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## Title

## Lithospheric Structure, Seismicity, and Contemporary Deformation of the United States Cordillera

by

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# Lithospheric Structure, Seismicity, and Contemporary Deformation of the United States Cordillera

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## ABSTRACT

The structural evolution of the U.S. Cordillera has been influenced by a variety of tectonic mechanisms including passive margin rifting and sedimentation; arc volcanism; accretion of exotic terranes; intraplate magmatism; and folding and faulting associated with compression and extension -- processes that have profoundly influenced the lithospheric structure. As a result of this complex history, the Cordilleran crust is laterally inhomogeneous across its 2000 km east-west breadth. It is thin, < 25 km, along the West Coast where it has close oceanic affinities. The crust thickens eastward to ~ 50 km beneath the Sierra Nevada, then thins to 25 to 30 km beneath the Basin-Range. Crustal thickening to a depth of 40 to 50 km continues eastward beneath the Colorado Plateau, the Rocky Mountains, and the Great Plains. The total lithospheric thickness attains 65 km in the Basin-Range and increases eastward to > 80 km beneath the Colorado Plateau.

The upper-crust, including the crystalline basement of the Cordillera, has $P_g$ velocities of 6 km/s in the Basin-Range and Rio Grande Rift. Lower $P_g$ velocities of 5.4 to 5.7 km/s are associated with the youthful Yellowstone, Valles and Long Valley calderas and the Franciscan assemblage of the western coastal margin. Averaged crustal velocity reflects integrated tectonic evolution of the crust--thick silicic bodies, velocity reversals, and a thin crust produce low averaged velocities that are characteristic of a highly attenuated and thermally deformed crust. Averaged crustal velocities shows low values of < 6.2 km/s for the Basin-Range and the Rio Grande rift. Higher values, > 6.5 km/s, extend beneath the San fault system and the Columbia Plateau.

Zones of anomalously low velocity lower-crust, ~ 7.5 km/s, have been detected at the base of the crust beneath the Rio Grande rift, the eastern and western margins of the Basin-Range and the Columbia Plateau. These low velocity bodies are however, underlain by more normal, 7.9-8.0 km/s upper-mantle velocity material. The base of the crust is generally marked by upper-mantle velocities from 7.8 km/s to 8.4 km/s that extend beneath the Cordillera with a marked increase to the east.

The influence of large-scale crustal magmatism on lithospheric evolution is evident in the velocity structure of the Quaternary Yellowstone-Snake River Plain (Y-SRP) volcanic-tectonic system. Surface basalts thin northeastward from 1-2 km to zero thickness in concordance with a decrease in age of the silicic volcanics in a northeasterly direction up to 4 cm/yr. The upper-crustal silicic volcanics correspondingly thicken from 1 km at the southwest to 2 km beneath the Yellowstone Plateau. The normal Pg, 6.0 km/s upper-crustal velocity layer, of the Y-SRP system has been nearly destroyed by the volcanism, thermal and metamorphic processes. A high velocity layer, 6.5 km/s, not seen in other continental crustal sections, has been emplaced in the intermediate crust and is thought to represent a mafic residuum of the bi-modal silicic-basaltic volcanics. Beneath the Yellowstone, Long Valley and the Valles calderas small volumes of anomalously low P-wave velocities are thought to reflect upper-crustal layers that are consistent with partial melt.

Seismic reflection profiling for parts of the Cordillera has revealed the geometry and structural style of basins and faults. Low-angle thrusts and detachments are evident from the reflection data beneath central California and the eastern Great Basin. Across the central Cordillera reflection profiling, along a 40° N. transect by COCORP, demonstrates the presence of widespread upper-crustal, west-dipping structures in the eastern Basin-Range;

but low-angle structures become opaque or are not present beneath western Basin-Range and eastern California. The lower crust is best imaged across the central Basin-Range and reveals a horizontal fabric of refletions.

Seismicity of the Cordillera has been dominated by large earthquakes that accommodate the principal interplate motion along the San Andreas system, by subduction beneath the Pacific northwest, and by normal- and oblique-slip faulting in the Basin-Range. In the Basin-Range, large magnitude earthquakes, M7+, have occurred on 45° to 62° dipping planar normal faults that nucleated at mid- crustal depths of 10 to 16 km. Several reflection profiles in this region reveal Quaternary normal faults with shallow- to moderate-dip, planar and listric geometries that extend to shallow depths of 4 to 8 km in comparison to the steeper planar faulting associated with the large earthquakes--an intriguing paradox.

Contemporary deformation derived from seismic moment tensors of historic earthquakes, shows maximum values of ~ 55 mm/yr displacement along the San Andreas system, rates that are similar to a ~ 50 mm/yr convergent rate deduced for subduction along the Pacific Northwest margin. Basin-Range extension of 3 to 10 mm/yr, compares to a 7.5 mm/yr rate deduced from intraplate models constrained by satellite geodesy. These data demonstrate that interplate deformation of the Cordillera is occurring at rates of about one order of magnitude greater than that of the intraplate deformation.

# I. INTRODUCTION

The lithospheric structure, seismicity and contemporary tectonics of the western U.S. Cordillera (Figure 1) reflect a complex history associated with the evolution of the western border of North America. Initially, the continental margin deformed in response to Precambrian rifting that occurred west of the Wasatch line (Bond and others, 1985). During Paleozoic time the eastern margin of this rift complex formed the edge of a passive margin that was characterized by extensive marine transgressions and regressions. Accretion of exotic continental terrane in the western Cordillera in pre-Cenozoic time produced additional complexities in crustal structure.

FIGURE 1 HERE

At about 90 mya, accelerated E-W compression of the North American plate produced major thrust and fold belts that was accompanied by crustal intrusion and island-arc volcanism--fundamental mechanisms that formed tectonic welts and zones of weakness that influenced the lithospheric structure. Following a decrease in the plate-wide regime of compression, at 30 - 40 m.y. ago, the island-arc retreated westward. Transform faulting along the San Andreas system began to accommodate much of the interplate deformation by lateral slip that is now manifest by the occurrence of large earthquakes. Further north, subduction continued beneath the Pacific northwest margin. At about 30 m.y. ago, with the reduction of the compressive stress, intraplate extension of the Cordillera began to accommodate intraplate deformation by normal faulting in the Basin-Range province and the Rio Grande rift. Active earthquake belts now mark these regions of contemporary intraplate extension.

Scope--Many questions have been posed regarding the characteristics of the Cordillera lithosphere. For example what is the age and detailed structure of the Mohorovicic (Moho) discontinuity? Does an eastward dipping Benioff zone underlie the Pacific Northwest north of the Mendocino triple junction? What is the evidence for and the significance of velocity reversals in the crust? Are the low-velocity upper- and lower-crustal layers of the eastern Basin-Range products of crustal extension? How do the upper-mantle and lower-crustal low-velocity layers relate to contemporary tectonics? Does the contemporary deformation associated with historic earthquakes reliably account for all inter- and intra-plate motion? To what degree do wide-angle reflection/refraction measurements of lithospheric structure match those of vertical-incidence reflection data? While I will not entirely answer these important questions, I hope to provide some new data and ideas on their solutions, particularly as they pertain to the structure and evolution of the Cordillera lithosphere.

It is generally thought that the three-dimensional velocity structure of the crust and upper-mantle is related to surface tectonics, temperature and driving mechanisms. The composition, stress-state, and pore-fluids are the principal parameters that control the P- and S-wave velocity structure. These parameters are also important in understanding the regional seismicity and contemporary deformation. I will review the structure of the continental lithosphere, its seismicity and current state of deformation, and correlate the velocity structure to the regional tectonic patterns of the Cordillera.

Numerous papers in this volume, "The Cordilleran Orogeny: Conterminous U.S." provide the geologic history of this region and are recommended to the reader for background information. The volume also contains compilations of regional heat flow (plate X), magnetic (Plate X), gravity (Plate X), stress directions (Plate X), and topography (Plate X) that will be referred to as they relate to my discussions.

Area--The U.S. Cordillera, as used in this paper, corresponds to the area outlined by Burchfiel and others (1983) for the conterminous western U.S. interior (Figure 1). It includes the active interplate boundaries between the North American, Pacific, and Juan de Fuca plates (the San Andreas fault system and the subduction region of the Pacific Northwest); the volcanic provinces: Cascade Ranges, Columbia Plateau and Snake River Plain; the Coast Ranges and the Great Valley; the Sierra Nevada; the youthful extensional regime of the Basin-Range and Rio Grande rift; and the stable Colorado Plateau and Rocky Mountains.

Data Base--The generalized P-wave velocity structure of the Cordilleran lithosphere (maps of three-dimensional velocity layering) presented here were based upon a new compilation of seismic refraction profiles at the University of Utah. Two-dimensional cross-sections of lithospheric velocity structure, heat flow, Bouguer gravity and topography have been generalized from the Continental Transects profiles, C-1 and C-2 (Speed, this volume, 1986). Detailed information on upper-crustal structure: fault geometry, structural style of basin configurations, sedimentary layering, etc. was derived from vertical-incidence seismic reflection data.

FIGURE 2 HERE

The discussions of seismicity is intended to focus on the relationship between earthquakes and tectonics and not on earthquake hazards. Thus small to moderate magnitude events, particularly in areas of low seismicity, were considered important. Information on recurrence intervals, maximum magnitude estimates, effects of large events, etc. are not included.

Crustal deformation accompanying historic earthquakes was provided by the conversion of seismic moment to strain- and displacement-rates. Regional strain data were compiled from geodetic measurements. These data are synthesized to define the kinematics of the Cordillera.

## II. LITHOSPHERIC STRUCTURE

The term lithosphere is a definition based in a sometimes confusing way upon two connotations; 1) seismic velocity structure, and 2) mechanical properties. The mechanical origin relates to the developement of a brittle layer that rides passively upon a plastically deforming layer. In the seismic context, the base of the continental lithosphere was taken to be the top of the upper mantle, the top of the S-wave low-velocity zone.

In a more static sense, rheological models of the lithosphere define a brittle layer 7 to 15 km thick with strain rates of $10^{-13}$ $s^{-1}$ to $10^{-17}$ $s^{-1}$ and capable of sustaining shear stress (of order 10 to 100 bars) sufficient to generate earthquakes. Beneath this layer, a quasi-plastic layer reduces the shear stress. Hence this definition of the lithosphere defines a layer whose thickness is limited by the maximum depth of earthquakes rather than a definite velocity boundary. In general the mechanical, brittle layer corresponds to the upper few km of the crust--from the surface to the depth of maximum earthquake nucleation, 5 to 50 km, depending upon heat flow and composition.

In terms of a seismic velocity structure, the lithosphere includes the crust and the upper-mantle high velocity lid. The underlying upper-mantle low velocity layer is thought to mark the beginning of a ductilely deforming layer and hence the top of the aesthenosphere. In the Cordillera, the continental crust ranges in thickness from 25 km to 50 km and is underlain by an upper-mantle lid with velocities of 7.8 to 8.3 km/s.

The composition of the continental crust is considered to be primarily composed of metamorphic components subdivided into: 1) A surface sedimentary layer, zero to a few km thick; 2) A well defined upper-crustal layer, averaging 6 km/s that begins at the top of the "crystalline basement". This layer is sometimes referred to as the "granitic" layer but is more likely composed of supracrustal granites and granulites; 3) A poorly resolved intermediate layer of about 6.5 km/s thought to reflect a mixed migmatite layer; and 4) A well-defined lower layer, 6.7 km/s, with an intermediate composition more felsic than gabbro (Mueller, 1977).

## Refraction/Wide-angle Reflection and Vertical Incidence Reflection Methods

Crustal velocity structure has been determined primarily by the recording of seismic waves along refraction/wide-angle reflection profiles and at distances of hundreds of kilometers from explosive sources. These waves propagate along velocity-density boundaries generally as head waves and as wide-angle reflections. Because of the large horizontal offset between the source and receiver and the low-angle of incidence, these waves are sensitive to lateral velocity variations and hence to two-dimensional velocity structure. This technique has highest resolution of structures to a few km in scale. A typical upper-crustal velocity of 6 km/s, with a 1 hz to 10 hz dominant frequency, results in a horizontal resolution of 2 to 5 km and a vertical resolution of ~ 1 km (Thompson, 1984). However, because of the large horizontal dimension of the wide-angle ray paths compared to the vertical dimension, this technique averages or smears out small-scale structures and hence diminishes its resolution. For two-dimensional structural resolution, refraction profiles must have reversed ray-path coverage.

Vertical-incidence seismic reflection methods, pioneered by the oil industry, have been employed by universities in the last two decades for lithospheric exploration of the Cordillera. These techniques use vibratory or small explosions as a source with a short source-detector offset distance compared to the depth of penetration. The reflection technique gives increased spatial resolution, for example ~ 100's of m for a 5 hz to 50 hz dominant frequency (Thompson and others, 1984). However, it does not resolve velocity structure and does not provide the depth of penetration as well as the refraction method. Ideally the refraction technique, in combination with reflection profiling, provides the optimum method for lithospheric exploration.

For a general discussion of seismic methods used to explore the continental lithosphere the reader is referred the National Academy of Sciences report, Seismological Studies of the Continental Lithosphere (Thompson and others, 1984) and the Science Plan for PASSCAL, Program for Array Seismic Studies of the Continental Lithosphere the Integrated Institutes for Research in Seismology (1984).

Background Information--The Cordillera is one of the most seismically explored regions of the continent and numerous papers have been published on its lithospheric structure and seismicity. This paper presents a new compilation of refraction and reflection data (Figure 2) and synthesizes the relation between tectonics and structure as well as assessing the state of contemporary deformation of the Cordilleran lithosphere based upon seismicity and geodetic measurements.

For earlier descriptions of regional crustal structure of the western U.S. the reader is referred to the review papers of Pakiser (1963), Warren and Healy (1973), Hill (1978), Smith (1978), Prodehl (1979), Allenby and Schnetzler (1983) and Braile and others (1986). New data will be discussed that have been acquired since the late 1970's for the Yellowstone Snake River

Plain region, the Cascades, the Basin-Range, the Columbia Plateau, the Great Valley, the Coast Ranges, and the Imperial Valley, California.

I have used the original interpretations of the velocity models for the discussions here and assumed constant layer velocities and simple velocity gradient models (see Figure 2 for profile locations). In cases of overlapping refraction lines or differing interpretations of the same data by more than one author, we have chosen the interpretation that fit the above criteria. Because of the limited scope of this paper I will only show the results for the refraction-reflection profiles discussed. A detailed bibliography for these data is available on microfilm at the Geological Society of America office, Boulder, Colorado.

Reflection data have just become available in sufficient coverage to make tectonic-scale comparisons. Several detailed reflection profiles acquired by industry and universities in the Basin-Range and California will also be discussed. The COCORP 40° N. transect provided reconnaissance data across the western Colorado Plateau-Basin and Range-Sierra Nevada and gives a good summary of crustal structure from reflection data.

## Seismic Velocity Structure Of The Cordillera

<u>Upper-Crustal, $P_g$-Velocity Distribution</u>--The upper-crust (exclusive of the sedimentary layer) is characterized by a pervasive, continent-wide layer thought to represent the laterally-variable crystalline basement, supracrustal granites and granulites. This layer generates the classic $P_g$ branch. Figure 3 (all depths relative to sea level) shows the distribution of velocity layering for the upper-crustal layer from interpretations of $P_g$ phases, that

in most cases reveals a good correlation between velocity, young tectonics and heat flow (see Plate X, this volume, for a map of heat flow data). The velocity of this layer averages 6.0 km/s. It ranges from a low of 5.4 km/s at the volcanically youthful Yellowstone Plateau, with heat flow > 1500 $mWm^{-2}$; to highest values of 6.3 km/s beneath the Columbia Plateau, with a regional heat flow of 70 to 85 $mWm^{-2}$).

FIGURE 3 HERE

$P_g$ velocities are characteristically low, 5.9 to 6.0 km/s, beneath the tectonically active Basin-Range and Rio Grande rift, heat flow = 90 $mWm^{-2}$, increasing to 6.2 km/s beneath the stable Colorado Plateau, heat flow = 60 $mWm^{-2}$, and 6.1 km/s beneath the cool and stable Sierra Nevada, heat flow = 25 $mWm^{-2}$.

A notable feature of the upper-crust beneath the eastern Basin-Range is the developement of a low velocity layer at depths of 7 to 15 km (Mueller and Mueller, 1979; Keller and others, 1974; Smith and others, 1975). This layer represents a velocity reversal of up to 0.3 km/s that has been suggested to reflect the influence of high pore pressure, high temperature or a granitic intrusion (Smith and others, 1975). Gants and Smith (1983) have shown, from a combined interpretation of refraction data and reflection data, that this shallow low-velocity layer underlays the prominent Sevier Desert detachment and correlates with a rheologically modeled quasi-plastic layer. The seismic data are not sufficient to resolve the structure of this low-velocity layer in detail, but its spatial correlation with the detachment structure in an area of high heat flow, > 90 $mWm^{-2}$, suggests that it is related to the mechanism that is associated with this broad region of crustal extension of western Utah.

The $P_g$ distribution from a recent NE-SW refraction profile across the Columbia Plateau (Catchings, 1985), suggests that this volcanic region has a high velocity of 6.3 km/s. This layer is interpreted to represent thick Columbia Plateau, Eocene basalt flows that are underlain by extensive pre-Cenozoic sediments. The upper-crustal velocity decreases laterally to 6.1 km/s westward beneath the Cascade Range.

A notable upper-crustal boundary, coincident with the San Andreas fault, separates upper-crustal velocities of < 5.9 km/s to the east, in association with the Franciscan melange, to 6.1 km/s material to the west in the Salinian block. The Central Valley and Sierra Nevada are both underlain by 6.1 km/s material with associated low heat flow of ~ 63 $mWm^{-2}$. The tectonically stable and relatively cool Rocky Mountains, heat flow < 63 $mWm^{-2}$, show a range of 5.8 km/s to a 6.1 km/s in $P_g$ velocity. The lower values are associated with a shallow, crystalline basement high, the Sweetgrass Arch, in northern Montana.

The general association of low heat flow, < 90 $mWm^{-2}$, and pre-Cenozoic tectonism with $P_g$ velocities of 6.1 km/s or higher; and high heat-flow, > 90 $mWm^{-2}$, Cenozoic tectonism, with velocities of 6.0 km/s or less, shows the general correlation between seismic velocity and tectonics. While higher temperatures are erroneously considered an attractive mechanism for velocity reduction in silicic rocks, laboratory studies (Spencer and Nur, 1976) show that composition and pore pressure are the dominant parameters for velocity variation. Thus low $P_g$ velocities are probably influenced much more by excess pore fluids than temperature. However, anomalous pore fluids may be produced by high temperature metamorphism. For example, the Yellowstone caldera and its associated hydrothermal systems with $P_g$ velocities of 5.4 to 5.7 km/s, with extremely high heat flow > 1500 $mWm^{-2}$, argues for this mechanism.

Direct evidence for magmas in the upper-crust would be the reduction in $P_g$ velocities, but silicic and basaltic magmas or partial melts are probably of relatively small size (a few kilometers in spatial dimension) and their storage times in the upper crust are relatively short (Hildreth, 1981). Thus the likelihood of sampling them with the seismic refraction method is small. Low $P_g$ velocities of 5.4 to 5.7 km/s have been observed at the Yellowstone caldera (Smith and others, 1982); at the Long Valley, California caldera (Hill and others, 1985); and at the Valles, New Mexico caldera (Ankenny and others, 1986). These low velocities are the product of caldera-wide thermal and metamorphism, but in restricted areas low velocities are consistent with small bodies of partial melt. Little evidence was noted for the presence an upper-crustal magma chamber at Mt. St. Helens, either before or after the 1980 eruption.

Evidence from reflection data for crustal magma bodies is limited by its limited geographic coverage. But data has been from the Rio Grande rift where earthquake-generated reflections and reflection profiles have revealed a strong impedance boundary at 18 to 24 km depth that was interpreted to be the top of a magma body (Sanford and others, 1977; Brown and others, 1980).

Upper-Mantle, Pn-velocity Distribution--The upper-mantle, P-wave branch, $P_n$, marks the pervasive, Mohorovicic (Moho) discontinuity between the crust and mantle (Figure 4). Its presence is based upon the recognition of the refracted wave, $P_n$, the critically reflected wave, $P_mP$, and upon discontinuous, vertically-incident reflections. Seismic models of the crust-mantle boundary suggests that it ranges from a first-order velocity discontinuity, corresponding to an abrupt change in composition; to a second-order discontinuity a gradient or laminated zone 1 to 3 km thick. A laminated Moho structure suggests that it may be a mixed metamorphic zone with a variable composition and state.

FIGURE 4 HERE

The most conspicuous features of the $P_n$ distribution of the Cordillera are the anomalously low upper-mantle velocities of 7.4-7.5 km/s along the eastern and western margins of the Great Basin, the Rio Grande rift and beneath the Columbia Plateau. Note that these areas are in turn underlain by a deeper 7.9 km/s layer that I suggest to be a continuation of normal continental upper-mantle material.

Whether the 7.4 to 7.5 km/s low velocity layer represents an anomalously high velocity lower crust or a low-velocity upper-mantle (also see York and Helmberger, 1973) is a semantic argument. The importance of this low velocity layer is its composition and depth -- crustal granulites of this velocity are not in equilibrium and it likely represents a zone of partial melt. Loeb (1986) has mapped this anomalously low-velocity body in the eastern Basin-Range using time-term analyses from earthquake data. His interpretation shows that it extends 400 km N-S and 200-300 km E-W, coincident with the Intermountain Seismc Belt in Utah. This low-velocity body may be a tectonic "cushion" representing the source region or a residue of basaltic magmas that underlie the zones of active crustal extension, a zone of partial melt of silicic composition, or possible remnants of partially melted mantle.

The Sierra Nevada is characterized by higher values of 7.9 km/s upper-mantle $P_n$, with 8.0 km/s material beneath the Great Valley and Coast Ranges to the west. The Rocky Mountains and Colorado Plateau reflect an increase of 7.9 km/s upper-mantal increasing northeasterly to 8.4 km/s--toward older Precambrian basement.

Crustal Thickness--A map of total crustal thickness (or equivalently the depth to the top of the mantle) is shown in figure 5. This map of crustal thickness and others discussed are relative to a sea level datumn. The Basin-Range has a thin, 22-23 km crust along its eastern and western margins and a 34 km maximum depth near the center of the province. The crust of the eastern Basin-Range is further underlain by higher velocity (~ 7.9 km/s) upper-mantle material at depths of 40 km (Pechmann and others, 1984; Loeb, 1986). The crustal thicknesses of the Great Basin are similar to that of the 24 km for Columbia Plateau (Catchings, 1985) and the 26 km for Rio Grande rift (Olsen and others, 1986). Both show high velocity, 7.9 km/s upper mantle at depths of 40 km and 33 km, respectively, underlying the anomalously low velocity lower crust.

FIGURE 5 HERE

In comparison, the crustal thickness of the Cascade Ranges, 46 km, and the Sierra Nevada, 55 km, imply deeper roots. The Yellowstone-Snake River Plain volcanic province has a ~ 43 km thick crust, similar to the thermally undeformed crust of the Rocky Mountains. Thickening of the crust increases eastward, to 41 km for the Colorado Plateau, to 50 km for the middle Rocky Mountains, and 50 km for the northern Great Plains.

Averaged Crustal Velocities--The total crustal column is the integrated product of thermal, mechanical and metamorphic evolution of its original composition. To compare crustal evolution to tectonics, mean crustal velocities were determined (Figure 6) by averaging the upper-, intermediate- and lower-crustal layer velocities (comparable to interval velocities) weighted by their respective thicknesses. The sediment layer was found to be so laterally variable that it was omitted from the calculation.

FIGURE 6 HERE

Because the averaged crustal velocity reflects the evolution of the entire crust, it can be interpreted to estimate gross composition. Thick, low-velocity upper-crustal layers of silicic composition, velocity inversions, excess felsic lower-crustal constituents, and a thin lower crust decrease the average crustal velocity. Thus the crust effected by youthful tectonism, large components of silicic intrusives and high heat flow, generally corresponds to low averaged velocities. Greater quantities of mafic constituents, thin silicic upper-crustal layers, basaltic intrusives, and thin to absent lower crustal layers (akin to an oceanic crust) correspond to higher averaged velocities.

The distribution of average crustal velocity (Figure 6) portrays the close correspondence between average velocity and tectonics. The eastern Basin-Range is characterized by a pronounced low of 6.0 km/s interpreted to be due to the thin crust, the presence of upper-crustal low velocity zones, a generally low $P_g$ velocity, and a thin lower-crust. The average velocity increases westward to 6.2 km/s, similar to that of the Rio Grande rift. Thus low average-crustal velocities characterize these tectonically active and high heat flow regions of intraplate extension.

The Columbia Plateau, with relatively high averaged values of 6.4 to 6.5 km/s, is thought to represent a more mafic upper-crust and a thin lower-crust in the vicinity of an early Tertiary graben (Catchings, 1985). However a notable 6.2 km/s low in northern Idaho corresponds to the Kettle Dome and a region of Belt age, Precambrian basement.

The southern Basin-Range values of 6.2 km/s grade increase northwesterly to a zone of high average-velocity, 6.5 km/s, beneath the Pacific border of California. This change may reflect the gross composition of a more mafic crust with oceanic affinities.

For the stable High Plains and the Rocky Mountains, a northeast increase of the average-crustal-velocity correlates with the direction of crustal thickening and suggests that the ancient Precambrian crust of this region has imprinted the entire Paleozoic and Mesozoic evolution of the stable interior.

## Lithospheric Cross Sections

Two east-west cross sections of the Cordilleran lithosphere show the relationship between surface geology, seismic velocity structure, Bouguer gravity and heat flow. These sections were generalized from detailed profiles and maps of geological and geophysical information compiled by authors of the Continental Transects (see Speed, 1986, this volume). The northern profile, Figure 7, corresponds to Continental Transect C-1 (Blake, 1986) and the southern profile, Figure 8, corresponds to Continental Transect C-2 (Saleeby, 1986). Also see the Bouguer gravity, magnetic anomaly and topography of the Cordillera in this volume (Plates, X, XX, XXX).

FIGURE 7 HERE

FIGURE 8 HERE

Northern Profile--The northern profile (Figure 7) begins at the west, near the Pacific-North American plate boundary in northern California where eastward subduction of the Gorda plate is responsible for a regional, eastward-decreasing, gravity gradient near the northern termination of the San Andreas Fault. High velocity lower-crust and upper-mantle material underlie the Coast Ranges and Great Valley in low heat flow areas. The root of the northern Sierra Nevada extends to about 40 km but is not well resolved here because of lack of seismic measurements.

The transition into the northern Basin-Range is marked by an abrupt decrease in crustal thickness, to 24 km; by the termination of the regional gravity gradient; and by a marked increase in heat flow to values in excess of 100 $mWm^{-2}$ in the Battle Mountain area of northern Nevada. The Moho deepens beneath the central Basin-Range, where regional heat flow decreases easterly, then shallows beneath northwestern Utah, to 24 km, beneath the Wasatch Front. If the trend of the 7.9 km/s layer recently identified along the Wasatch Front by Pechmann and others (1985) and Loeb (1986) marks the classic Moho, then the crust must begin to thicken west of the Wasatch Front. The Moho continues eastward at 40 km depth beneath the Wyoming Basin.

The broad gravity high associated with the eastern Basin-Range is thought to reflect the presence of a shallow, high-density mantle. The shallow upper-mantle correlates with the belt of active extension of the Great Salt Lake Desert, the seismicity of the Wasatch Front and the 7.5 km/s low velocity lower crust. This lower crustal, low-velocity body may reflect a buoyant mantle bulge, an upwelling limb of a convection cell, a zone of mantle underplating or a partial melt of original crust--all related to mechanisms consistent with intraplate extension.

Determinations of the thickness of the lithosphere in the Cordillera are poorly constrained. On the basis of surface-wave measurements of S-waves, Priestley and others (1980) shows that in the northern Basin-Range the lithosphere is 60 km thick with a poorly resolved high-velocity lid. Uppermost mantle velocities are relatively low beneath this region and may reflect some degree of partial melt.

Southern Profile--The lithospheric structure of central California, the central Basin-Range, and the western Colorado Plateau are seen in the east-west profile (Figure 8). The San Andreas fault separates high velocity material in the Salinian block, to the west, from the Franciscan melange, to the east, with a shallow, 25 km deep Moho. The Moho then deepens to, > 50 km, beneath the Sierra Nevada at its greatest depth where it is associated with 7.8 - 7.9 km/s upper-mantle material.

The Moho rapidly decreases in depth to less than 25 km at the eastern Sierra Nevada Front. Here the regional gravity field is reduced to 240 mGal and the heat flow increases to more typical Basin-Range values of 90 $mWm^{-2}$.

The Moho deepens to about 30 km beneath the central Basin-Range then shallows to 24 km beneath the Sevier Desert in western Utah. The upper-crust of western Utah has a well defined velocity reversal at depths of 7-10 km, near the depth of the Sevier Desert detachment. This region also corresponds to high heat flow, a regional gravity high and low velocity lower-crustal material, 7.5 km/s--all parameters consistent with an extending lithosphere.

Eastward beneath the Wasatch Plateau, the Moho deepens to 40-45 km beneath the Basin and Range-Colorado Plateau transition. Here the lower-crustal, low velocity layer of 7.4 km/s coincides with the transition. The Moho continues at 40 km beneath the Colorado Plateau.

A notable gravity high, that decreases in magnitude beneath the western Wasatch Plateau, may reflect a mantle wedge associated with active extension in the transition (Zoback and Lachenbruch, 1985) or an eastward dipping fault that cuts the entire crust (Wernicke, 1981). The high heat flow and anomalously lower crust low upper-mantle velocities are coincident with lithospheric extension in this transition region.

On the basis of surface wave analysis the lithosphere has a total thickness of 65 km in the central Basin-Range with a high-velocity 7.8-7.9 velocity lid (Priestly and others, 1980). It thickens to > 80 km beneath the Colorado Plateau, suggesting that these major tectonic provinces are influenced by deep asthenospheric mechanisms.

Yellowstone-Snake River Plain (Y-SRP) Province--The Late Cenozoic history of the Cordillera is punctuated by an important volcano-tectonic event, the developement of a major bi-modal silicic-basaltic volcanic sequence that was initiated at about -18 m.y. ago near southwestern Idaho. Centers of the silicic volcanism progressed northeasterly at a rate of 3 to 4 cm/yr (Armstrong et. al., 1975) for at least 800 km in a northeast direction along the Snake River valley of Idaho to its present position at the Yellowstone Plateau (Smith and Christiansen, 1980). The progression of this silicic volcanism is in the opposite direction as the motion of the North American plate across an upper-mantle source of the volcanism and heat, as a propagating lithospheric fracture, or a transform fault.

At the Yellowstone Plateau up to 6500 cubic km of silicic volcanic material has been expelled in the last 2 m.y. Plate X of this volume shows the marked topographic increases in elevation of the Snake River Plain toward Yellowstone that Brott and others (1981) and Braile and Smith (1986) interpret as systematic subsidence produced from cooling of the lithosphere upon passage of a thermal-tectonic event--the passage of the Yellowstone hot spot.

Volcanism along the Yellowstone-Snake River Plain (Y-SRP) trend is expected to have a profound influence upon the lithosphere. In a major seismic refraction experiment in 1978 and 1980, Braile and others (1982) and Smith and others (1982) describe several transverse and longitudinal reversed refraction profiles recorded across the Y-SRP from explosive sources. Their generalized results (Figure 9) demonstrate systematic variations in crustal thickness and velocity coincident with the direction of volcanic transgression of the Y-SRP silicic volcanic sequence.

FIGURE 9 HERE

The surface basalt layer thins from about 1 km near Boise to zero at Yellowstone (Figure 9). An upper-crustal layer with velocities of 4.9 to 5.4 km/s, beneath the basalt, is interpreted to be silicic volcanic material that thickens markedly toward Yellowstone. The characteristic upper-crustal "granitic" layer of 6 km/s is noticeably thin to absent beneath the entire Y-SRP and is thought to have been consumed and transformed by melting during passage of the thermal event that formed the Y-SRP.

The upper-crust of Yellowstone has a major low velocity body of 5.4 to 5.7 km/s that extends from 2 km to about 10 km depth and roughly coincides with the Yellowstone caldera (Smith and Braile, 1986). Within the caldera-wide low-velocity body, an additional very low-velocity body, 4.8 to 5.4 km/s, at the northeast of Yellowstone Plateau is thought to reflect an anomalous upper-crustal body that could range in composition and state from a zone of high volume pore-fluids to a 50 percent silicic partial melt -- the only distinct evidence for a crustal magma body beneath Yellowstone.

The intermediate crust of the Y-SRP has a pronounced high velocity layer, 6.5 to 6.6 km/s, that is not otherwise well observed on the U.S. continent. This layer is thought to be a remnant of a mafic extinct magma chamber, of the bi-modal silicic-basaltic volcanism. The lower crust of Yellowstone is however seismically homogeneous compared to surrounding thermally undeformed crust and suggests that it was seismically unaffected by penetration of basaltic mantle magmas. Iyer and others (1981) show an additional -10% velocity decrease in the upper-mantle beneath Yellowstone that may extend to depths of 250 km. This deep lithosphere anomaly may be interpreted as partial basaltic melt that has been the parental source of the Y-SRP volcanism and heat.

The lithospheric structure of the Y-SRP system thus suggests a model for thermal and metamorphic evolution of the continental crust. During passage of the transient thermal source, low-density mantle basaltic magmas penetrate the crust. Partial-melting and assimilation of silicic components in the intermediate and upper crust produces the rhyolitic magmas leaving a dense residual mafic body at intermediate-crustal depths. The rhyolitic magmas ascend through the upper-crust and are explosively erupted to form the large silicic calderas. Residual silicic magmas then solidify except for small pockets of partial melts.

## Crustal Structure From Reflection Data

The detailed structure of the crust is best resolved by the seismic reflection method where vertically-incident rays with high ray-path multiplicity (stacking) image the vertical structure at highest resolution of tenths of kms. This technique has been applied by the oil industry for decades but because of its high cost and equipment intensive requirements, applications to lithosphere exploration have been limited. The oil industry has acquired thousands of kilometers of data throughout the Cordillera and have been helpful by releasing some of their non-proprietary data to Universities for research.

In the past decade, Universities (for example Allmendinger and others, 1983; Smith and Bruhn, 1984) and the U.S.G.S. (Anderson and others, 1983; Zoback and Wentworth, 1986) have used reflection data to elucidate detailed crustal structure and geometry of the Cordillera. COCORP recently completed a major E-W traverse of the Sierra Nevada-Basin-Range-Colorado Plateau that provides province-wide comparative reflection data (Allmendinger and others, 1986). In this section I will review the evidence for the structural style and geometry of the crustal layering mapped by the reflection method and comment on its resolution and limitations.

Upper-Crustal Structure--The seismic reflection method is primarily used to map the upper-crust and has been effective to depths of 10 to 20 km. In this depth range, sedimentary layering and faults and are resolvable at scales of the same structures mapped on the surface. The principal limitation to the method is the lack of velocity information necessary to deduce compositions and the presence of complicated ray path geometries that are difficult to migrate into their correct spatial coordinates. As a result, most reflection data are displayed as travel-time versus distance sections and are not geologic cross- sections in true depth. Thus reflection profiles must be interpreted with caution and with an understanding of the process that produced the data. Ideally the reflection and refraction data should be interpreted together; using refraction data for gross structure and velocity control that can be applied to processing the reflection data in order to place it at its proper depth-distance location (migration) for geologic interpretation.

Limited reflection data are available for the Cordillera but are sufficient to assess the form and extent of some sedimentary basins and faults. For example, Zoback and Wentworth (1986) show excellent reflection data beneath the west side of the Great Valley, California that reveal a westward directed up-thrust. The Coast Range appears to be underlain by a low-angle thrust and a wedge of Franciscan rock that is interpreted to have been emplaced eastward onto the continental margin. Along the east side of the Great Valley midcrustal reflectors dip westward and may relate to a deeper thrust with eastward up-thrusting motion. These interpretations suggest an important tectonic origin for the Great Valley--the influence of low-angle thrust tectonics not originally considered on the basis of surface geology.

Several examples of reflection data across Cenozoic normal faults in the Basin-Range reveal structural styles much different than inferred from the surface geology. Zoback and Anderson (1983) interpret three modes of extensional deformation for the central Basin-Range from reflection profiles: 1) simple asymmetric sags bounded by 60° dipping normal faults, 2) tilted ramps associated with moderately to deeply penetrating listric normal faults, and 3) assemblages of complexly deformed subbasins associated with both planar and listric normal faults that sole into a low-angle detachment.

In the Dixie Valley, Nevada (location shown in Figure 1), Okaya and Thompson (1985) interpreted a west dipping, asymmetric, sediment filled valley from reflection data. These data are interpreted to show a 62° eastward dipping planar fault (Figure 10a) on the west side of the valley, near the site of the 1954, M7.1 Dixie Valley earthquake.

FIGURE 10 HERE

In northern Nevada, Smith and Smith (1984) have reprocessed and modeled reflection data from the valley adjacent to the west side of the Ruby Mountains. Their data reveal a listric normal fault, dipping 40° west, near the surface, but shallowing to less than 10° at 4 km beneath a Paleozoic-Cenozoic sediment filled asymmetric basin. This structure is notable because the surface manifestation of the fault is a 70° dipping Quaternary scarp in unconsolidated alluvium and adjacent to low-angle, west-dipping normal faults of Tertiary origin within the Ruby Range core complex. Several other reflection profiles for eastern Nevada (Effimoff and Pinezich, 1981) show a range of listric to planar normal faults dipping from 60° to 40° and generally bounding asymmetric sedimentary basins.

High quality reflection data for eastern Basin-Range normal faults are shown by Smith and Bruhn (1984) have a range of listric to planar geometries. Figure 10b is an east-west profile (see Figure 1 for location) across the Great Salt Lake that demonstrates the asymmetric geometry of the lake-basin sediments truncated against a west dipping listric fault. Near the surface, the fault dips ~55° but decreases to 4° at a depth of 3.5 km beneath the basin.

The Sevier Desert detachment, western Utah, was defined by the reflection method (McDonald, 1976; Allmendinger and others, 1983; Smith and Bruhn, 1984). The data reveal a 5° to 12° west-dipping reflector that begins near-suface on the west flank of the Canyon Range and extends to depths of 15 km at a distance of over 150 km to the west. Smith and Bruhn (1984) show that this structure extends beneath most of the western Utah region--an area of maximum Cenozoic extension. Whether the detachment is a reactivated thrust or a youthful normal fault is not resolved, but the stratigraphic displacement of the fault in a normal fault sense, may be as great as 60 km (Allmendinger and others, 1983).

Overall, the reflection data for the central Cordillera reveal a persistence of 40° to 60° dipping normal faults with both planar to listric geometries. Some of these faults are in turn underlain by deeper sub-horizontal detachments that are particularly evident beneath the eastern Basin-Range. Some of the normal faults are located near pre-existing thrusts suggesting reactivation of the ancient structures. However arguments for and against this mechanism (Wernicke and Burchfiel, 1982; Allmendinger and others, 1983) shows that this problem has not been resolved.

<u>Lower Crustal Structure</u>--Reflection data acquired by industry (Smith and Bruhn, 1984; Zoback and Wentworth, 1985) and COCORP (Allmendinger and others, 1983; Klemperer and others, 1986) have revealed the presence of intermediate-crustal detachments, thrusts, pervasive sub-horizontal lower crustal layering, and Moho reflections. In a review of the COCORP 40° North transect, from the Colorado Plateau to the Sierra Nevada, Allmendinger and others (1985) define

prominent features of the entire crust revealed by the reflection method: 1) complex dipping reflections and diffractions, as deep as 48 km, beneath the western Colorado Plateau and Sierra Nevada; 2) the asymmetry of seismic fabrics in the Basin-Range, with W-dipping reflections in the eastern part of the province and sub-horizontal reflections in the west; and 3) a discontinuous Moho reflector at 30 $\pm$ 2 km in the Basin-Range (Figure 11).

FIGURE 11 HERE

# III. SEISMICITY

The U.S. Cordillera is a complex and active tectonic regime: eastward subduction beneath the Pacific Northwest; left-slip transform motion along the San Andreas system, and extension within its interior--processes that are associated with brittle failure in the upper lithosphere in the form of earthquakes. Bolt (1979) has tabulated the occurrence of large earthquakes for the Cordillera and shows that since the early 1900's, when accurate historic data began to be kept, that one M > 8, ten M > 7, and fifty-seven M > 6 earthquakes have occurred in the Cordillera. As many as eleven, M > 7 earthquakes occurred from 1800 to 1900 but are not accurately documented.

A perspective of the temporal sequence of the large earthquakes in the Cordillera is given in Figure 12 where the occurrence of large earthquakes is plotted versus time and by tectonic province. These data portray the rather continuous occurrence of large earthquakes associated with the San Andreas system, also but point out the occurrence of three large extensional and two subduction related events in the past four decades.

FIGURE 12 HERE

General Seismicity--To portray the historic seismicity of the Cordillera, post 1960 for network data and post 1900 for large events, a new epicenter map has been produced for this volume (Figure 13 and Plate X). The map was constructed by plotting events of magnitudes greater then 4 for the San Andreas fault system and greater than 3 for the remaining area. Computerized tabulations of regional seismographic network data (described by Eddington and others, 1986) from Washington, California, Nevada, Utah, and Montana were supplemented by the National Earthquake Information Service historic catalog for the intraplate Cordillera.

FIGURE 13 HERE

Discussions of the seismicity of the U.S. Cordillera were summarized by Hill (1978) and Smith (1978) and their observations and conclusions remain valid. A summary of the long-term characteristics of the seismicity relevant to the structure of the lithosphere and tectonics relations can be seen by comparing the epicenter map (Figure 13) with the crustal structure (Figures 3, 4, 5, 6) and are summarized as follows:

1. The deformation of the main plate boundaries is not confined to a single through-going fault, rather it is distributed in a zone up to 100 km wide on either side of the major branches of the San Andreas system (Hill, 1978). This pattern is particularly apparent between the Transverse Ranges and the Salton Trough. Active subduction beneath the Pacific Northwest is manifest by a 200 km wide zone of earthquakes north of Cape Mendodcino and from the Puget Sound to Vancouver Island, but with a gap between northern California and southern Washington.

2. Intraplate earthquakes are more diffuse with broad zones of up to 200 km wide around the margins of the Basin-Range-- along the Sierra Front, the central Nevada seismic belt, and the Intermountain Seismic Belt (Smith and Sbar, 1974; Smith, 1978). Epicenters are scattered

and when accurately located with detailed portable network surveys do not coincide with Cenozoic faults. Listric and low- to moderate-dip normal faults as revealed by reflection data are present beneath the Basin-Range, however, seismic slip predominates on fault segments of > 30°, to > 60° dip for small to moderate sized earthquakes (Arabasz and Julander, 1986) in the Basin-Range.

Three large magnitude, normal fault events (Figure 14), the M7.1, 1954, Dixie Valley, Nevada; the M7.5, 1959, Hebgen Lake, Montana; and the M7.3, 1983, Borah Peak, Idaho earthquakes nucleated at mid-crustal depths of 10 to 15 km, on 48° to 62° dipping, planar faults (Smith and Richins, 1984). This planar geometry is distinctly different from the shallow planar and listric faulting observed on reflection profiles discussed above.

FIGURE 14 HERE

3. Temporal variations of large intraplate Cordillean earthquakes associated with extension suggest return rates of several hundreds to thousands of years for M>7+ events as compared to tens to hundreds of years for large events on the San Andreas system (Schwartz and Coppersmith, 1984).

4. The maximum magnitude event for the San Andreas system is 8.5 compared to 7.5 for the intraplate regimes and may be as high as 8+ for the subduction zone beneath the Pacific Northwest (Heaton and Kanamori, 1984).

<u>Focal Depths</u>--Hypocenters map the shape and depth of active seismic zones and provide thickness estimates of the mechanically brittle lithosphere. In the past decade sufficiently accurate hypocenter data have been acquired, primarily by regional and portable seismic networks, to make useful meaningful cross-sections for tectonic considerations.

Figure 15 shows two east-west hypocenter cross-sections across the Pacific Northwest subduction zone; 1) across western Washington, Puget Sound and the Olympic Range (from Taber and Smith, 1985); and 2) across the Pacific Coast in northern California (from Cockerham, 1984). These data demonstrate the presence of shallow, eastward dipping Benioff zones associated with active subduction of the Juan de Fuca and Gorda plates.

FIGURE 15 HERE

The 11° eastward-dipping hypocenter zone beneath Washington is 10 km thick and extends 150 km inland. It is characterized by normal fault mechanisms that are interpreted as accommodating extension in the upper part of subducting oceanic lithosphere. The northern California zone also dips 11° east for a length of 120 km then steepens to 25 degrees. Focal mechanisms here are also consistent with downdip tension and imply that the earthquakes are occurring in the subducting oceanic slab.

Focal depths along the San Andreas are summarized by Sibson (1982) and show that the majority of hypocenters are confined to the top 12 km of the lithosphere. Ellsworth's (1975) and Lindh and Boore's (1981) cross-sections of hypocenters the San Andreas fault in central California suggest strong space-time variations in earthquake nucleation, controlled by fault zone asperities and variations in displacement rates. The maximum depth of earthquakes is considered to be controlled by a change in rheological properties of the lithosphere--a transition from brittle to quasi-plastic creep (Sibson, 1982).

Smith and Bruhn (1984) hypothesized a rheological model of the western U.S. (Figure 16) where the maximum depth of earthquakes, especially those in an extensional regime where the principal stress is vertical, correlated with about the 80 percentile of numbers of events (also see Sibson, 1982). This depth matched qualitatively the theoretically derived transition to ductile flow and the depth of maximum shear stress (Figure 14). However, the three large, M>7, normal faulting earthquakes of the Basin-Range (discussed above) nucleated at mid-crustal depths, 12 to 15 km--deeper than the theoretical shear stress peak. This suggests a model in which large normal faulting events may occur where large strain rates, $\sim 10^{-4}$ $s^{-1}$, are necessary to fracture the more ductile material. Large earthquakes of this magnitude are interpreted to be associated with faults that propagate upward from the top of the ductile layer and penetrate the passive brittle layer completely through to the surface.

FIGURE 16 HERE

# IV. CONTEMPORARY DEFORMATION

Deformation of the lithosphere is accommodated by two mechanisms: brittle failure associated with elastic strain release and ductile flow associated with creep and plasticity. Fault plane solutions and slip data from active faults provide the sources of information on the directions of the principal stresses related to brittle deformation for the Cordillera (Smith, 1978; Zoback and Zoback, 1980). Trilateration, triangulation, leveling surveys (Savage, 1983) and satellite geodetic measurements provide estimates of strain associated with the total brittle and ductile contribution of deformation. For this volume a compilation of stress data for the Cordillera has been prepared by Zoback and others (1986) including focal mechanisms, fault slip, wellbore elongation, and hydrofrac measurements (Plate X). These data taken together with plate models provide an assessment of the contemporary state of stress of the lithosphere discussed here.

<u>Deformation From Earthquakes</u>--Brittle deformation of the lithosphere can be estimated by computing the contribution of strain release associated with earthquakes by summing the seismic moments. This method is outlined by Anderson (1979), Greensfelder and others (1980) and Doser and Smith (1982) for specific applications in the western U.S. In recent work by Eddington and others (1986) compilations of earthquake catalogs, fault plane solutions, and strain data for the U.S. Cordillera provide estimates of contemporary brittle deformation associated with earthquakes. Figure 17 shows the strain-rates, displacement-rates and the directions of the principal strain tensors for the intraplate Cordillera.

FIGURE 17 HERE

Seismic moment estimates of slip rates on specific faults for the southern San Andreas system (Anderson, 1979) vary from 55 mm/yr north of the Transverse Range and 42 mm/yr to the south. Summing over larger areas of the Mojave Desert and parts of the San Andreas system gives up to 60 mm/yr slip (Figure 17) associated with N-S compression. These large rates are primarily due to the contribution of two large, M8+ earthquakes in historic time.

Intraplate deformation characterizes N-S extension in central Idaho and Yellowstone at rates up to 4.7 mm/yr. NW-SE to E-W extension, at rates from 0.06 to 1.5 mm/yr, continue along the southern Intermountain seismic belt on the Wasatch Front. A notable change from E-W extension to easterly compression occurs in southern Utah in an area now known to have significant components of Quaternary strike-slip faulting (Arabasz and Julander, 1985).

The deformation then changes to a general NW direction and the rates of deformation increase to 7.5 mm/yr across central and western Nevada. NW extension occurs along the west and east flanks of the Sierra Nevada but at reduced rates up to 2.9 mm/yr.

The regional rates of earthquake related intraplate-deformation on the order of mm/yr compared to tens of mm/yr deformation for the interplate motion on the San Andreas system. These differences in displacement rates scale with the differences between the maximum magnitude earthquakes of 8.5 on the San Andreas system versus 7.5 for the intraplate Cordillera.

Overall Basin-Range deformation patterns reveal the general kinematics of regional deformation. Deformation and strain rates were calculated across the entire Basin-Range from the historic earthquake record, ~ 1850 to 1982 at various azimuths in the general direction of openings (profiles B-B', B-B'' and C-C', Figure 18 is taken from Eddington and others 1985). The components along each profile were then summed to give the integrated opening rate.

Profile B-B' across northern California, Nevada, and northern Utah had a 10.0 mm/yr deformation rate. Profile, B-B'', is a more general east-west line with an 8.4 mm/yr rate. The southern line, C-C', extends across southeast California, southern Nevada, and southern Utah. Here, the deformation rate diminishes to 3.5 mm/yr. However, if the 1883 $M_s$8.3 Owens Valley earthquake is included on profile C-C', the deformation rate increases to 29.2 mm/yr. When strain rates were considered, it was found that profile B-B' experienced $2.7 \times 10^{-16} sec^{-1}$, B-B'' gave $2.2 \times 10^{-16} sec^{-1}$ and C-C' yielded $1.4 \times 10^{-16} sec^{-1}$. The northern profiles displayed almost twice the strain rate of the southern profile, consistent with deformation rate results.

The deformation rate in the northern Basin-Range is thus more than twice as large as that in the southern part. This pattern implies fan-shaped opening of the Basin-Range similar to a late Cenozoic pattern of deformation that was deduced from fault patterns by Wernicke and others (1982).

Earthquake induced deformation rates of 10.0 mm/yr on B-B' and 8.4 mm/yr on B-B'' determined along the two northern profiles (shown in Figure 16) compare well with deformation rates determined from other studies (Table 1). For example, Lachenbruch and Sass (1978) and Lachenbruch (1979) determined 5-10 mm/yr extension for the Basin-Range using heat flow constraints and thermal models of extension. Beroza and others (1985) estimated a deformation rate across the Basin-Range of 7.4 mm/yr (along profile A-A' in Figure 18) from North American-Pacific plate intraplate tectonic models constrained by satellite geodesy, while the seismically determined deformation rate along line B-B'' was 8.4 mm/yr--a remarkable similarity for two different methods. This result implies that the North American-Pacific plate interaction, modeled by Minster and Jordan (1984) and Beroza and others (1985) may contribute a significant component to the intraplate extension. This comparison also leads to the conclusion that much of the Basin-Range extension is expressed as earthquake-generated brittle fracture in the upper 10-15 km of the lithosphere.

TABLE 1 HERE

Geologically determined paleo-deformation rates, established by other workers (Table 1), ranged from 1-20 mm/yr, except for Proffett's (1977) deformation rate of ~ 200 mm/yr. A range of 1-20 mm/yr is consistent with the deformation produced by contemporary seismicity. These comparisons suggest that since geologically inferred and contemporary strain rates are similar, and that the mechanism that facilitates Basin-Range extension today probably operated throughout Quaternary time. Had the mechanism changed, we would expect to see greater differences in deformation rates between the contemporary and paleo-estimations.

Similar contemporary and paleo-strain rates in the Basin-Range suggest that the historic seismic record coupled with the Quaternary record, though experiencing short-term local variability, is a reasonable indicator of future seismicity on a regional scale.

<u>Geodetically Measured Horizontal Deformation</u>--Savage (1983) and Savage and others (1985) have compiled trilateration data for the western U.S. that Eddington and others (1986) converted (Figure 19) to strain and displacement rates to compare with the earthquake related rates. These data are from small networks concentrated along the San Andreas system and show rates of 2.5 to 16 mm/yr--consistent with the plate models and seismic moment inferred rates for individual faults.

FIGURE 19 HERE

Within the interior of the Cordillera the geodetic data are sparse, but in central Nevada geodetically determined displacement rates of 3.6 mm/yr compare to 7.5 mm/yr deduced from active seismicity. Along the Wasatch Front geodetic rates of 0.6 to 1.9 mm/yr compare to 0.4 mm/yr from seismicity. At Hebgen Lake, Montana geodetic rates of 11 mm/yr compare to seismic related rates of 2.8 mm/yr. These rates are rather similar and suggest that the principal strain release, measured geodetically, is from brittle failure associated with earthquakes. Across Puget Sound, plate convergent rates measured geodetically are ~ 50 mm/yr (Hyndman and Wiechert, 1983) measured from active interplate and intraplate seismicity.

Vertical Deformation of the Cordillera--Little data exists on vertical deformation of the Cordillera because of the general lack of precision re-leveling. Brown and others (1985) have analyzed re-leveling data taken from early Coast and Geodetic Surveys observations for a regional E-W profile that extends from the West Coast to western Wyoming and crosses the Central Valley, Sierra Nevada, the Basin-Range and terminates in the Wyoming Basin (Figure 20).

FIGURE 20 HERE

The vertical deformation data were arbitrarily referenced to a sea level datum. They show little deformation in California, but a marked uplift or equivalently an increase in uplift rate across the Basin-Range with maximum rates greater than 3 mm/yr near the Battle Mountain heat flow high. The uplift rates then decrease toward the Wasatch Front with a pronounced doming over the active rebound area of Lake Bonneville. At the Wasatch fault the rate diminishes to relative negative value of - 6 mm/yr.

These data are important in assessing the contemporary deformation of the Cordillera but they must be taken in the proper perspective of their accuracy and their respective time spans. For example, if the stable interior were chosen as the base, for example a site in Wyoming, then the entire Basin-Range would be in an uplift region of up to 10 mm/yr and the West Coast would also be correspondingly high.

If we chose a province-wide linear decrease in the regional deformation field then the profile could be interpreted as a major tilt, down to the east, with a superposed high over the central Basin-Range and at Lake Bonneville. This interpretation would be consistent with the remnant effects of deformation associated with the extinct subducted plate beneath the Cordillera, perhaps in response to a rising mantle diapir. Nonetheless, the systematic vertical deformation as measured by the various surveys (Figure 20) and the uplift over Lake Bonneville lend credence to the data and suggest a broad warping of the Basin-Range of order mm/yr, or regional eastward tilt of the Cordillera.

## V. SUMMARY

The lithospheric structure of the Cordillera has been effected by diverse tectonic mechanisms: passive margin rifting, subsidence and miogeosynclinal sedimentation; accretion of exotic terrane; magmatism; thrust-compression; and normal faulting-extension. Together these mechanisms have transformed the lithosphere into its current state. The correlation between velocity structure, Late Cenozoic tectonics and seismicity demonstrate this important correspondence.

While quantitative lithospheric-tectonic models are beyond the scope of this discussion, qualitative comparisons between velocity structure and tectonics are possible. For example, the correlation between continental upper-mantle $P_n$-velocity and tectonics is seen in the comparison (from Black and Braile, 1982) between observed heat flow, crustal age, and $P_n$ velocity (Figure 21). These data suggest that the thickness of the lithosphere and an increase in upper mantle $P_n$ velocity are related processes produced by cooling of the continental lithosphere with time after a thermo-tectonic event. While the range of continental upper mantle $P_n$ velocities, 7.4 to 8.4 km/s, can also be explained by: 1) regional differences in temperature at the Moho, 2) by differences in composition that vary with age, or by 3) anisotropy, it is a viable thermal-tectonic model to apply to continental lithospheric evolution.

FIGURE 21 HERE

If the regional differences in $P_n$ velocities are related to the temperature of the Moho discontinuity, using the correlation between heat flow and age of continental crust (Figure 21), an estimate of the age of the Moho (Table 2) can be made. These data suggest that the Moho may be as young as 15 to 30 m.y. for the Columbia Plateau, Cascade Range and the Basin-Range, areas of Late Cenozoic volcanism and extension. For the Pacific border and the Colorado Plateau--the Moho is estimated to be 45 m.y. Whereas for the cool, tectonically stable and pre-Cenozoic, Rocky Mountains and Sierra Nevada, the Moho is estimated to be 150 m.y. .

TABLE 2 HERE

The contemporary and Late Cenozoic deformation of the Cordillera is summarized in Table 1. These data compare the rates of deformation for the transform-fault dominated San Andreas system; plate convergence in the Pacific Northwest, and the intraplate extensional regime of the Basin-Range. Contemporary deformation rates were summarized from seismic moment and geodetic data. Prehistoric deformation was determined from interplate models, oceanic geomagnetic data, heat flow and geological strain.

The general conclusions of these data (Table 1) are that the active lateral-slip of the San Andreas system occurs at rates up to 55 mm/yr, compared to estimates from 13 to 45 mm/yr for Late Cenozoic time--a difference that could be attributed to an incomplete geologic record. These rates are close considering that they were deduced by completely different methods and suggest the continuity of tectonic mechanisms through Late Cenozoic time to the present.

Plate convergence by active suduction of the Juan de Fuca plate beneath the North American plate varies from 20 to 50 mm/yr--surprisingly similar in magnitude to that of the San Andreas system. The rates of contemporary deformation include the effects of earthquakes at the top of the subducting Benioff zone as well as from shallow intraplate deformation in the the Puget

Sound and Cascade Ranges. This contemporary rate compares rather well to 15 to 35 mm/yr estimated for the Quaternary time.

Intraplate extension of the Cordillera occurs at almost an order of magnitude smaller with deformation rates of 3.5 to 10 mm/yr for the northern Basin-Range. Late Cenozoic rates of 1 to 20 mm/yr are nearly the same as the contemporary rates and suggest that assessments of future seismicity (locations and general timing of likely large events) can be made using the Late Cenozoic geologic information (fault locations, slip rates, magnitude of individual slip events, etc.). This basis is useful particularly in areas where historic seismicity is low or Quaternary faulting appears quiescent.

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Table 2. Heat Flow, $P_n$-Velocity, Age of Continental Crust and Tectonic Event (data taken from Black and Braile, 1982).

| Tectonic Province | Heat Flow (mWm-2) | $P_n$-Velocity (km/s) | Predictated Age of Moho (m.y.) |
|---|---|---|---|
| Basin-Range | 85 | 7.79 | 25 |
| Columbia Plateau | 20 | 7.83 | 15 |
| Colorado Plateau | 64 | 7.83 | 45 |
| Pacific border | 67 | 8.06 | 45 |
| Sierra Nevada | 34 | 7.92 | 110 |
| N. Rocky Mountains | 87 | 8.02 | 140 |
| M. Rocky Mountains | 69 | 7.86 | 130 |
| S. Rocky Mountains | 97 | 7.90 | 150 |

Table 1 Cordillera Deformation Rates

a. Basin-Range Extension Rates (modified from Minster and Jordan, 1985; Jordan and others, 1986; Eddington and others, 1986)

| Time | Opening Rate (mm/yr) | Method |
|---|---|---|
| Late Cenozoic | 3 - 20 | Geological Strain |
| Late Cenozoic | 3 - 12 | Heat Flow |
| Holocene Paleoseismicity | 1 - 12 | |
| Historic Seismicity | 3.5 - 10 | Historical |
| Historic Model | <9 | Intraplate |

b. Pacific Northwest Subduction--Convergence

| Time | Convergence-Subduction Rate (mm/yr) | Method |
|---|---|---|
| Late Cenozoic (Riddihough, 1977) | 35 - 55 | Paleomagnetic |
| Quaternary deposits (Von Huene and Kulm (1973) | 16 -27 | Sedimentary |
| Historic (Nishimura and others, 1981) | 20 - 40 | Interplate Model |
| Historic Seismicity (Hyndmann and Wiechert, 1983) | 20 - 50 | Historic |

c. San Andreas Fault System (summarized from Minster and Jordan, 1984)

| Time | Slip Rate (mm/yr) | Method |
|---|---|---|
| Historic, Seismicity | 45 -55 | Historic |
| Historic, Model | 56 | Interplate |
| Historic, Measurements | 30 - 45 | Geodetic |
| Holocene | 35 | Offset of Geologic Units |
| Late Cenozoic | 13 - 25 | Offset of Geologic Units |

# Figure Captions

1. Area of discussion, including the Cordilleran Orogen, with a province boundary map. Irregular rectangles correspond to locations of Continental Transects, C-1 (north) and C-2 (south). Locations of the COCORP 40° N. Transect (Allmendinger and others, 1985) and reflection profiles Nevada (Okaya and Thompson, 1985) and Great Salt Lake (Smith and Bruhn, 1984) are also shown.

2. Locations of seismic refraction/wide-angle reflection profiles used to compile the P-wave lithospheric structure of the Cordillera. Numbers correspond to an author-index available on microfilm at Geological Society America Offices, Boulder, Colorado.

3. Upper-crustal, $P_g$-velocity map of the Cordillera. P-wave velocities in km/s and are located at mid-point of the $P_g$-branch. Contours are in 0.1 km/s.

4. Upper-mantle, $P_n$-velocity map. Contours in 0.1 km/s intervals.

5. Crustal thickness of the Cordillera. Values in km relative to sea level. Contour interval 5 km.

6. Averaged crustal P-wave velocities of the Cordillera. Velocities averaged by weighting layer velocities by their respective layer thicknesses. Contour interval 0.1 km/s.

7. Cross-section of continental lithosphere across northern California, northern Nevada, northern Utah and Wyoming. See Figure 1 for cross-section location. Surface geology highly generalized from Continental Transects profile C-1 (Blake, 1986). P-wave velocities are given in bold letters, S-wave velocities are in parentheses, densities (gm/cm-$^3$) are in italics. The sparsity in heat flow data for the Middle Rocky Mountains is due to the lack of measurements for this area.

8. Cross-section of continental lithosphere across central California, central Nevada, and central Utah (see Figure 1 for cross-section locations). Surface geology highly generalized from Continental Transects profile C-2 (Saleeby, 1986). P-wave velocities are given in bold letters, S-wave velocities are in parentheses, densities (gm/cm-$^3$) are in italics.

9. Lithospheric cross-section (longitudinal) of the Yellowstone-Snake River Plain volcano-tectonic province (from Braile and Smith, 1986). P-wave velocities in km/s.

10. Seismic reflection profiles of the upper-crust: a) upper; Dixie Valley, Nevada (from Okaya and Thompson, 1985), and b) lower; Great Salt Lake, Utah (From Smith and Bruhn, 1984).

11. Generalized line drawing of the COCORP 40° N. Transect seismic reflection data (from Allmendinger and others, 1985). Line drawing constructured from original seismic reflection sections. Transect is shown in four parts. Vertical boundaries between different line segments have been omitted for legibility.

12. Temporal plot of large, M6+, Cordilleran earthquakes (taken from Smith and Richins, 1984).

13. Seismicity map of the Cordillera superimposed upon a tectonic base. Earthquake data from Eddington and others (1985).

14. Upper; Cross-section and idealized stress-rheology model for the 1983, M7.3, Borah Peak, Idaho, earthquake (taken from Smith and others, 1985); Lower; cross-section of normal faults and focal depths associated with large interplate earthquakes of the Cordillera (taken from Smith and Richins, 1984).

15. Earthquake focal-depth cross sections of the Pacific margin: a) Puget Sound, Washington, (from Taber and Smith, 1985), and b) northern California, (from Cockerham, 1984).

16. Hypothetical rheologic model for the upper-lithosphere of the U.S. Cordillera (taken from Smith and Bruhn, 1984). Dark pattern corresponds to modeled brittled layer, light pattern corresponds to ductile layers. Focal depths are from regional seismic networks and detailed microearthquake surveys.

17. Great Basin strain and deformation rates from historic earthquakes. In each area, top value is deformation rate in mm/a, bottom value is strain rate in $s^{-1}$; second number is power of 10; * from Hyndman and Wiechert (1983) # from Anderson (1979).

18. Regional extenion of the Great Basin. A-A' is from Jordon and others 1986) intraplate kinematic model of motion between North American and Pacific plates constrained by satellite geodetic data; B-B', B-B", and C-C' from Eddington and others (1985). Value in parentheses below C-C' includes deformation from the 1883, M8.3 Owens Valley, California earthquake.

19. Geodetically determined extensional deformation and strain rates for the Cordillera (from Eddington and others, 1985). The top number is the deformation rate (mm/a) and the bottom is strain rate ($s^{-1}$). The second number is power of 10. Data are from Savage (1983) and Savage and others (1985).

20. Profile of rates of relative elevation change across Cordillera from precise re-leveling surveys (modified from Brown and others, 1985).

21. Relationship between observed heat flow, crustal age and $P_n$ velocity (from Black and Braile, 1982). BR = Basin-Range, CA = Columbia Plateau, CO = Colorado Plateau, CR = Cascade Range, PB = Pacific Border, MR, SR, NR = Middle, Southern and Northern Rocky Mountains, SN = Sierra Nevada.

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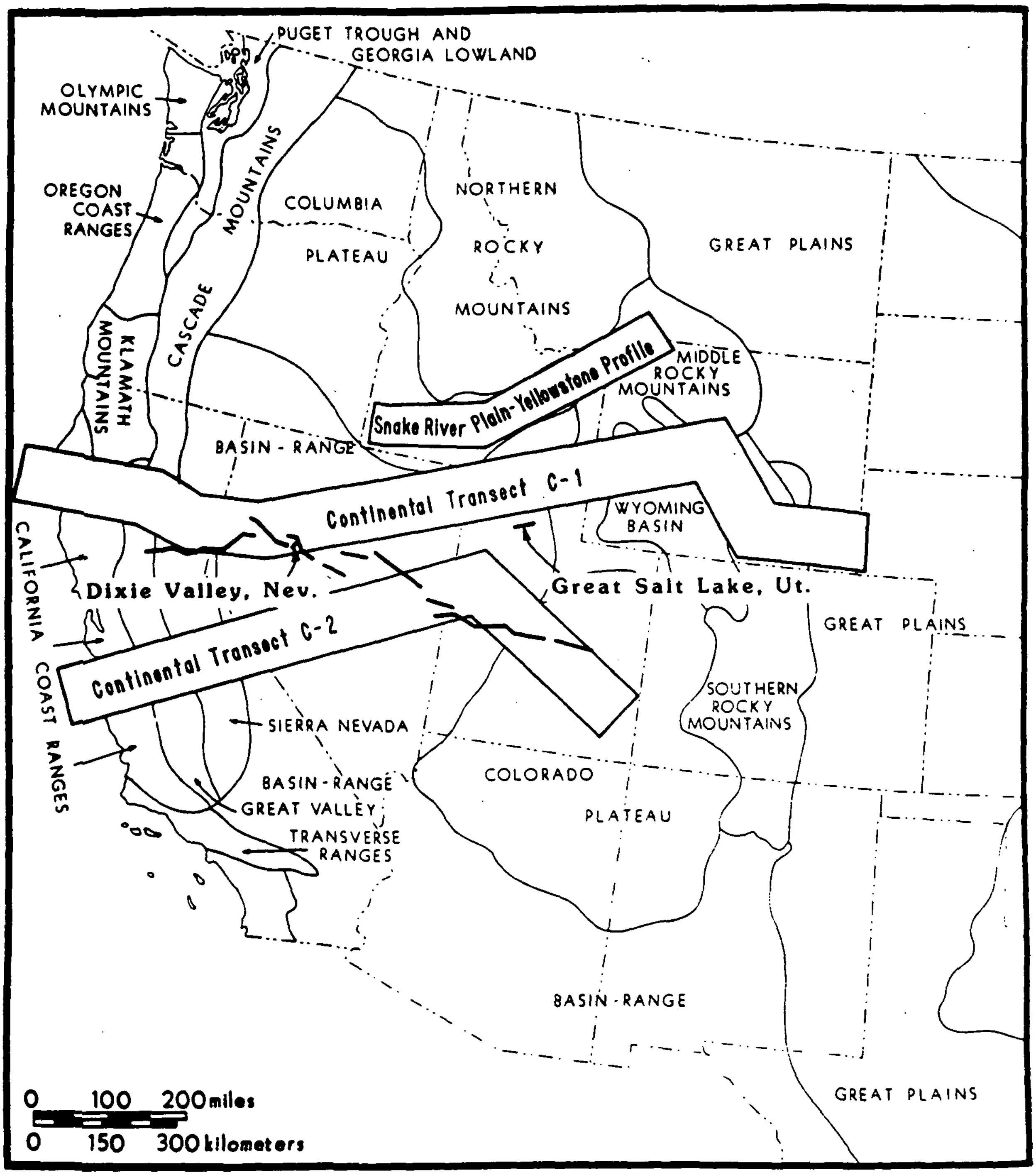

PUGET TROUGH AND GEORGIA LOWLAND
OLYMPIC MOUNTAINS
OREGON COAST RANGES
CASCADE MOUNTAINS
COLUMBIA PLATEAU
NORTHERN ROCKY MOUNTAINS
GREAT PLAINS
KLAMATH MOUNTAINS
Snake River Plain-Yellowstone Profile
MIDDLE ROCKY MOUNTAINS
BASIN - RANGE
Continental Transect C-1
WYOMING BASIN
CALIFORNIA COAST RANGES
Dixie Valley, Nev.
Great Salt Lake, Ut.
GREAT PLAINS
Continental Transect C-2
SOUTHERN ROCKY MOUNTAINS
SIERRA NEVADA
COLORADO PLATEAU
BASIN-RANGE
GREAT VALLEY
TRANSVERSE RANGES
BASIN-RANGE
GREAT PLAINS
0 100 200 miles
0 150 300 kilometers

Figure 1

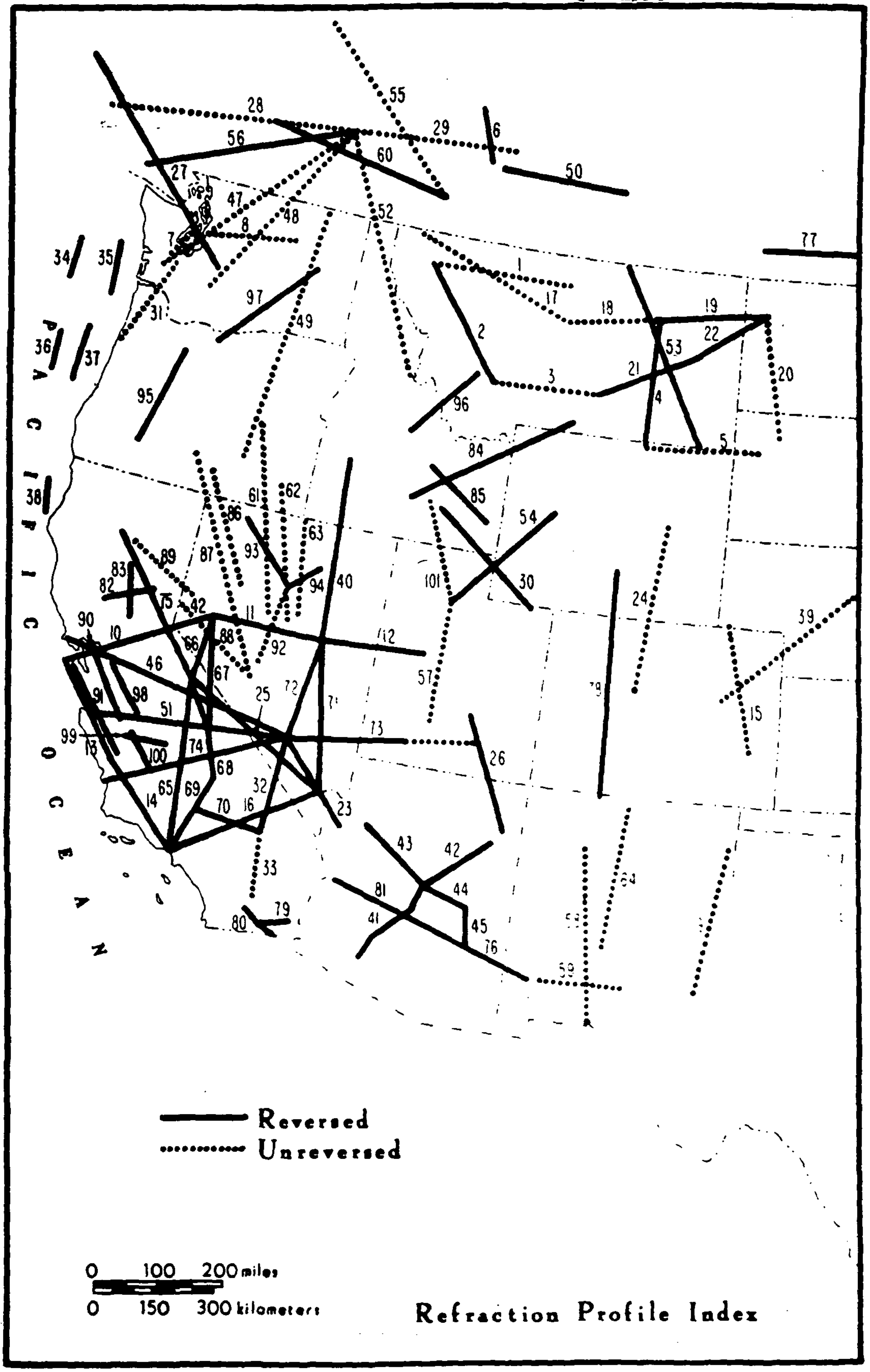
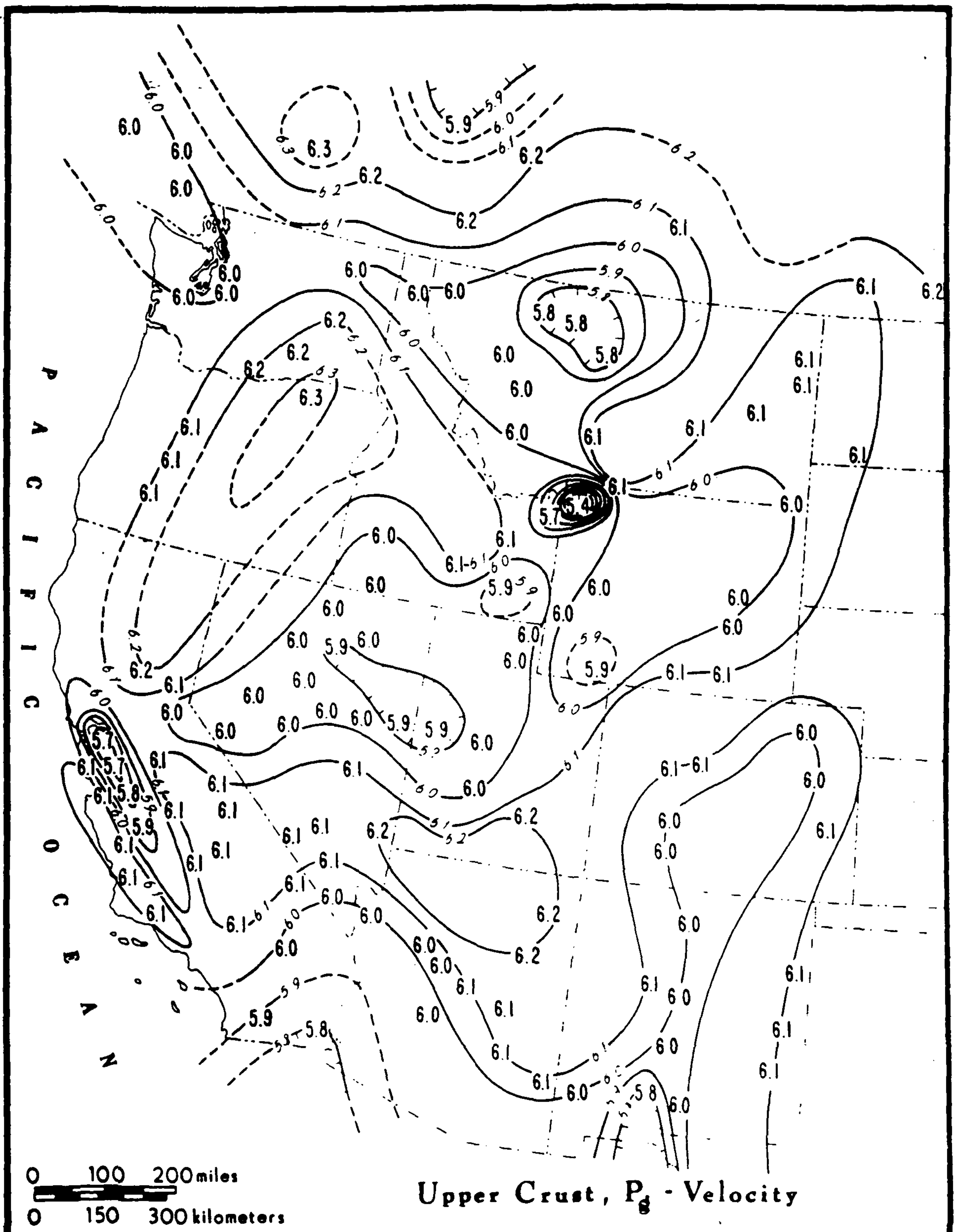

PACIFIC
OCEAN
Reversed
Unreversed
0 100 200 miles
0 150 300 kilometers
Refraction Profile Index

Figure 2




Upper Crust, $P_g$ - Velocity

Figure 3

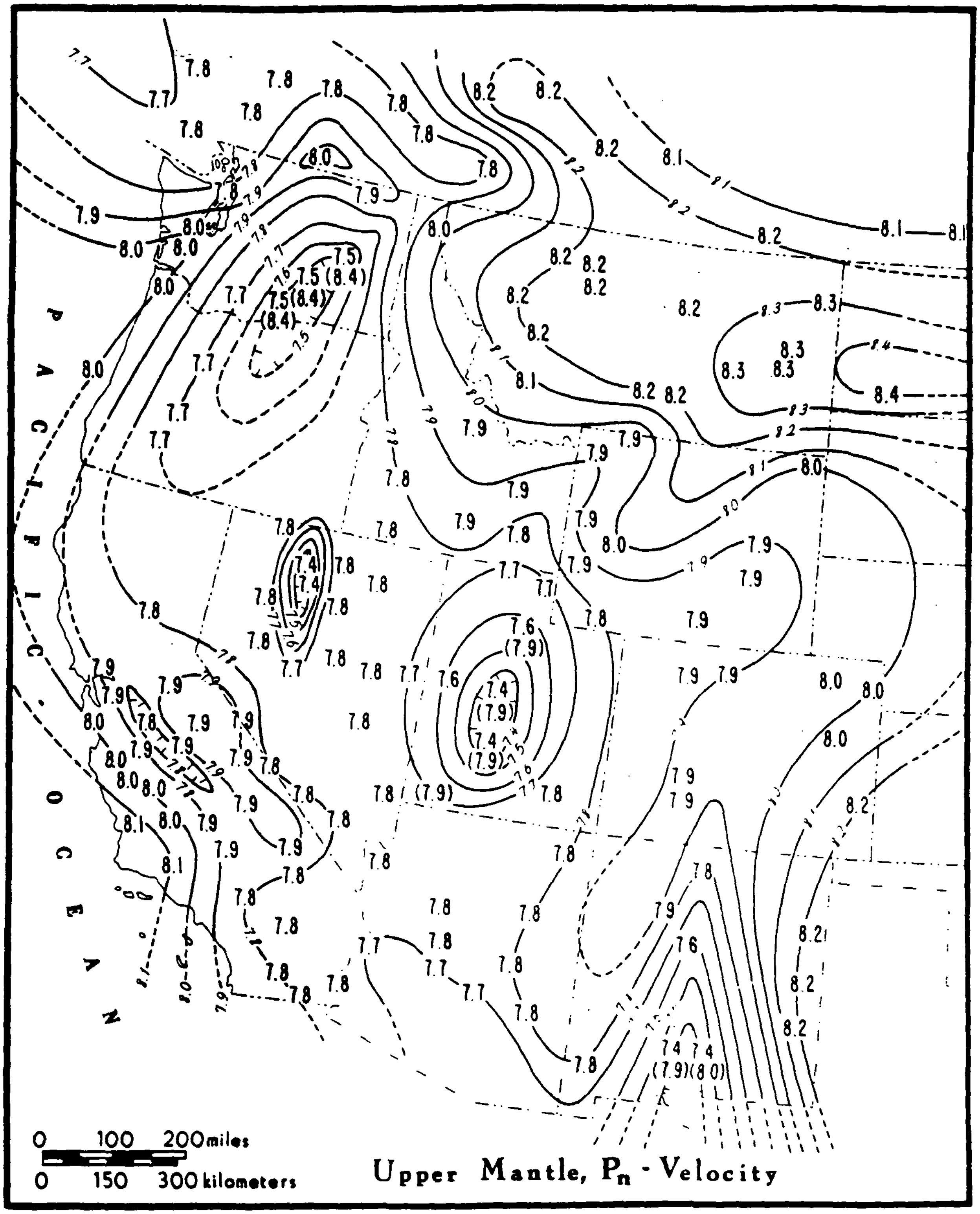

PACIFIC OCEAN
0 100 200 miles
0 150 300 kilometers
Upper Mantle, $P_n$ - Velocity

Figure 4

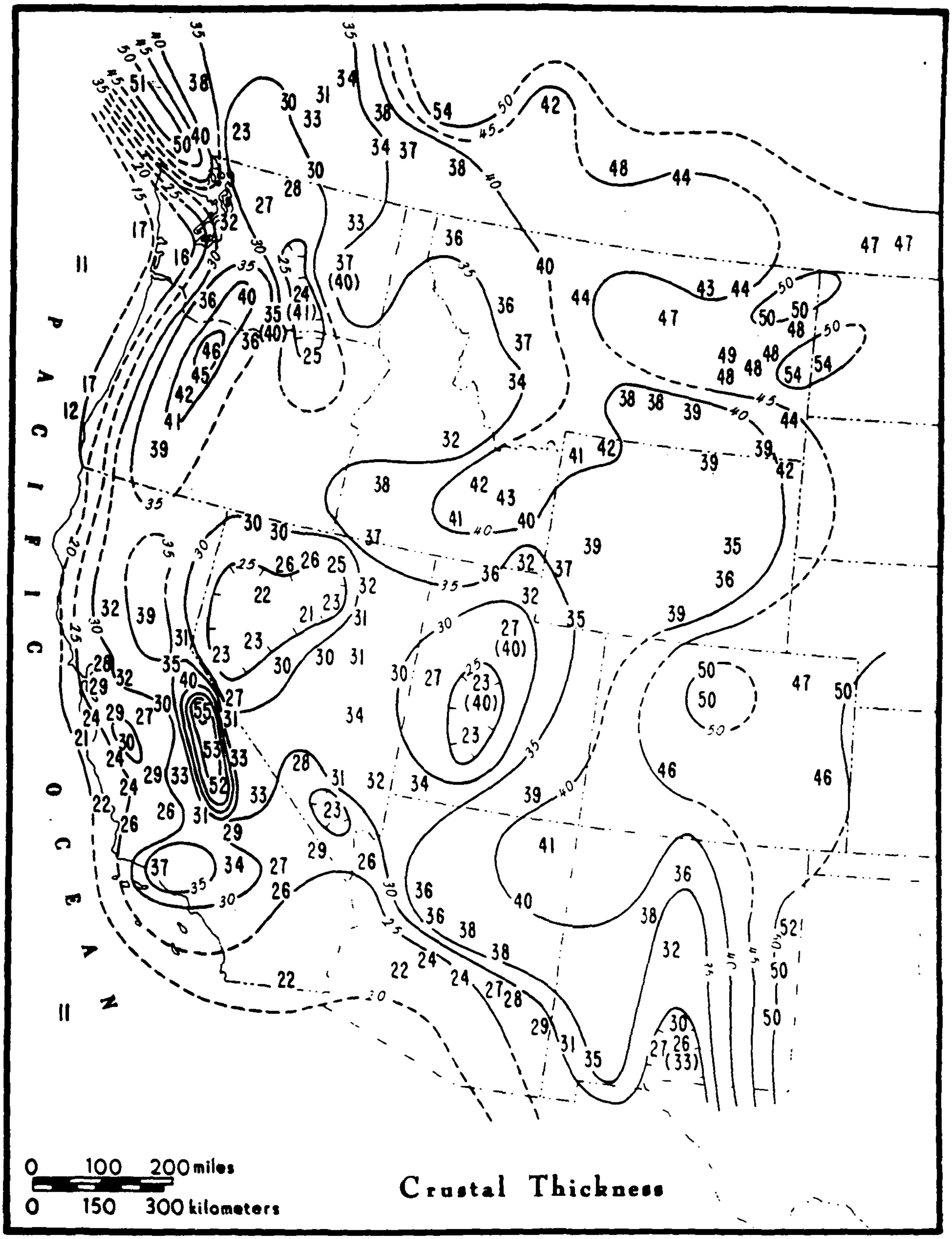
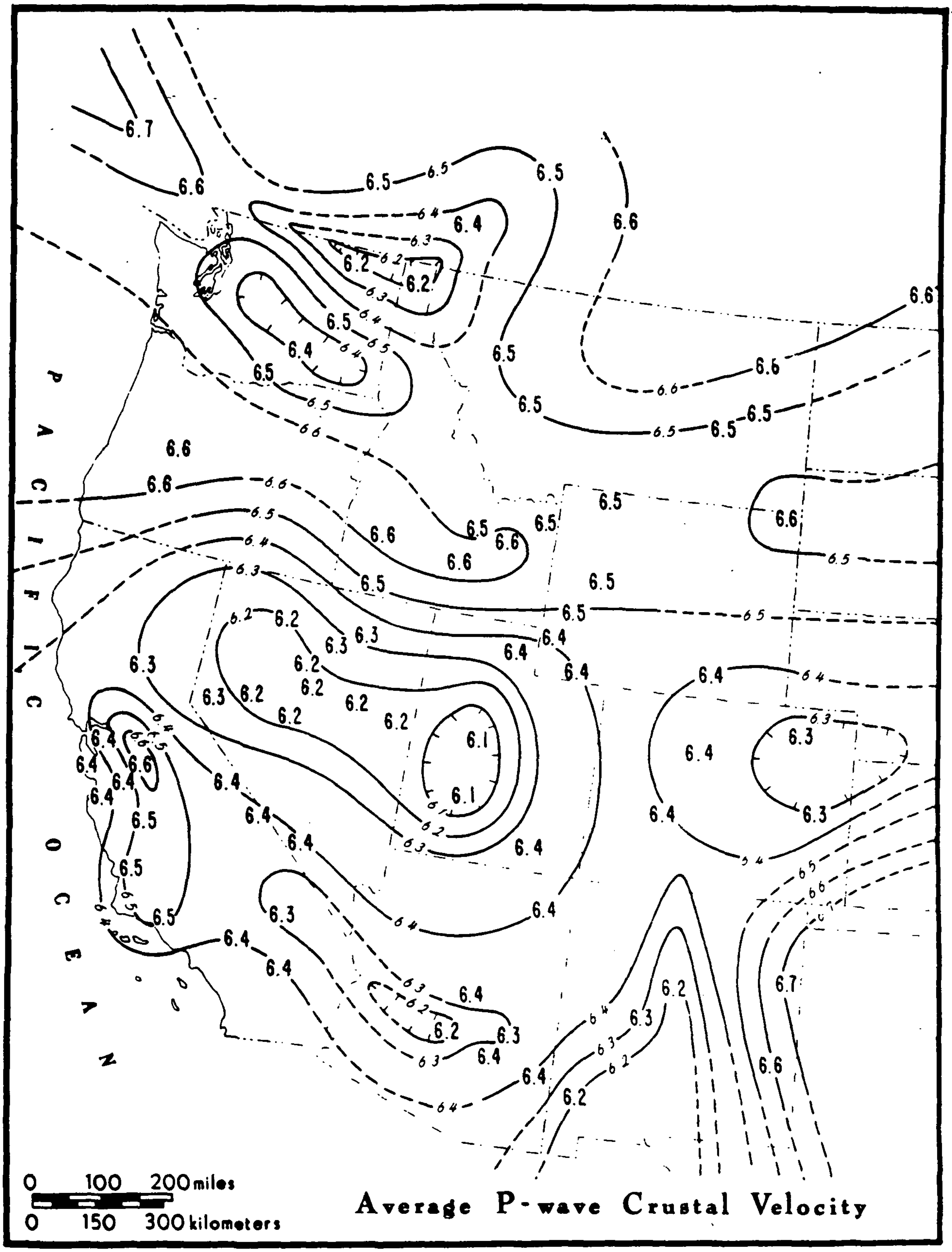

PACIFIC OCEAN
0 100 200 miles
0 150 300 kilometers
Crustal Thickness

Figure 5


Average P-wave Crustal Velocity
0 100 200 miles
0 150 300 kilometers
PACIFIC OCEAN
6.7
6.6
6.5
6.4
6.3
6.2
6.1
Figure 6

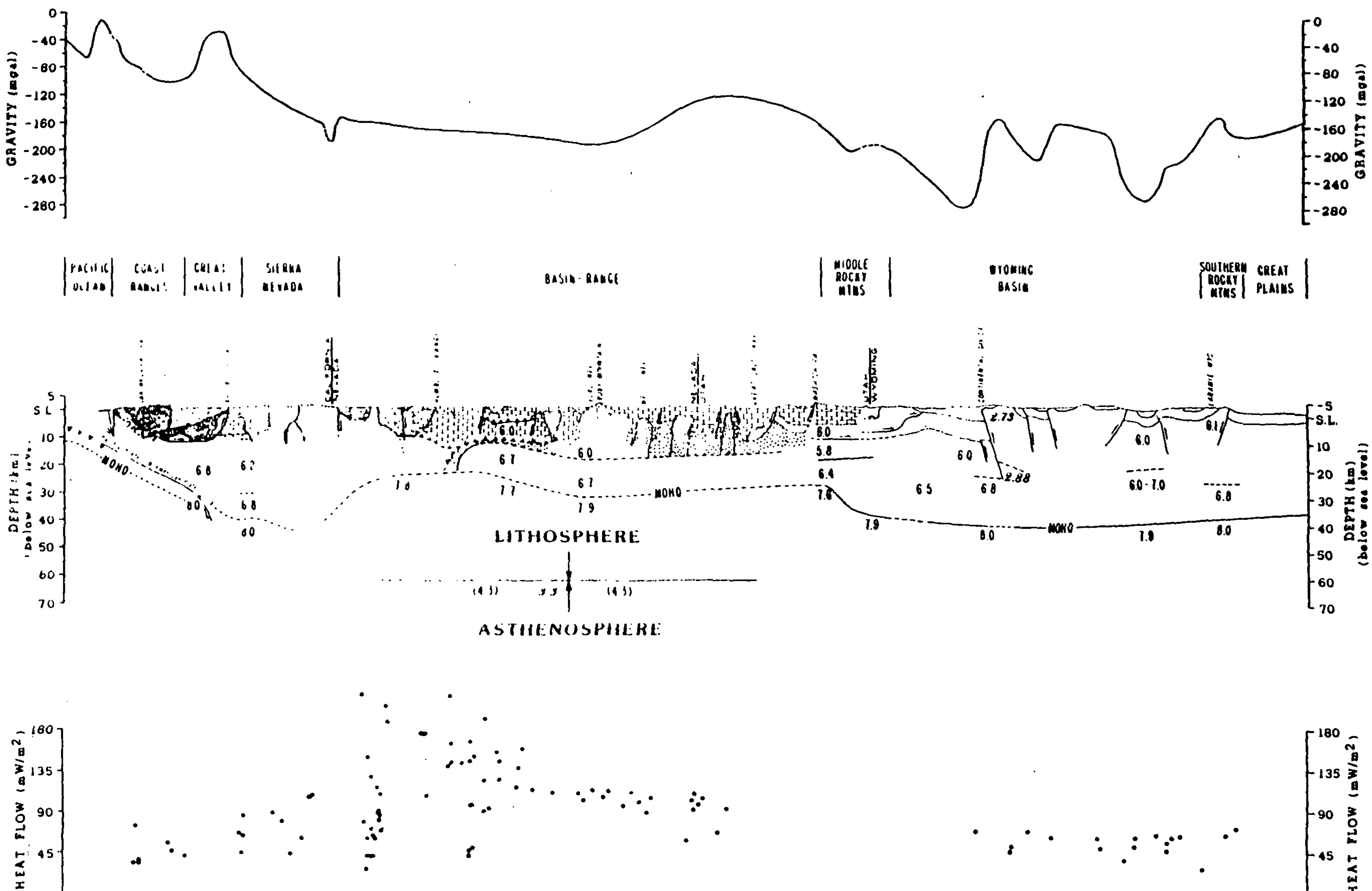

GRAVITY (mgal)
PACIFIC OCEAN
COAST RANGES
GREAT VALLEY
SIERRA NEVADA
BASIN - RANGE
MIDDLE ROCKY MTNS
WYOMING BASIN
SOUTHERN ROCKY MTNS
GREAT PLAINS
DEPTH (km) (below sea level)
MOHO
LITHOSPHERE
ASTHENOSPHERE
HEAT FLOW (mW/m²)

Figure 7

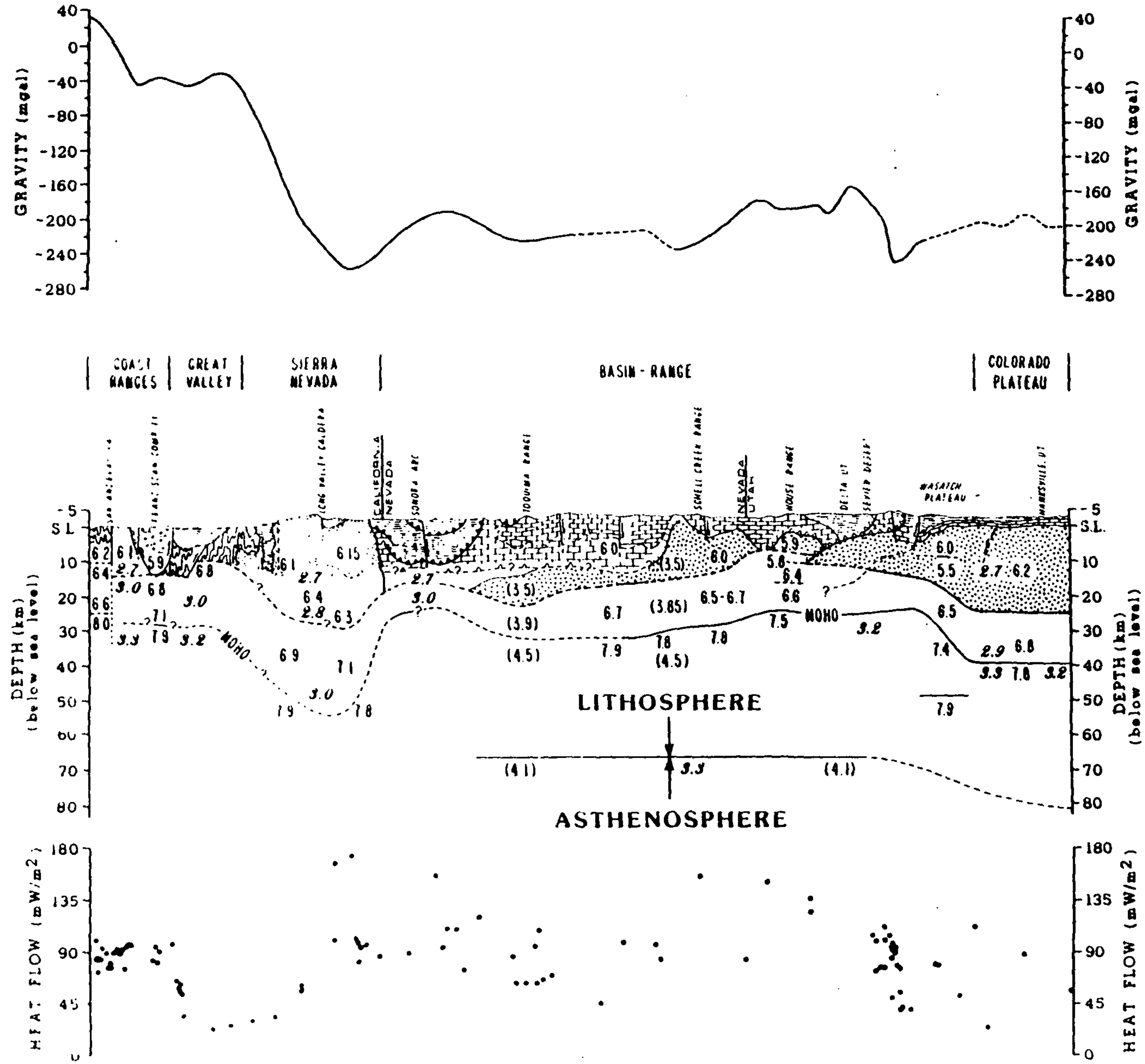

GRAVITY (mgal)
COAST RANGES
GREAT VALLEY
SIERRA NEVADA
BASIN - RANGE
COLORADO PLATEAU
S.L.
MOHO
LITHOSPHERE
ASTHENOSPHERE
DEPTH (km) (below sea level)
HEAT FLOW (mW/m²)

Figure 8

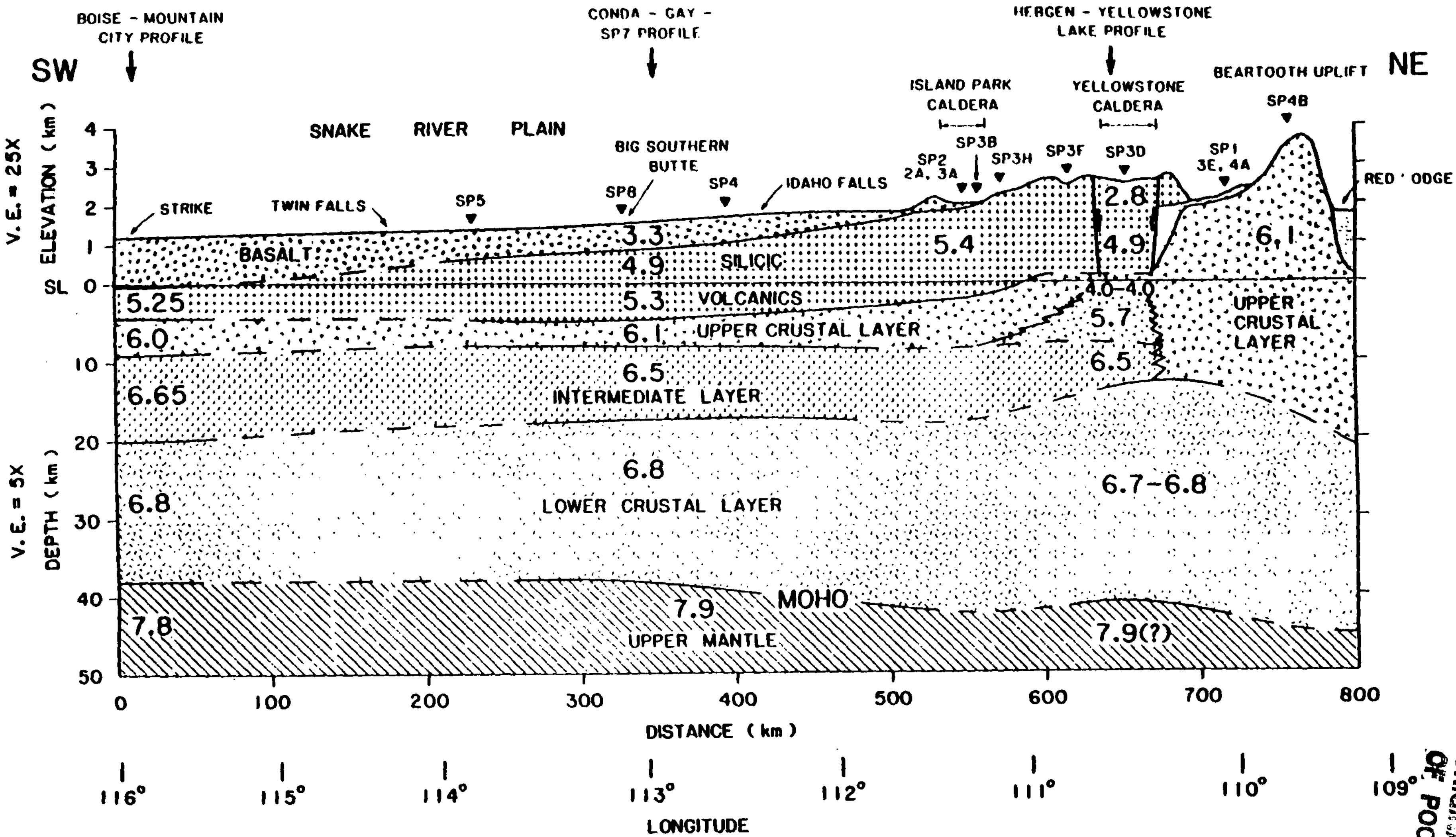
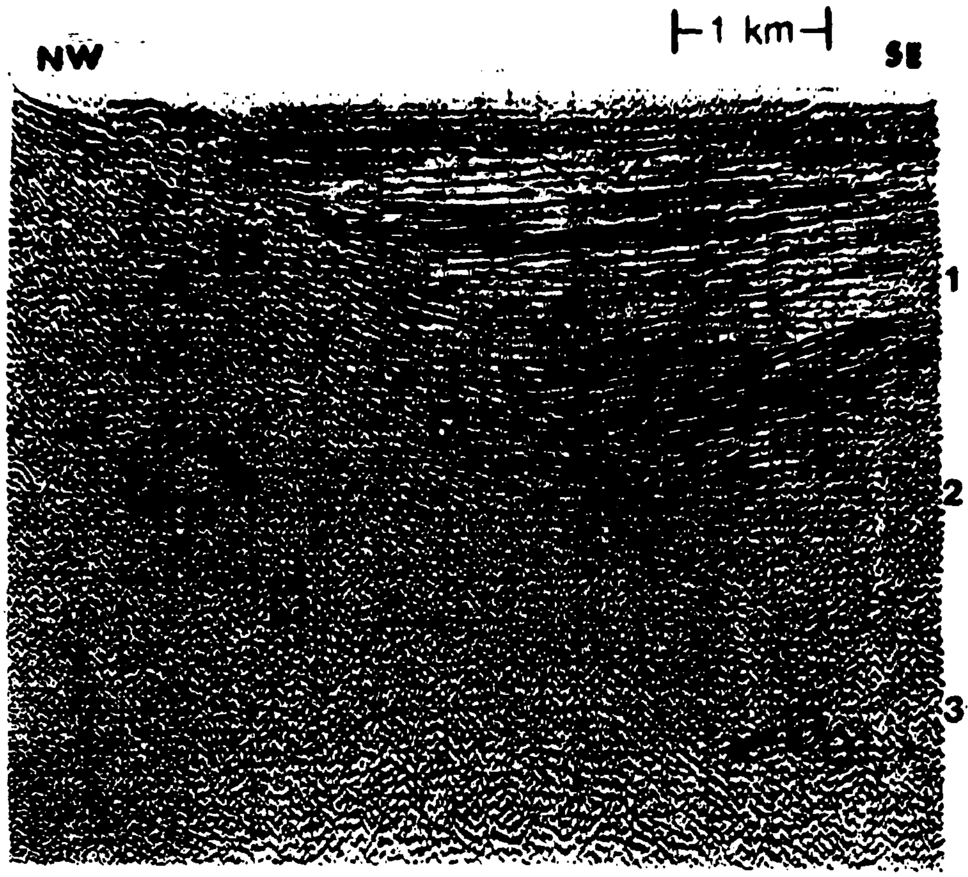
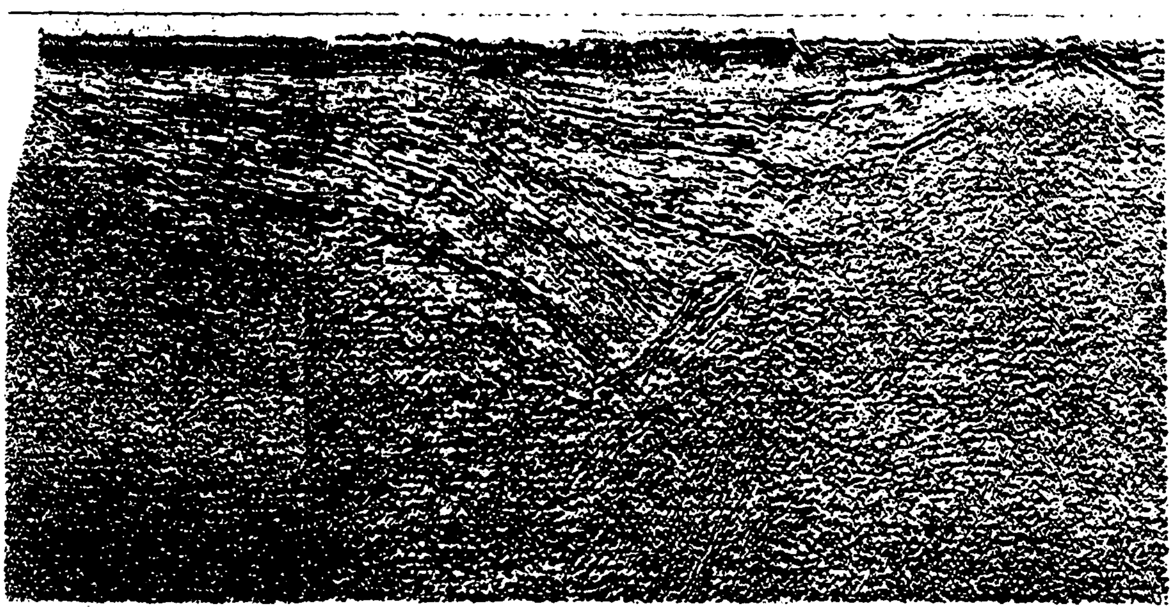



Figure 9

ORIGINAL PAGE IS OF POOR QUALITY




(a)



(b)

Figure 10

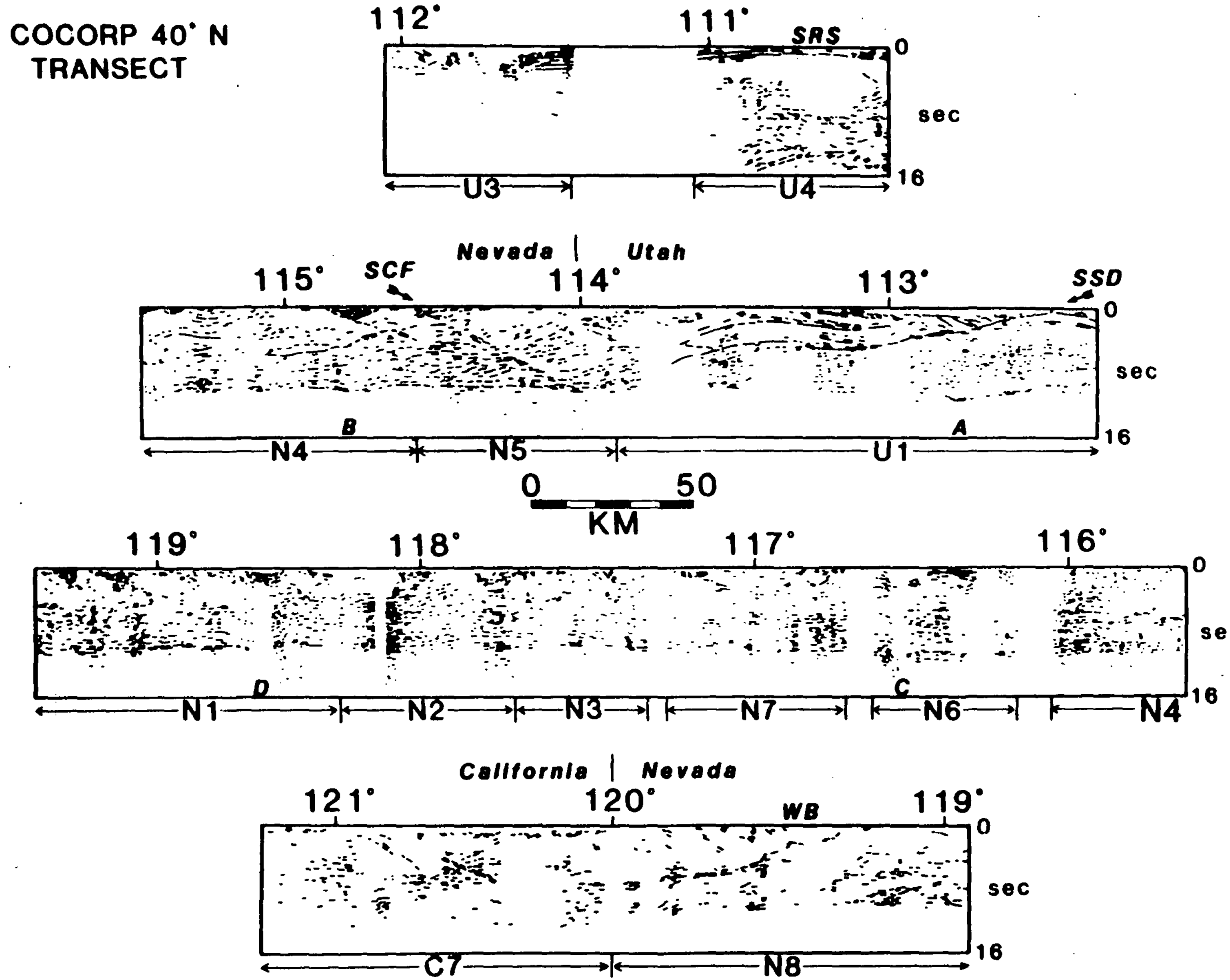
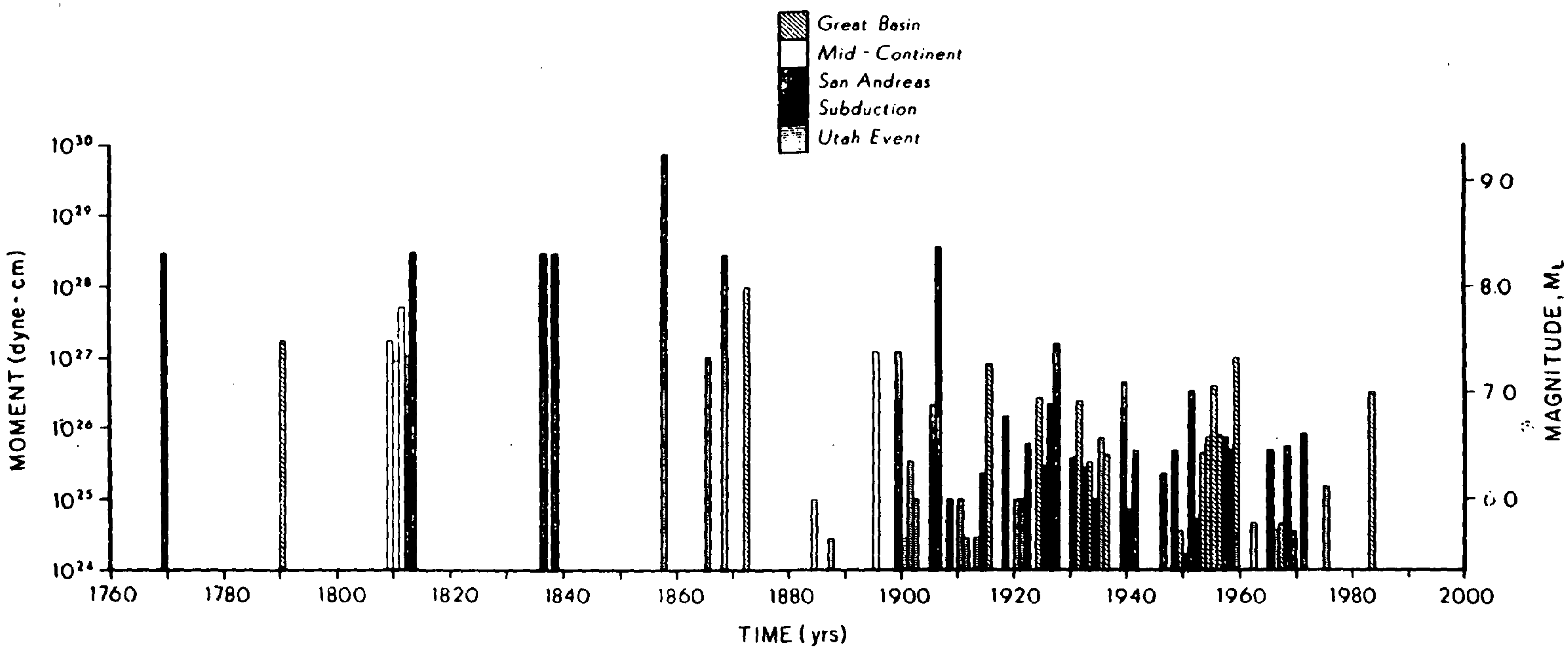

COCORP 40° N
TRANSECT
112°
111°
SRS
0
sec
16
U3
U4
Nevada
Utah
115°
SCF
114°
113°
SSD
0
sec
16
B
A
N4
N5
U1
0
50
KM
119°
118°
117°
116°
0
sec
16
D
C
N1
N2
N3
N7
N6
N4
California
Nevada
121°
120°
WB
119°
0
sec
16
C7
N8

Figure 11



Great Basin
Mid - Continent
San Andreas
Subduction
Utah Event
MOMENT (dyne - cm)
MAGNITUDE, ML
TIME ( yrs)


Figure 12

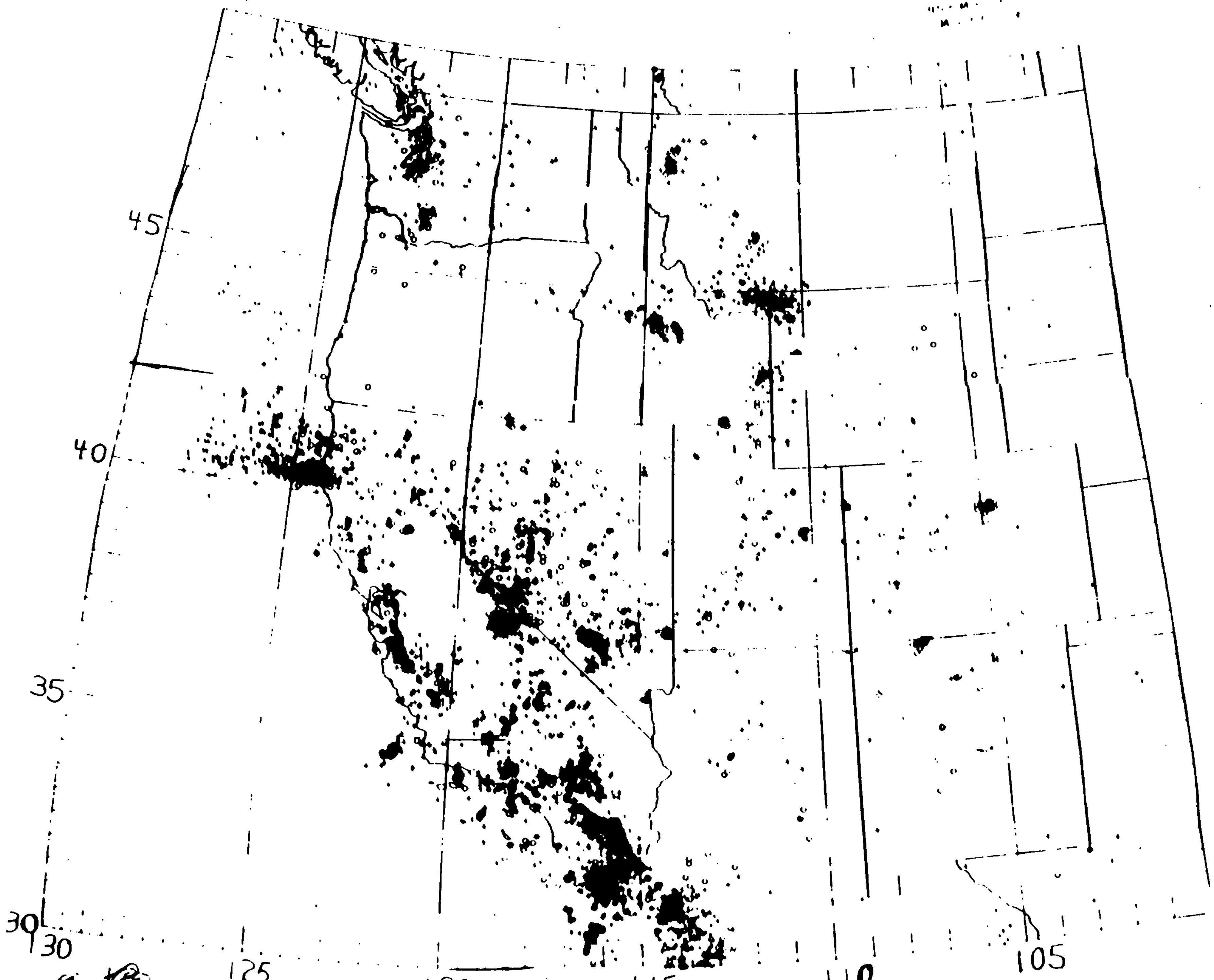



Figure 13

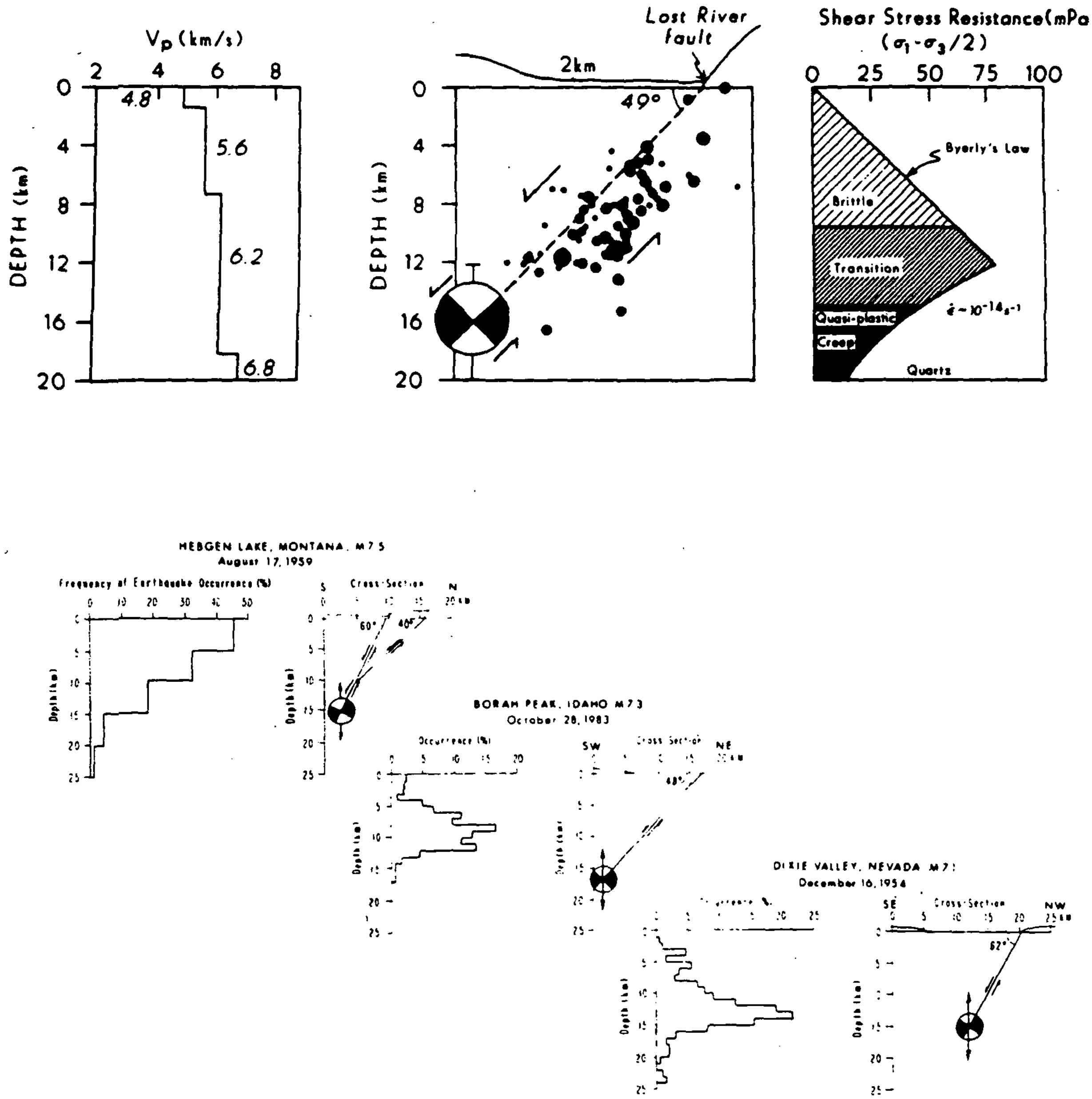

Vp (km/s)
2
4
6
8
0
4
8
12
16
20
DEPTH (km)
4.8
5.6
6.2
6.8
Lost River fault
2km
49°
Shear Stress Resistance(mPa)
($\sigma_1$-$\sigma_3$/2)
0
25
50
75
100
Byerly's Law
Brittle
Transition
Quasi-plastic
Creep
Quartz
HEBGEN LAKE, MONTANA, M7.5
August 17, 1959
Frequency of Earthquake Occurrence (%)
Cross-Section
60°
40°
BORAH PEAK, IDAHO M7.3
October 28, 1983
Occurrence (%)
SW
NE
DIXIE VALLEY, NEVADA M7.1
December 16, 1954
SE
NW
62°

Figure 14

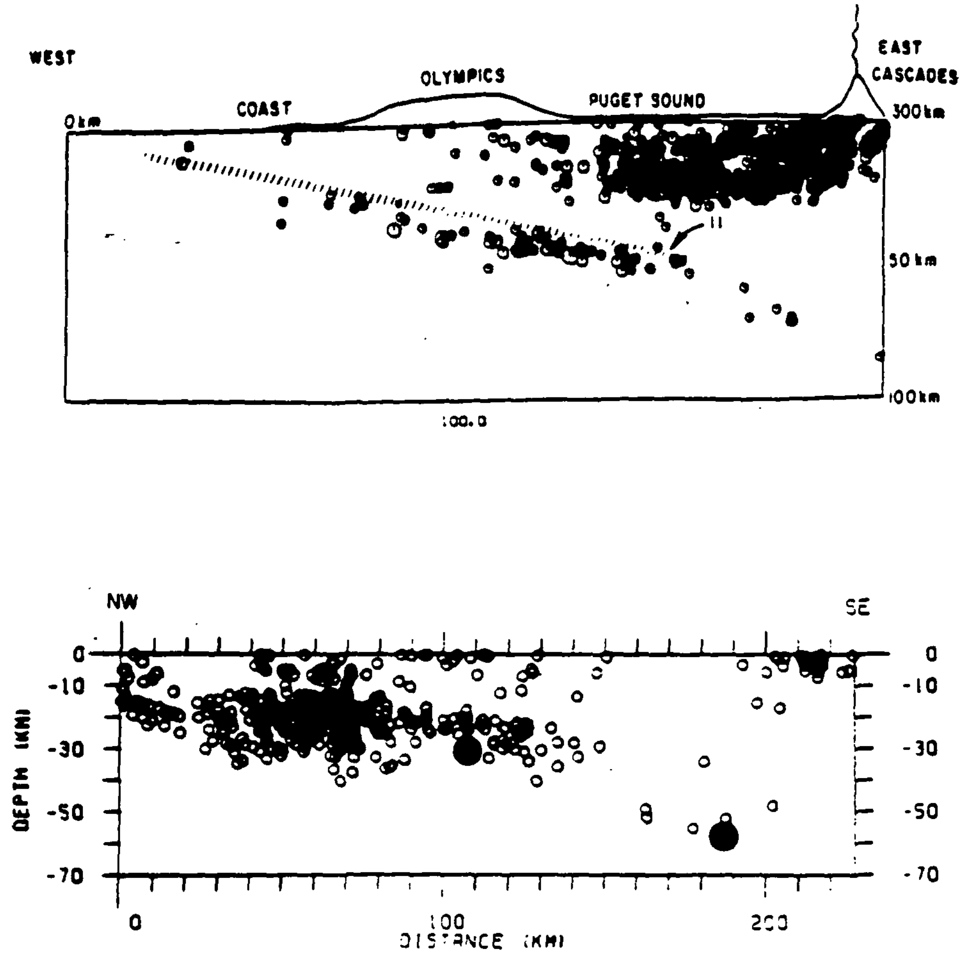

WEST
OLYMPICS
COAST
PUGET SOUND
EAST
CASCADES
0km
300km
50km
100km
100.0
NW
SE
0
-10
-30
-50
-70
DEPTH (KM)
0
100
200
DISTANCE (KM)

Figure 15

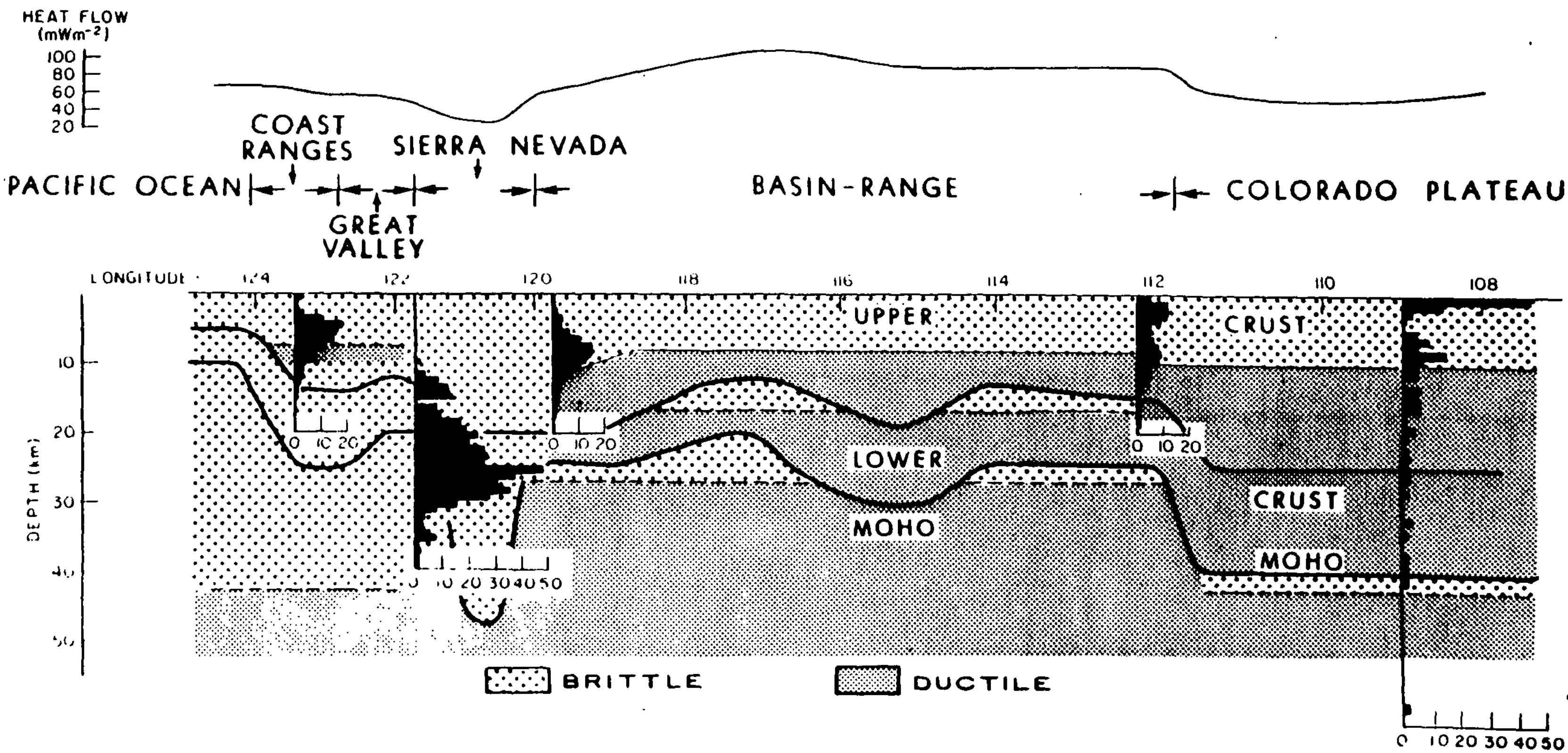
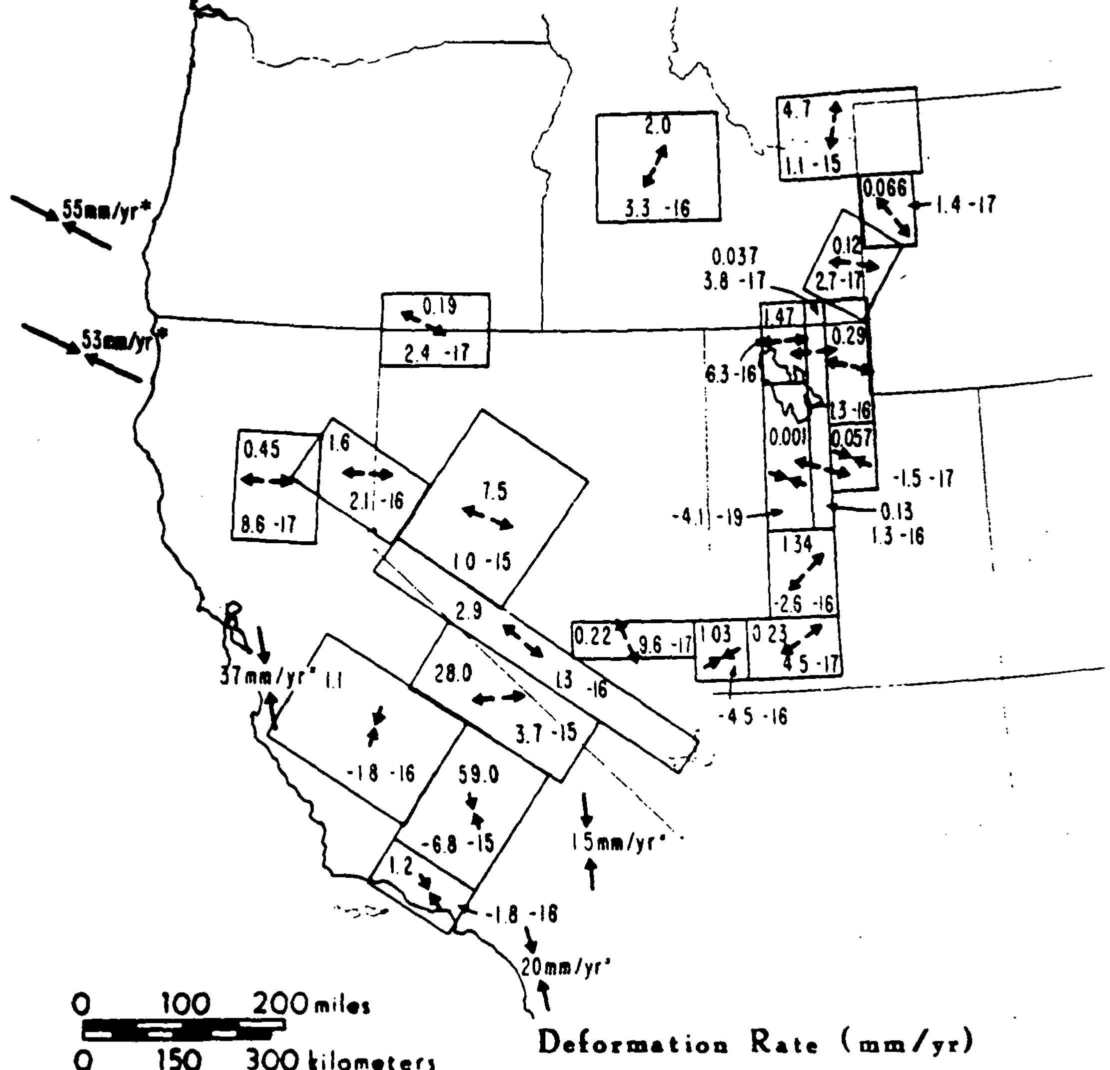

HEAT FLOW (mWm-2)
100
80
60
40
20
COAST RANGES
SIERRA NEVADA
PACIFIC OCEAN
BASIN-RANGE
COLORADO PLATEAU
GREAT VALLEY
LONGITUDE
124
122
120
118
116
114
112
110
108
DEPTH (km)
10
20
30
UPPER
CRUST
LOWER
CRUST
MOHO
MOHO
BRITTLE
DUCTILE
0 10 20 30 40 50

Figure 16

# GREAT BASIN SEISMICALLY DETERMINED DEFORMATION AND STRAIN RATES




Deformation Rate (mm/yr)
Strain Rate (s-1)

Figure 17

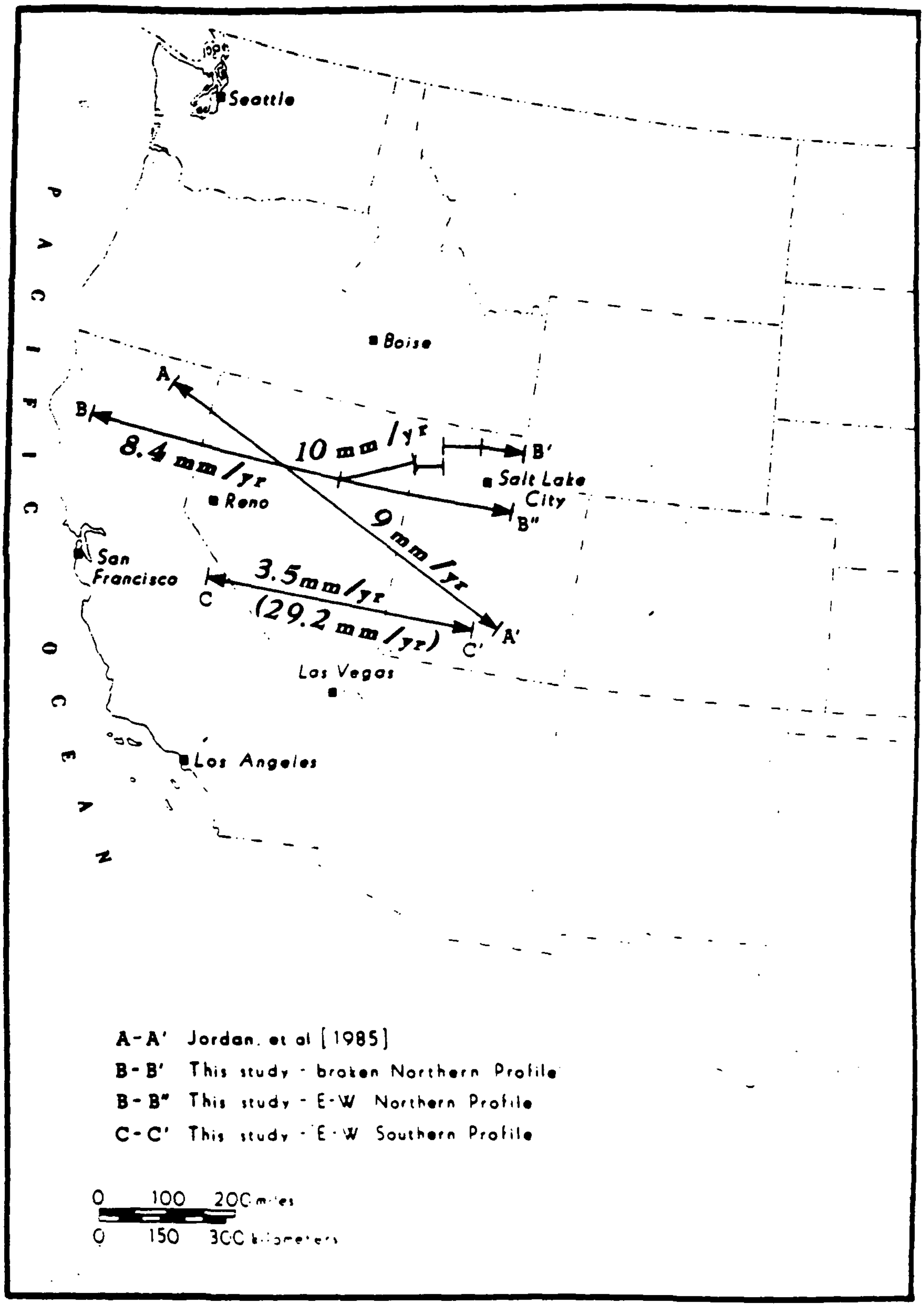

Seattle
Boise
Salt Lake City
Reno
San Francisco
Las Vegas
Los Angeles
PACIFIC OCEAN
A
A'
B
B'
B"
C
C'
10 mm/yr
8.4 mm/yr
9 mm/yr
3.5mm/yr
(29.2 mm/yr)
A-A' Jordan, et al [1985]
B-B' This study - broken Northern Profile
B-B" This study - E-W Northern Profile
C-C' This study - E-W Southern Profile
0 100 200 miles
0 150 300 kilometers

Figure 18

ORIGINAL PAGE IS
OF POOR QUALITY

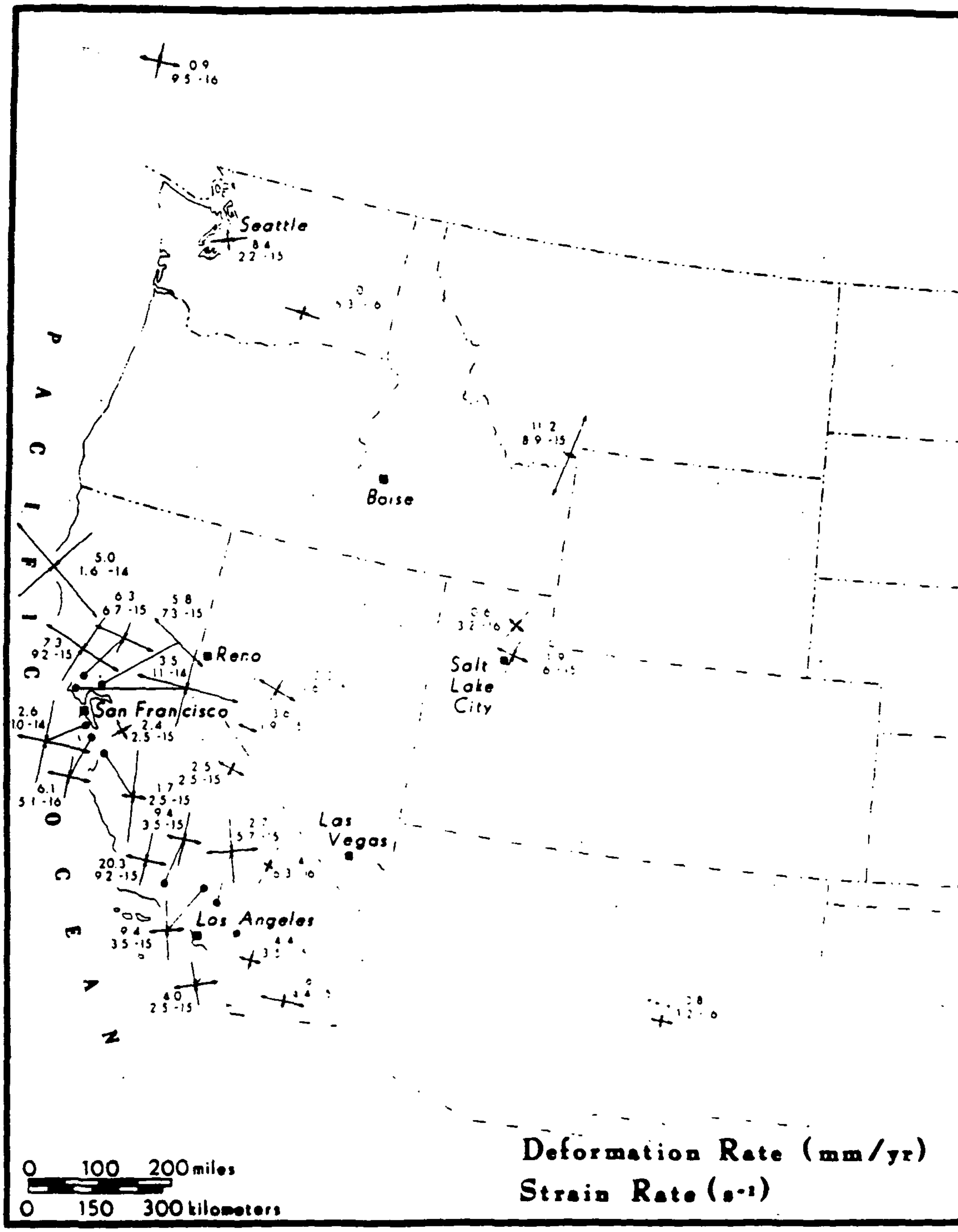



Figure 19

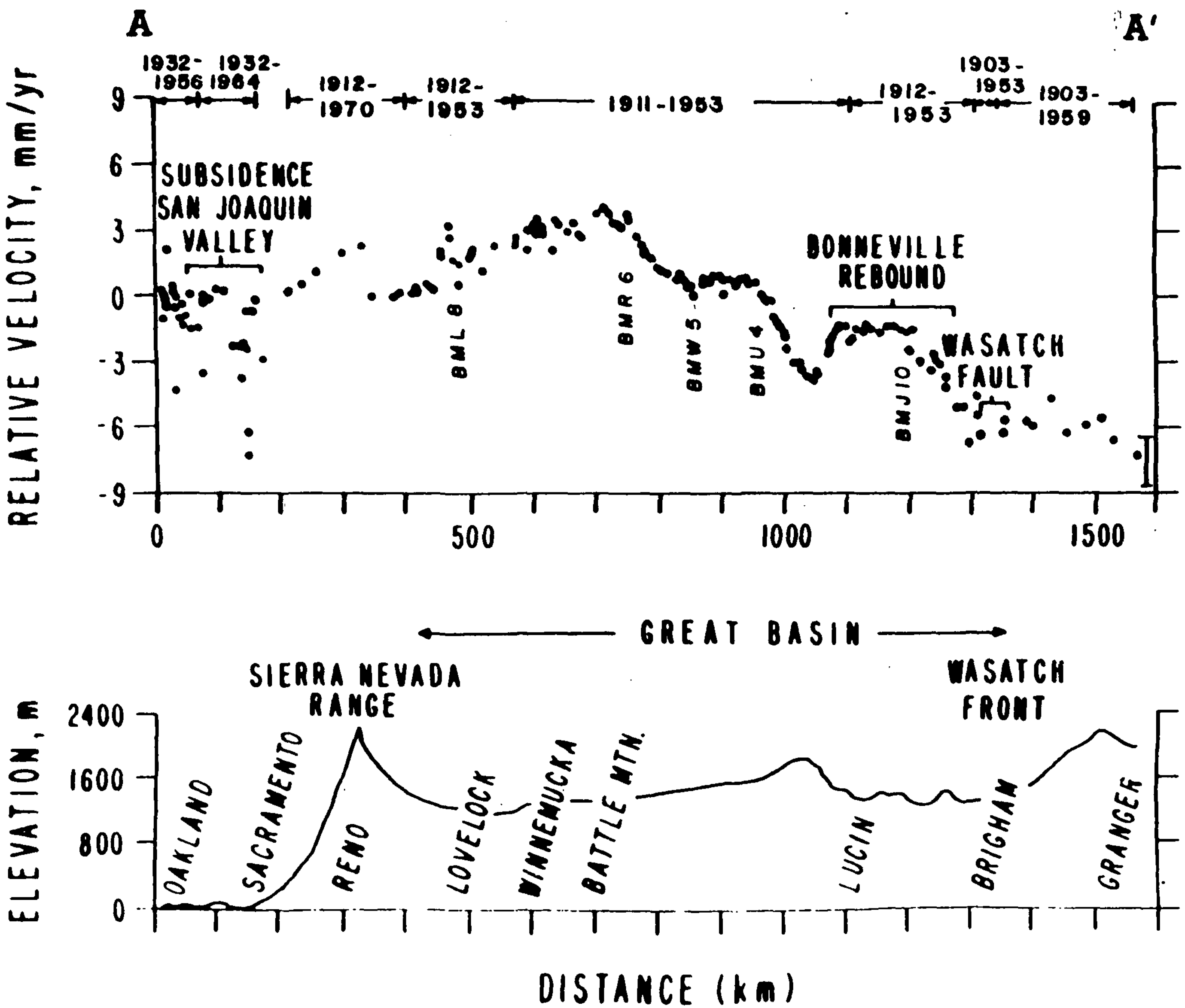

A
A'
1932-1956
1932-1964
1912-1970
1912-1953
1911-1953
1912-1953
1903-1953
1903-1959
RELATIVE VELOCITY, mm/yr
9
6
3
0
-3
-6
-9
SUBSIDENCE
SAN JOAQUIN
VALLEY
BML 8
BMR 6
BMW 5
BMU 4
BONNEVILLE
REBOUND
BMJ10
WASATCH
FAULT
0
500
1000
1500
GREAT BASIN
SIERRA NEVADA
RANGE
WASATCH
FRONT
ELEVATION, m
2400
1600
800
0
OAKLAND
SACRAMENTO
RENO
LOVELOCK
WINNEMUCKA
BATTLE MTN.
LUCIN
BRIGHAM
GRANGER
DISTANCE (km)

Figure 20

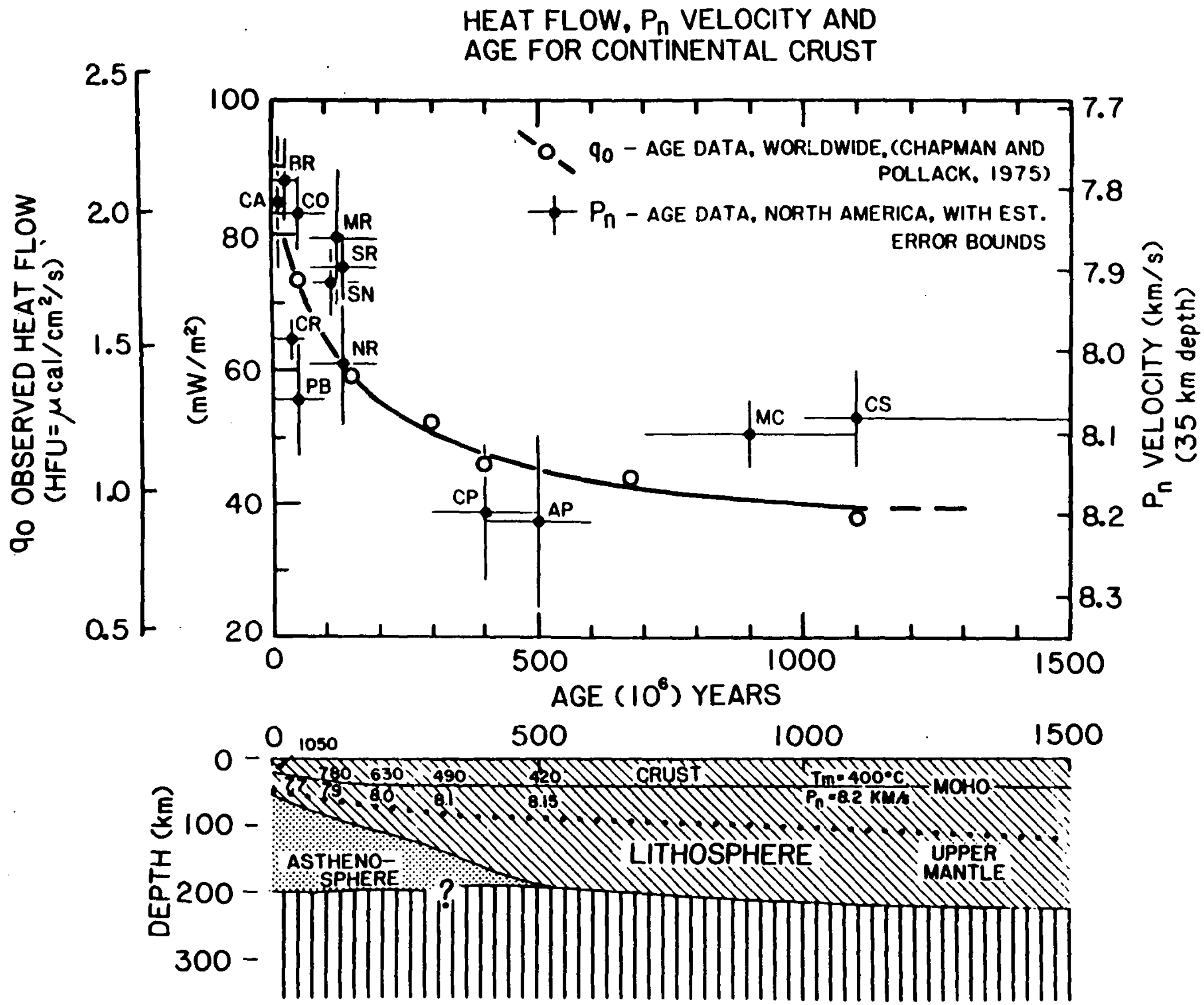

HEAT FLOW, Pn VELOCITY AND
AGE FOR CONTINENTAL CRUST
q0 OBSERVED HEAT FLOW
(HFU=μcal/cm²/s)
(mW/m²)
Pn VELOCITY (km/s)
(35 km depth)
q0 – AGE DATA, WORLDWIDE, (CHAPMAN AND POLLACK, 1975)
Pn – AGE DATA, NORTH AMERICA, WITH EST. ERROR BOUNDS
BR
CA
CO
MR
SR
SN
CR
NR
PB
MC
CS
CP
AP
AGE (10⁶) YEARS
DEPTH (km)
CRUST
MOHO
Tm=400°C
Pn=8.2 KM/s
LITHOSPHERE
ASTHENO-
SPHERE
UPPER
MANTLE
?

Figure 2.1