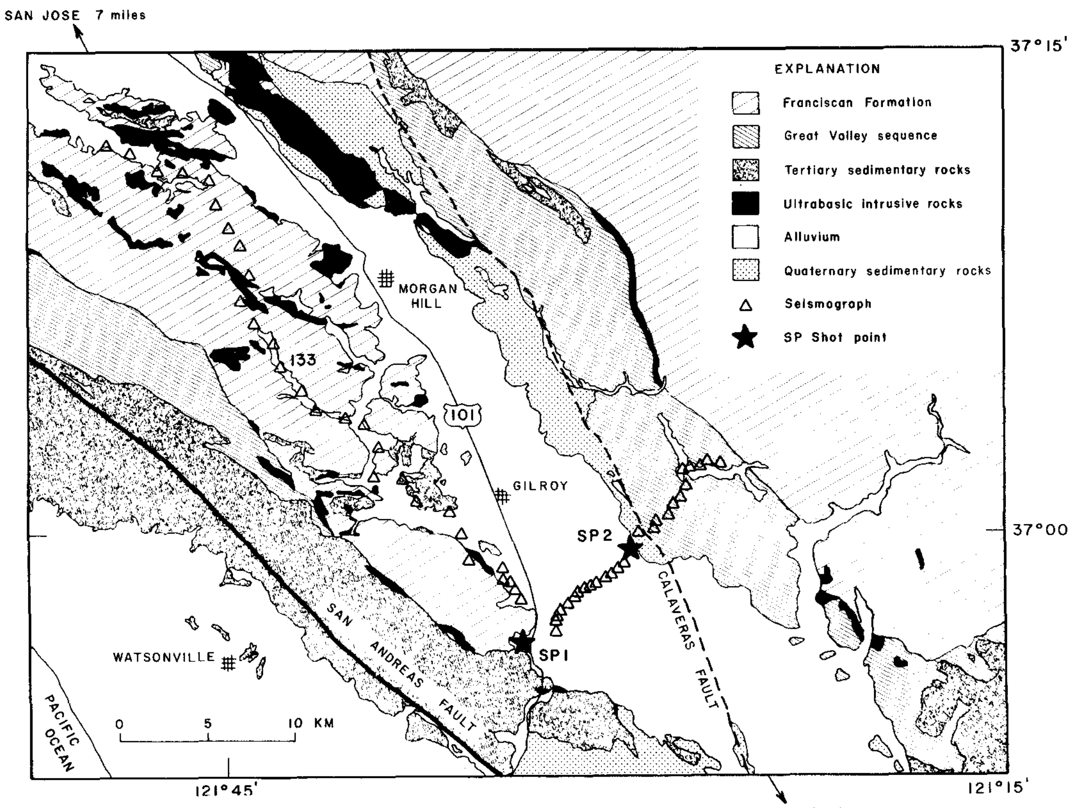

FIG. 2. Geologic map of the Santa Clara Valley and adjacent regions showing locations of shotpoints and portable seismograph stations. Geology simplified from Rogers (1966) and Jennings and Strand (1958).

Nomenclature of the profiles consists of the shotpoint number followed by the azimuth of the profile away from the shotpoint. Two shots were fired; the west shotpoint (SP1; 400 lb of ammonium nitrate) was drilled in alluvium and the underlying consolidated sedimentary rocks; the east shotpoint (SP2; 600 lb of ammonium nitrate) was drilled entirely in valley alluvium. Seismograph station spacing along the profile between the shotpoints was about 250 m. In addition, 11 stations were deployed to the east of SP2 at about 600 m-spacing (profile 2NE) with the easternmost station near the contact between the Great Valley Sequence and Franciscan assemblage (Figure 2). This portion of the profile was unreversed because a shotpoint permit was unobtainable for the east side of the Calaveras fault.

In addition to the profile across the valley, stations were deployed north of SP1 at about 1,000-m spacing along an unreversed northwest-trending profile in the southern Santa Cruz Mountains. These stations recorded both shots, providing a profile (1NW) with propagation paths strictly within the southern Santa Cruz Mountains and a second profile (2NW) with propagation paths within the basement of both the Santa Clara Valley and the southern Santa Cruz Mountains.

Data and Interpretation

The record sections for the five profiles (1NE, 2SW, 2NE, Figure 3; 1NW, 2NW, Figure 4) obtained from the two shots were used to determine the velocity structure

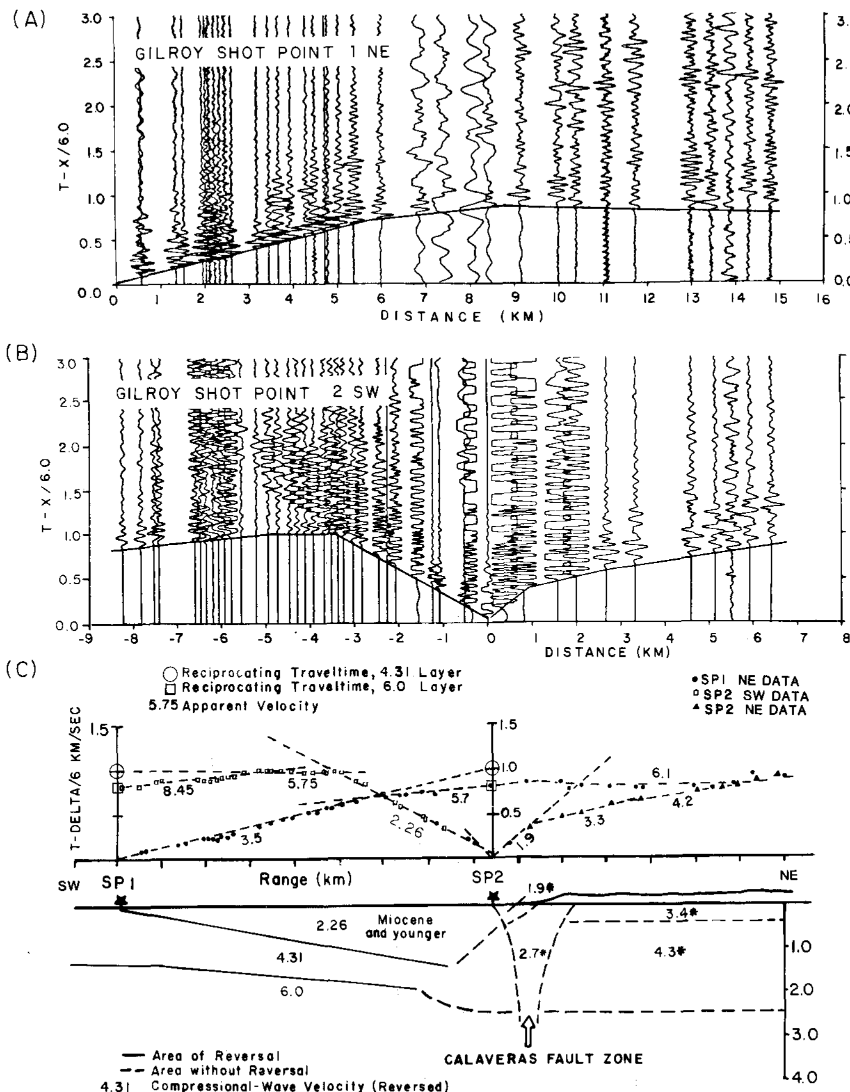

FIG. 3. Record sections (reduction velocity 6.0 km/sec) for profile 1NE (A) and 2SW and 2NE (B); reduced travel-time plot and velocity model crossing the Santa Clary Valley and Calaveras fault (C).

in and near the Santa Clara Valley. The analysis methods used were conventional travel-time solutions for reversing profiles checked by both computer ray tracing for refracted and reflected rays in laterally varying media and by graphical calculation of diffracted rays at structural discontinuities. The amplitudes of the arrivals have not been considered quantitatively in this study.

Valley Profiles. Traditional dipping-layer calculations were used to analyze the reversed profile 1NE–2SW. Profile 1NE shows apparent velocities of 3.51 and 5.71 km/sec and profile 2SW shows apparent velocities of 2.26, 5.75, and 8.45 km/sec (Figure 3); profile 1NE does not show arrivals through the sediments as first arrivals, so that profile has one less apparent velocity branch than profile 2SW. The apparent velocities and their intercept times are explained by a model consisting of three layers with compressional-wave velocities of 2.26, 4.3, and 6.0 km/sec (Figure 3) and by the wedging out of the sediments (Vp = 2.26 km/sec) from east to west. The

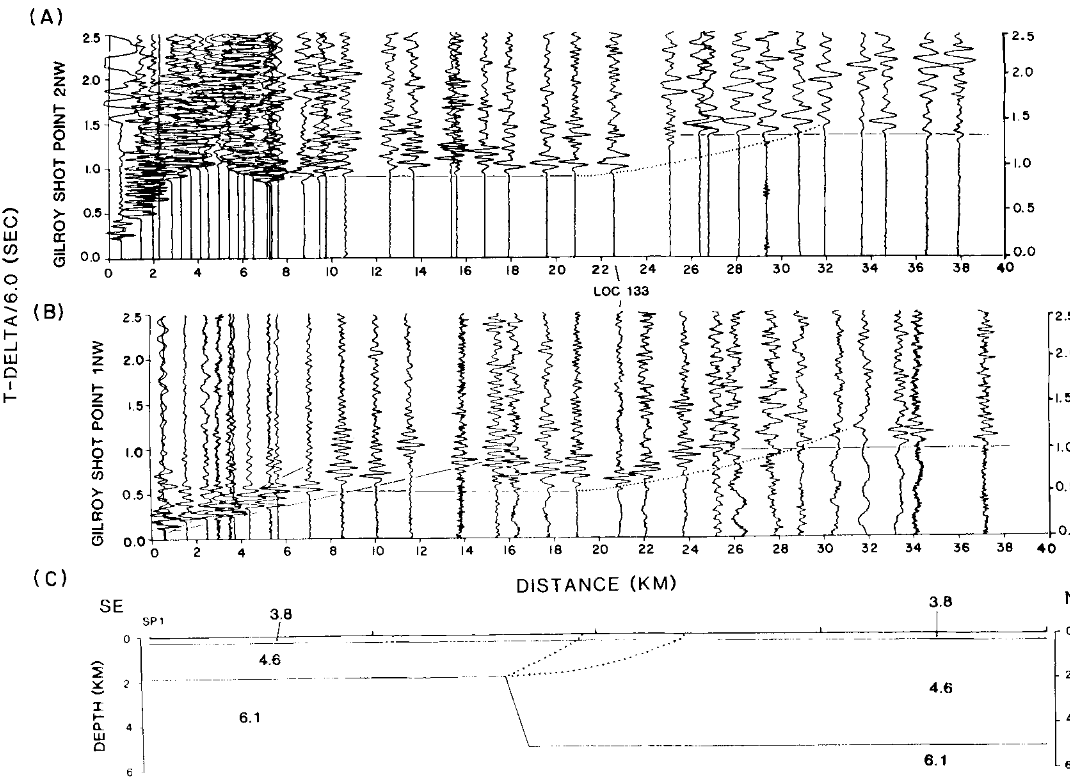

FIG. 4. Record sections (reduction velocity 6.0 km/sec) for profiles 2NW (A) and 1NW (B); velocity model for profile 1NW (C). Calculated travel-time curve on profile 1NW is for the velocity model (C); the same travel-time curve is shown on profile 2NW with a time shift of 0.37 sec and range shift of 1.6 km (see text). Dotted lines are diffracted travel times (B) and ray paths (C) off the fault scarp. Seismograph location 133 is indicated (see Figure 2).

wedge shape of the valley basin is responsible for the exceptionally high-apparent velocity (8.45 km/sec) observed for the refraction from the 6.0-km/sec medium on profile 2SW. We note that the interpretation of the valley as asymmetrical in cross section is supported by the asymmetry of the Bouguer gravity anomaly (Oliver *et al.*, 1981) and by data from a limited number of drill holes (W. Joyner, personal communication, 1981). The sediment-basement contact beneath the valley appears to be a seismic discontinuity. The first arrivals of profile 2SW abruptly change in apparent velocity from 2.26 to 5.75 km/sec at a range of 3.5 km, thus indicating a velocity discontinuity. In contrast, the transition from 4.3 to 6.0 km/sec may occur over a depth of several hundred meters. The first arrivals from these layers curve into one another more smoothly and there is no evidence of a secondary reflected phase from a seismic discontinuity in the 4- to 8-km distance range.

The region east of SP2 is of considerable interest because it crosses the Calaveras fault. Unfortunately, the present investigation does not adequately define the velocity structure there because it is an area of refraction overlap rather than reversal. It is, however, clear from the differing apparent velocities observed from the two shots that the arrivals in profile 1NE are propagating via a deeper, higher velocity layer (apparent velocity 6.1 km/sec) than those in profile 2NE (apparent velocity ~4.2 km/sec). Even more significantly, the first arrivals from SP1NE show a travel-time advance of only 0.1 sec upon leaving the Santa Clara Valley. If the approximately 1.3 km of valley sediments (Vp = 2.26 km/sec) terminated against typical near-surface Franciscan material (Vp = 4.3 km/sec), then a travel-time advance of 0.27 sec would occur. To match the observations, the valley alluvium must terminate near the low-velocity material within the Calaveras fault zone. Low-velocity zones ($Vp < 3.0$ km/sec) within active fault zones have previously been reported for the Calaveras fault (Mayer-Rosa, 1973) and San Andreas fault (Healy and Peake, 1975). In the present study, a velocity of 2.7 km/sec was found by iterative ray tracing to provide the best fit to the data (i.e., a velocity of 2.7 km/sec was not directly measured). In addition, because the inclusion in the model of this low-velocity material did not allow prediction of the travel times for profile 1NE, it was also necessary to deepen the 6.0-km/sec layer beneath SP2. However, specific details of the model in the region of the Calaveras fault are not uniquely determined by the data. For instance, the low-velocity material and the depth of the 6.0-km/sec layer may be traded off against one another. In addition, the 6.0-km/sec layer is shown as deepening east of SP2. The model is, of course, not unique; detailed reversed profiles are needed to provide further constraints.

Santa Cruz Mountain profiles. Profile 1NW shows details of the velocity structure of the southern Santa Cruz Mountains (Figure 4). SP1 produced impulsive first arrivals only to a distance of 25 km. This was sufficient, however, to define a flat-layer model of the upper three refractors of the southern Santa Cruz Mountains. Considering first the arrivals recorded to a range of 21 km, the model near SP1 consists of a 0.3-km-thick layer of 3.8-km/sec material overlying material with an apparent velocity of 4.6 ± 0.3 km/sec. Underlying the 4.6-km/sec material at a depth of 1.9 ± 0.2 km is a refractor having an apparent velocity of 6.1 ± 0.15 km/sec. The uncertainty in the velocity is due to scatter in first arrival times; this scatter is not surprising in light of the highly variable lithology along the profile (Dibblee, 1973). The apparent velocities and unreversed depth determinations are consistent with the true velocities and reversed depth determinations obtained for the Santa Clara Valley, which implies that the rocks of the southern Santa Cruz Mountains occur beneath the valley.

The arrivals beyond 21 km on profile 1NW can best be understood by considering first the data of profile 2NW, for which impulsive arrivals were obtained along the entire 38-km length (Figure 4) because of a higher shot efficiency at SP2. In particular, the high signal-to-noise ratio of profile 2NW helps clarify the travel-time behavior of the 6.1-km/sec arrival branch at the distant end of both profiles. Unlike profile 1NW, which is a nearly linear profile entirely within the Santa Cruz Mountains, profile 2NW has propagation paths crossing the Santa Clara Valley in a sweep of azimuths (Figure 2). In the record section (Figure 4) for profile 2NW, the records ranging from 0 to 7 km are selected from the previously described profile 2SW; those beyond 7 km are a fan spread and only at ranges greater than 20 km does the profile become more nearly linear. The records taken between the range of 10 and 23 km show an apparent velocity of 6.1 km/sec, approiximately equal to the 6.0-km/sec true velocity determined by the reversed valley profiles, as is expected, since these arrivals refract beneath the Santa Clara Valley. The most notable feature of profile 2NW is the approximate 0.45-sec travel-time delay in the 6.1-km/sec arrival branch occurring between 22 and 26 km. The same travel-time delay is observed on profile 1NW. To illustrate this, the travel-time curve of profile 2NW has been overlain on profile 1NW, with a time shift of 0.37 sec which is the difference in the travel-time down to the 6.1-km/sec refractor at the two shotpoints (c.f. Figure 3). In the absence of a reversed profile, we can only speculate as to the cause of this delay. For example, by considering it along with the 15- to 20-mgal decrease in Bouguer gravity which occurs at this range in profiles, we can postulate a model in which the 6.1-km/sec material is down-faulted to the north. Since the 6.1-km/sec material is modeled as being overlain with 4.6-km/sec material, the lower material must be down-faulted 3 km to give a 0.45-sec travel-time delay. Assuming densities of 2.5 and 2.7 gm/cm^3 for the 4.6- and 6.1-km/sec materials, respectively, a gravity decrease of (2.7 − 2.5 gm/cm^3) (3 km) (41 mgal-cm^3/gm-km) = 24.6 mgal is predicted by the model. This is reasonably close to the observed gravity decrease (Oliver *et al.*, 1981).

Discussion and Summary

The shallow compressional-wave velocity structure of the Santa Clara Valley consists of three materials with velocities of 2.26, 4.3, and 6.0 km/sec and that of the southern Santa Cruz Mountains of three media with velocities of 3.8, 4.6, and 6.1 km/sec. These compressional-wave velocities, when interpreted in the light of laboratory measurements of seismic velocities of rocks and descriptions of the local geology, can be used to infer the probable lithology of the subsurface rock units. The 2.26-km/sec velocity is typical for unconsolidated sediments which often have a near-surface velocity of 1.8 km/sec and a velocity gradient, due to compaction, of 0.7 km/sec/km (e.g., Fuis *et al.*, 1981). A sedimentary layer 1 km thick would have a velocity of 2.5 km/sec at its base and, thus, an average velocity of approximately 2.15 km/sec, which is close to the velocity cited here. The surficial 3.8-km/sec velocity in the Santa Cruz Mountains corresponds to the fractured near-surface of the Franciscan rocks. The 4.3- to 4.6-km/sec material found beneath both the mountains and the valley is typical of near-surface Franciscan rocks (Stewart, 1968; Stewart and Peselnick, 1978), but is atypical of Great Valley Sequence rocks which are of a lower velocity (Mooney and Walter, 1981). Thus, the eastward continuity from SP1 of the 4.3- to 4.6-km/sec material supports the postulated continuity of the Franciscan assemblage of the Santa Cruz Mountains beneath the Santa Clara Valley.

The identification of a velocity of 6.1 km/sec at about 2-km depth in the Franciscan terrane of the southern Santa Cruz Mountains distinguishes this area from a previously studied area of the Franciscan terrane in the Diablo Range, where a velocity of ~6.0 km/sec is not reached until 6.3-km depth (Stewart, 1968; Walter and Mooney, 1981). This striking difference can be explained by a comparison of the dominant rocks comprising the two terranes. The Franciscan terrane of the Diablo Range consists of 90 per cent sedimentary and metamorphic rocks and only 10 per cent altered basalt (greenstone), whereas the first 15 km of the profile in the southern Santa Cruz Mountains cross a region of greenstone outcrop (Dibblee, 1973). Laboratory velocity measurements of Franciscan sedimentary and low grade metamorphic rocks show most to be characterized by a velocity of 4.2 to 5.6 km/sec at low confining pressure, with the exception of metagreywackes containing jadeite which are characterized by a velocity of 5.5 to 6.2 km/sec at these pressures (Stewart and Peselnick, 1977, 1978; Lin and Wang, 1980). Laboratory velocity measurements for the greenstones of the Santa Cruz Mountains are not available in the literature; however, based on their petrologic descriptions (Bailey *et al.*, 1964), they are expected to have velocities similar to slightly metamorphosed oceanic basalts which have been measured in the laboratory (Salisbury and Christensen, 1978; Kern and Richter, 1979), *in situ* in the ocean (c.f. Spudich and Orcutt, 1980), and *in situ* on land in orogenic belts (Mooney *et al.*, 1979). These measurements indicate that a velocity of 5.8 to 6.3 km/sec is typical for Franciscan-type greenstones at low confining pressure (i.e., 2-km depth). Pending detailed petrologic and laboratory velocity studies of the greenstones and greywackes of the southern Santa Cruz Mountains, the 6.0- to 6.1-km/sec velocity at 2-km depth beneath both the Santa Clara Valley and the southern Santa Cruz Mountains is best attributed to an extensive greenstone body; based on the local geology (Dibblee, 1973), the presence of abundant jadeitized metagreywacke is a second, less likely, possibility. The amount of greenstone required to explain the seismic observations described here is at least 120 km^2.

In general, the study area is characterized by strong lateral variations in structure. The valley is wedge-shaped in cross section, with the basement dipping 10° to the east. The Calaveras fault zone is expressed as a 1-km-wide zone containing low-velocity material ($Vp \approx 2.7$ km/sec). In the southern Santa Cruz Mountains, the 6.1-km/sec basement layer appears to be down-faulted 3 km near latitude 37°05′ (16 km north of SP1). Continued geologic and geophysical studies are needed to futher describe and better understand the origin of these lateral variations in structure.

Acknowledgments

Field operations were planned and coordinated by V. D. Sutton, S. K. Gallanthine, L. R. Hoffman, W. J. Lutter, R. P. Meyer, Jr., J. N. Roloff, and S. S. Wegener assisted in recording the data and/or loading and shooting the shots. We appreciate numerous helpful discussions with W. P. Irwin and P. A. Spudich. R. M. Rebello typed and D. Kruger edited the manuscript.

References

Bailey, E. H., W. P. Irwin, and D. L. Jones (1964). Franciscan and related rocks, and their significance in the geology of western California, *Calif. Div. Mines and Geol. Bull.* **183,** 177.

Bailey, E. H., M. C. Blake, and D. L. Jones (1970). On-land Mesozoic oceanic crust in California Coast Ranges, *U.S. Geol. Surv. Profess. Paper 700-C,* C70–C81.

Bakun, W. H. (1980). Seismic activity on the southern Calaveras fault in central California, *Bull. Seism. Soc. Am.* **70,** 1181–1197.

Brady, A. G., P. N. Mork, V. Perez, and L. D. Porter (1981). Processed data from the Gilroy array and Coyote Creek records, Coyote Lake, California Earthquake 6 August, 1979, *U.S. Geol. Surv., Open-File Rept. 81-42,* 171 pp.

Dibblee, T. W., Jr. (1973). Geological maps of the Morgan Hill, Mt. Madonna, Mt. Sizer, Gilroy Hot Springs, and Gilroy quadrangles, California, *U.S. Geol. Surv., Open-File Maps,* 1:24,000.

Fuis, G. S., W. D. Mooney, J. H. Healy, G. A. McMechan, and W. J. Lutter (1981). Crustal structure of the Imperial Valley region, in *The Imperial Valley Earthquake of October 12, 1979,* C. E. Johnson, C. Rohan, and R. U. Sharp, Editors, *U.S. Geol. Surv. Profess. Paper.*

Healy, J. H. and L. G. Peake (1975). Seismic velocity structure along a section of the San Andreas fault near Bear Valley, California, *Bull. Seism. Soc. Am.* **65,** 1177–1197.

Jennings, C. W. and R. G. Strand (1958). Geologic map of California, Santa Cruz sheet, *Calif. Div. Mines and Geol.,* 1:250,000.

Kern, H. and A. Richter (1979). Compressional and shear wave velocities at high temperature and high confining pressure in basalts from the Faerol Islands, *Tectonophysics* **54,** 231–252.

Lee, W. H. K., D. G. Herd, V. Cagnetti, W. H. Bakun, and A. Rapport (1979). A preliminary study of the Coyote Lake earthquake of August 6, 1979, and its major aftershocks, *U.S. Geol. Surv., Open-File Rept. 79-1621*, 43 pp.

Lin, W. and C. Y. Wang (1980). Compressional-wave velocity in rocks at high pressure and temperature and the constitution of the central California crust, *Geophys. J.* **61,** 379–400.

Mayer-Rosa, D. (1973). Traveltime anomalies and distribution of earthquakes along the Calaveras fault zone, California, *Bull. Seism. Soc. Am.* **63,** 713–729.

Mooney, W. D., R. P. Meyer, J. P. Laurence, H. Meyer, and J. E. Ramírez (1979). Seismic refraction studies of the western Cordillera, Colombia, *Bull. Seism. Soc. Am.* **69,** 1745–1761.

Mooney, W. D. and A. W. Walter (1981). Seismic refraction studies in the Coast Ranges, central California (abstract), *Trans. Am. Geophys. Union* **62,** 328.

Oliver, H. W., R. H. Chapman, S. Biehler, S. L. Robbins, H. F. Hanna, A. Griscom, L. Beyer, and E. A. Silva (1981). Preliminary gravity map of California and its continental margin, *Calif. Div. Mines and Geol.*, 1:750,000.

Rogers, T. H. (1966). Geological map of California, San Jose sheet, *Calif. Div. Mines and Geol.*, 1:250,000.

Salisbury, M. H. and N. I. Christensen (1978). The seismic velocity structure of a traverse through the Bay of Islands Ophiolite Complex, Newfoundland, and exposure of oceanic crust and upper mantle, *J. Geophys. Res.* **83,** 805–817.

Spudich, P. A. and B. G. Angstman (1980). Lateral variations in velocity and Q structure in the region of the 1979 Coyote Lake, California earthquake (abstract), *Earthquake Notes* **50,** 64.

Spudich, P. A. and J. Orcutt (1980). A new look at the oceanic crust, *Rev. Geophys. Space Phys.* **18,** 627–645.

Stewart, R. and L. Peselnick (1977). Velocity of compressional waves in dry Franciscan rocks to 8 kilobars and 300°C, *J. Geophys. Res.* **82,** 2027–2039.

Stewart, R. and L. Peselnick (1978). Systematic behavior of compressional velocity in Franciscan rocks at high pressure and temperature, *J. Geophys. Res.* **83,** 831–839.

Stewart, S. W. (1968). Preliminary comparison of seismic traveltime and inferred crustal structure adjacent to the San Andreas fault in the Diablo and Gabilan Ranges of central California, in *Geological Problems of San Andreas Fault System Conf. Proc.* W. R. Dickinson, and A. Grantz, Editors, Stanford Univ., *Publ. Geol. Sci.* **11,** 218–230.

Walter, A. W. and W. D. Mooney (1981). Crustal structure of the Diablo and Gabilan Ranges, Central California: a reinterpretation of existing data (submitted for publication).

Office of Earthquake Studies
U.S. Geological Survey
Menlo Park, California (W.D.M.)

University of Wisconsin
Madison, Wisconsin (J.H.L.)

Manuscript received 9 July 1981