SHEAR-WAVE VIBRATIONAL DIRECTIONS AND RELATED FAULT MOVEMENTS IN SOUTHERN CALIFORNIA EARTHQUAKES*

By Peter Dehlinger

ABSTRACT

Vibrational directions of direct shear waves from a number of small local earthquakes in southern California, recorded at Pasadena and Riverside, are determined and related to corresponding faulting at the source. A theoretical relationship between wave vibrational directions and fault displacements is proposed. Directions of SV and SH motions from various fault types are adduced from this relationship. Observations of initial shear wave motions indicate generally consistent SH displacements, usually less consistent SV displacements, and ratios of SV/SH which usually vary widely. Polarization of SH waves is indicated; that of SV waves, suggested. The entire shear wave is probably approximately plane-polarized.

The results of this study indicate that horizontal components of faulting in southern California usually follow the same general direction, whereas vertical fault components appear to vary in direction. Comparison of observed SV and SH motions with (1) theoretical shear motions and (2) Gutenberg's (1941) observations of compressional wave impulses, provides analysis of faulting at the source. Seismic data and regional surface geology indicate a fault pattern involving, primarily, northwesterly-trending right-handed transcurrent faults in some parts of southern California, approximately east-west-trending reverse or thrust faults in other parts, and the coexistence of the two in a few localities.

Simplified stress distributions in agreement with the data are discussed briefly.

Introduction

The purpose of this study is to determine the directions of initial motions of transverse waves from southern California earthquakes, and to correlate them with fault displacements. Data consist of initial amplitude measurements of shear waves recorded from more than 200 small local earthquakes occurring between 1941 and 1949. Only direct waves between the focus and the surface were investigated in order to minimize effects of reflections and refractions on vibrational directions.

First impulses of longitudinal waves depend upon directions of fault displacements at the focus of the earthquake. Early literature on this subject has been summarized by Kawasumi (1937). Several Japanese writers, notably Honda (1932), Kawasumi (1933, 1934), Kawasumi and Yosiyama (1935), and Sezawa and Kanai (1936), have presented detailed mathematical treatments of vibrational properties of seismic waves. They have applied some of their analyses to specific Japanese shocks. Gutenberg (1941) investigated first impulses of longitudinal waves from a large number of southern California shocks, and discussed related fault motions.

Acknowledgments

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THEORY

Wave motions can be described in terms of componenents u, horizontal in the plane of propagation; v, horizontal perpendicular to that plane; and w, vertical. Transverse waves are customarily broken into SV and SH components: the SV vibrating in the plane of propagation, containing the directions u and w; the SH vibrating horizontally in the direction v.

Amplitudes of SV and SH waves arriving at the earth's surface can be described as functions of ground displacements. Equations for the partitions of energies and amplitudes at discontinuities in the ground, also applicable at the earth's surface, were developed by Knott (1899) and Zoeppritz (1907, published posthumously in 1919). Equations relating ground motions to incident wave displacements at the surface were presented by Wiechert (1907) and reproduced by Gutenberg (1944*b*), who also presented curves showing the partitioning of SV energy and ratios of ground to incident displacement at the surface as functions of incidence angles.

Observations of ground displacements of large earthquakes suggest that small shocks of magnitudes 2.5 to 4.0 on the Richter scale (1935) involve displacements of less than a few feet, and faulting varying in length from several hundred meters to more than a kilometer. Waves generated from small shocks are nearly spherical in isotropic media at distances of more than several kilometers from the source.

The displacement of particle $\bar{u}$ in the wave fronts occurring on either side of a plane containing the fault surface can be expressed by the known equation

$$\frac{\partial^2 \bar{u}}{\partial t^2} = V_p^2 \operatorname{grad} \operatorname{div} \bar{u} - V_s^2 \operatorname{curl} \operatorname{curl} \bar{u} , \tag{1}$$

where V_p and V_s are the compressional and shear wave velocities, respectively. The displacement $\bar{u}$ can be represented by an irrotational component $\bar{p}$, where curl $\bar{p} = 0$, and a solenoidal component $\bar{s}$, where div $\bar{s} = 0$. Introducing $\bar{u} = \bar{p} + \bar{s}$ into the foregoing equation leads to the familiar wave equations

$$\begin{aligned} \frac{\partial^2 \bar{p}}{\partial t^2} &= V_p^2 \nabla^2 \bar{p} \\ \frac{\partial^2 \bar{s}}{\partial t^2} &= V_s^2 \nabla^2 \bar{s} . \end{aligned} \tag{2}$$

Expressions for displacement components of spherical waves in directions r, θ, ϕ, viz., p_r, p_θ, p_ϕ, and s_r, s_θ, s_ϕ, have been given by Kawasumi (1933) in terms of radial distances, Hankel cylindrical functions of the second kind, and surface harmonics of order n. Equations of these displacements indicate that compressional waves consist not only of a radial component, p_r, but also transverse components, p_θ and p_ϕ. However, the transverse components are of a higher order than the radial component with respect to $1/r$. Similarly, shear waves consist of radial and transverse components s_r, s_θ, and s_ϕ, in which the radial component is of higher order with respect to $1/r$ than are the transverse components. Spherical waves approach true compressional and shear types of displacements as they recede from the source.

If a small displacement acting over a small fault surface can be represented by equal and opposite vectors $\bar{A}$, then approximately spherical waves, formed within hemispheres in each fault block, would appear to have azimuthal symmetry about $\bar{A}$. Solutions of Kawasumi's equations implying azimuthal symmetry, and involving either one or two nodal cones in the wave fronts, indicate that the components of displacement p_r, p_θ, s_r, and s_θ exist, but that the components p_ϕ and s_ϕ vanish. A reasonable and physically intuitive assumption, which also results in azimuthal symmetry and not more than two nodal cones in the wave fronts, is that just beyond the zone of fracturing at the source a wave displacement $\bar{u}$ is about parallel to a fault displacement $\bar{A}$. Since the components p_ϕ and s_ϕ are then nearly zero, displacements $\bar{p}$ and $\bar{s}$ will lie approximately in a plane formed by the vectors $\bar{A}$ and $\bar{R}$, where $\bar{R}$ is the ray path. Vectorially this relationship can be expressed as

$$\bar{A} \times \bar{R} \cdot \bar{s} \approx 0 \tag{3}$$

Based on equation (3), amplitudes of compressional and shear waves are related to the displacement $\bar{u}$ by approximately (fig. 1)

$$\begin{aligned} p &\approx u \cos \theta \\ s &\approx u \sin \theta . \end{aligned} \tag{4}$$

Initial motions of shear waves resulting from fault displacements of small magnitudes can be approximated by equation (3). This analysis is used in figures 2 through 6, illustrating surface distributions of initial SV and SH displacements generated from five types of faults:

1. Transcurrent (strike slip)
2. Vertical, with vertical displacements
3. Horizontal
4. Normal
5. Reverse and thrust

The following assumptions are made in determining theoretical wave displacements in this discussion:

1. The earthquake originates at a point
2. Fault displacements are linear
3. Spherical waves are radiated (implying isotropic media)
4. Initial shear and compressional wave displacements remain essentially in the same fault block in which they originate

Transcurrent (*strike slip*) *fault.*—Transcurrent faulting at normal depths of focus, about 16 km. in southern California (Gutenberg, 1943, 1950), produces the surface distribution of motion illustrated in figure 2. In the plan view of the figure, arrows indicate initial motions in the horizontal directions u and v; "up" and "down" indicate displacements in the vertical direction. In the cross section, "in" refers to motion normal to and into the plane of the paper; "out" refers to motion out of the plane of the paper.

Both SV and SH waves arrive at the surface at random wave-path orientations. Only SV components exist in directions normal to the fault strike. SV and SH amplitudes are both small in the vicinity of the plane containing the fault surface. The amplitude ratio SV/SH is usually less than unity in intermediate directions.

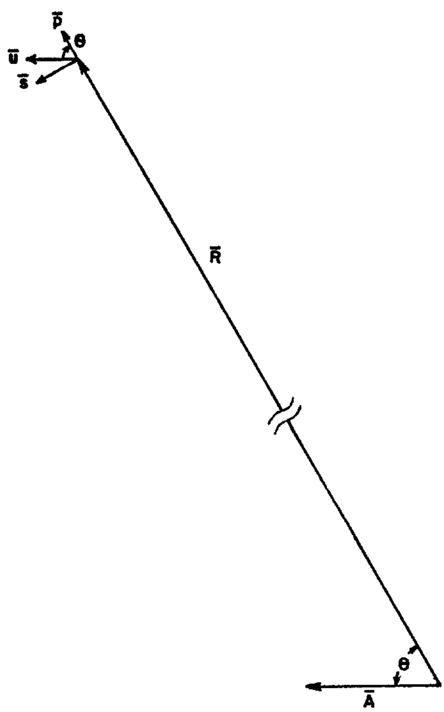

Fig. 1.

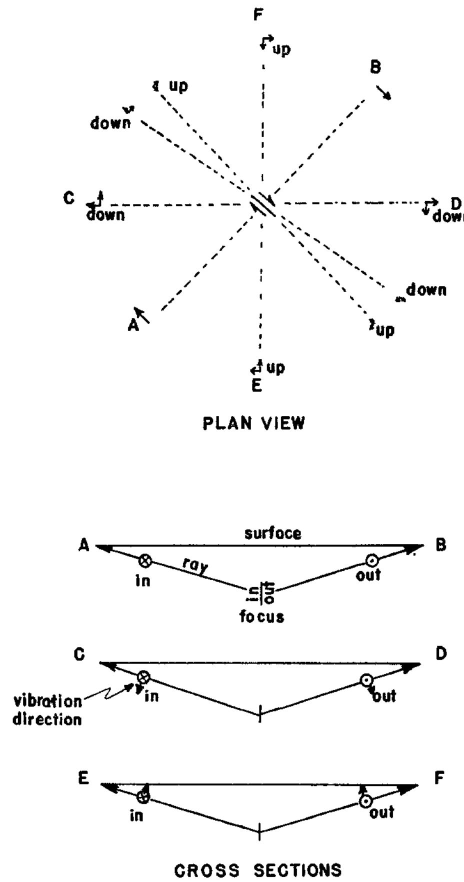

Fig. 2.

Fig. 1. Relationship between the direction of fault movement ($\bar{A}$), ray path ($\bar{R}$), and vibration directions $\bar{p}$ and $\bar{s}$, assuming a displacement $\bar{u}$, just beyond the zone of fracturing parallel to $\bar{A}$.

Fig. 2. Surface distribution of initial SV and SH motions generated by a transcurrent fault displacement at normal depth of focus. Motions in plane of paper are indicated by arrows; motions perpendicular to paper, by "in" if directed into paper, and "out" if out of paper. "Up" and "down" refer to directions of vertical components of SV.

Vertical displacement (vertical fault).—Shear waves generated by vertical faults with vertical displacements consist only of SV components. SV amplitudes for the surface distribution illustrated in figure 3 are approximately constant at given radial distances except near the plane containing the fault surface, where they approach zero. It can be seen in figure 3 that changing the focal depth for this type of fault alters the ratio u/w of the SV waves.

Horizontal fault.—Horizontal faulting at normal depths of focus produces surface distributions of initial shear motions as shown in figure 4. Rays normal to the direction of faulting contain no SV components; those in the same direction, no SH components. Generally, both SV and SH waves arrive at the surface.

Normal fault.—Normal faults having dips of approximately 60 degrees, and originating at about 16-km. depths, produce initial SV and SH motions at the surface, as illustrated in figure 5. Rays perpendicular to the strike of the fault contain no

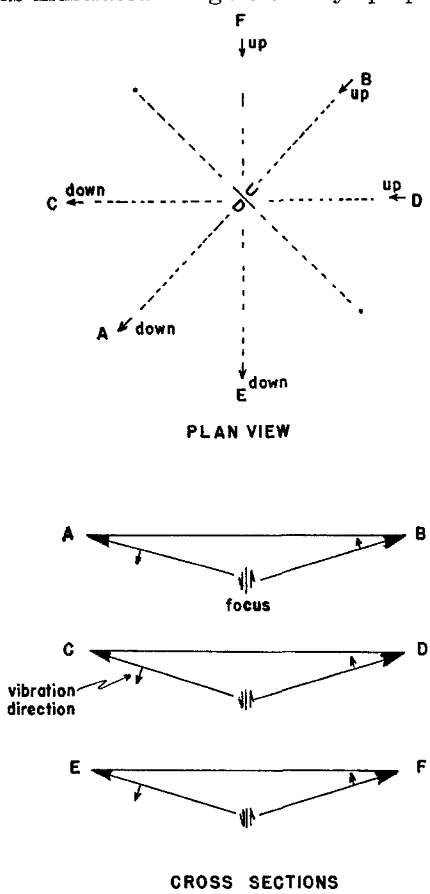

Fig. 3.

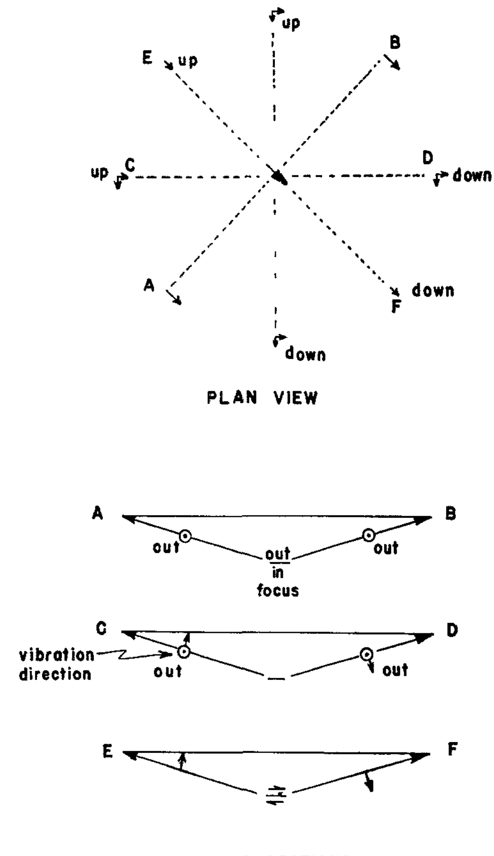

Fig. 4.

Fig. 3. Surface distributions of initial SV motions generated by a vertical fault displacement at normal depth of focus. No SH waves are generated by such fault movements.

Fig. 4. Surface distributions of initial SV and SH motions generated by a horizontal displacement at normal depth of focus.

SH components. In the vicinity of a plane containing the fault surface, SV and SH amplitudes are small and the ratio SV/SH is a minimum for the distribution shown in figure 5. SV and SH waves exist between these two directions, and the ratio SV/SH is greater than unity for the fault dips assumed. The ratio increases as the dip of the fault increases.

Reverse and thrust faults.—Dips of reverse and thrust faults, ranging from about 15 to 75 degrees and originating at normal depths of focus, result in identical surface distributions of initial directions of SV and SH displacements (fig. 6). Rays perpendicular to the strike of the fault contain no SH components. In the vicinity of the plane containing the fault surface, SV and SH amplitudes are small and the ratio SV/SH is the smallest for the distribution shown in the figure. At random wave paths, both SV and SH waves arrive at the surface. The ratio SV/SH increases as the fault dip increases.

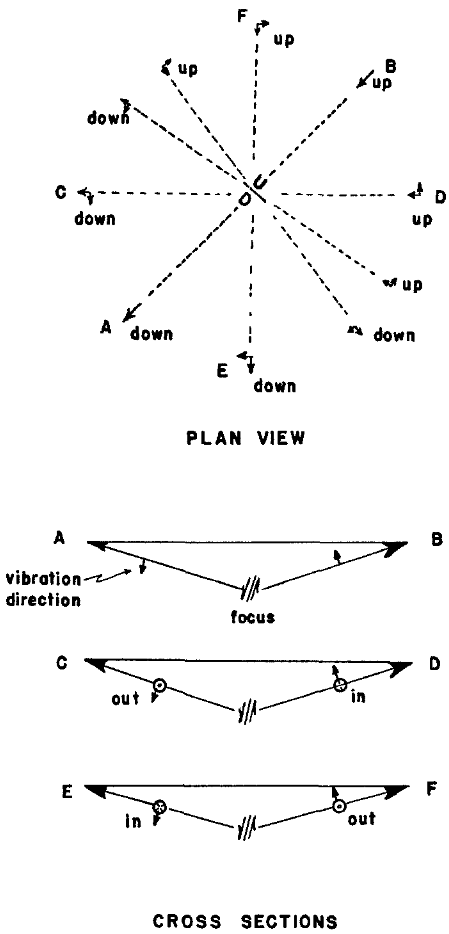

Fig. 5.

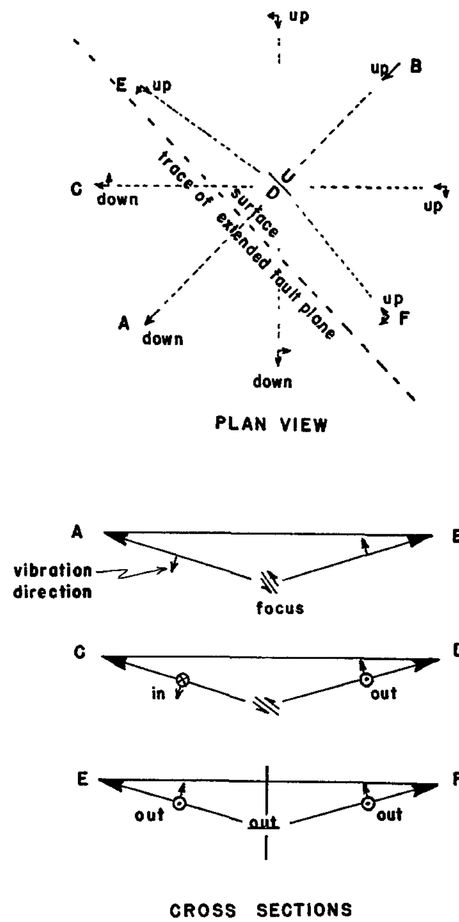

Fig. 6.

Fig. 5. Surface distribution of initial SV and SH motions generated by a normal fault displacement at about a 16-km. depth of focus.

Fig. 6. Surface distributions of initial SV and SH motions generated by a reverse or thrust fault at normal depth of focus.

Each of the four fault types illustrated in figures 2 through 6, originating at normal depths of focus, is seen to result in distinctively different over-all surface distributions of initial SV and SH displacements.

Methods and Materials

To determine shear-wave vibrational directions least affected by discontinuities, measurements were limited to shocks at epicentral distances of less than 130 km. It was considered that if wave paths according to Gutenberg's (1950) hypothesis of horizontal velocity layering in the upper crust were assumed, the vibrational directions of the waves within this epicentral range would not be altered unduly.

Initial amplitudes of transverse waves were measured from records of numerous local southern California earthquakes and resolved into corresponding incident motion. Shocks of small magnitude (2.5 to 4.0 with a few up to 4.5 on the Richter [1935] earthquake magnitude scale) were selected.

Pasadena and Riverside seismograms were used for amplitude measurements. Instruments at the Pasadena station include two horizontal-component short-period Wood-Anderson torsion seismographs and three three-component long- and short-period Benioff electromagnetic seismographs. At the Riverside station, two horizontal-component torsion seismographs and one short-period vertical instrument of the Benioff type have been installed. Most useful to this study were the short-period torsion seismographs, recording through optical systems.

Transverse waves were identified on the seismograms with the aid of southern California travel-time curves (Gutenberg, 1944*a*). Directions and magnitudes of total horizontal ground displacements were calculated as vector sums of north-south and east-west displacements. Horizontal components u in the direction of propagation and v normal to that direction were resolved from these total values. Vertical displacements w were obtained from vertical-component instruments.

Incident SV and SH amplitudes were resolved from displacements u_g, v_g, and w_g in accordance with Wiechert's (1907) equations for partitions of amplitudes incident to the earth's surface. Incident SV amplitudes were determined from curves (Gutenberg, 1944*b*, fig. 3b, p. 99) relating amplitude ratios u_g/SV and w_g/SV to incidence angles i_0. Incident SH amplitudes have comparatively simple reflection characteristics and are taken as half the magnitudes of the v_g ground displacements.

Incidence angles used for SV amplitude determinations are computed for direct rays, assuming a 16-km. depth of focus and ray paths according to Gutenberg's (1950) crustal velocity distribution. In regions where there are no sedimentary rocks, the upper layer appears to be about 5 km. thick and has a transverse velocity of 3.4 km/sec. A discontinuity appears to exist between the upper layer and the one directly beneath it, which latter seems to have an average velocity of 3.8 km/sec. The thickness of the second layer is not definitely known, though it grades into the next or third layer without evidence of discontinuity. At about 16 km. depth the velocity has decreased to approximately 3½ km/sec.

Initial SV and SH motions computed in this study are plotted on fault maps in southern California (figs. 7–12). Observed displacements are plotted at the epicenters.

Factors Affecting Reliability of Results

The reliability of SV, SH, and SV/SH determinations could be affected by several factors.

First, errors in epicentral locations. Except for shocks near the station, this factor has little influence on results obtained in this study, since u is assumed to be directed from the epicenter to the station; v is assumed to be normal to this direction, and epicentral locations are known within 5 to 15 km.

Second, initial amplitude identification on seismograms. The possibility exists that later phases of more distant shocks might be mistaken for initial wave displacements.

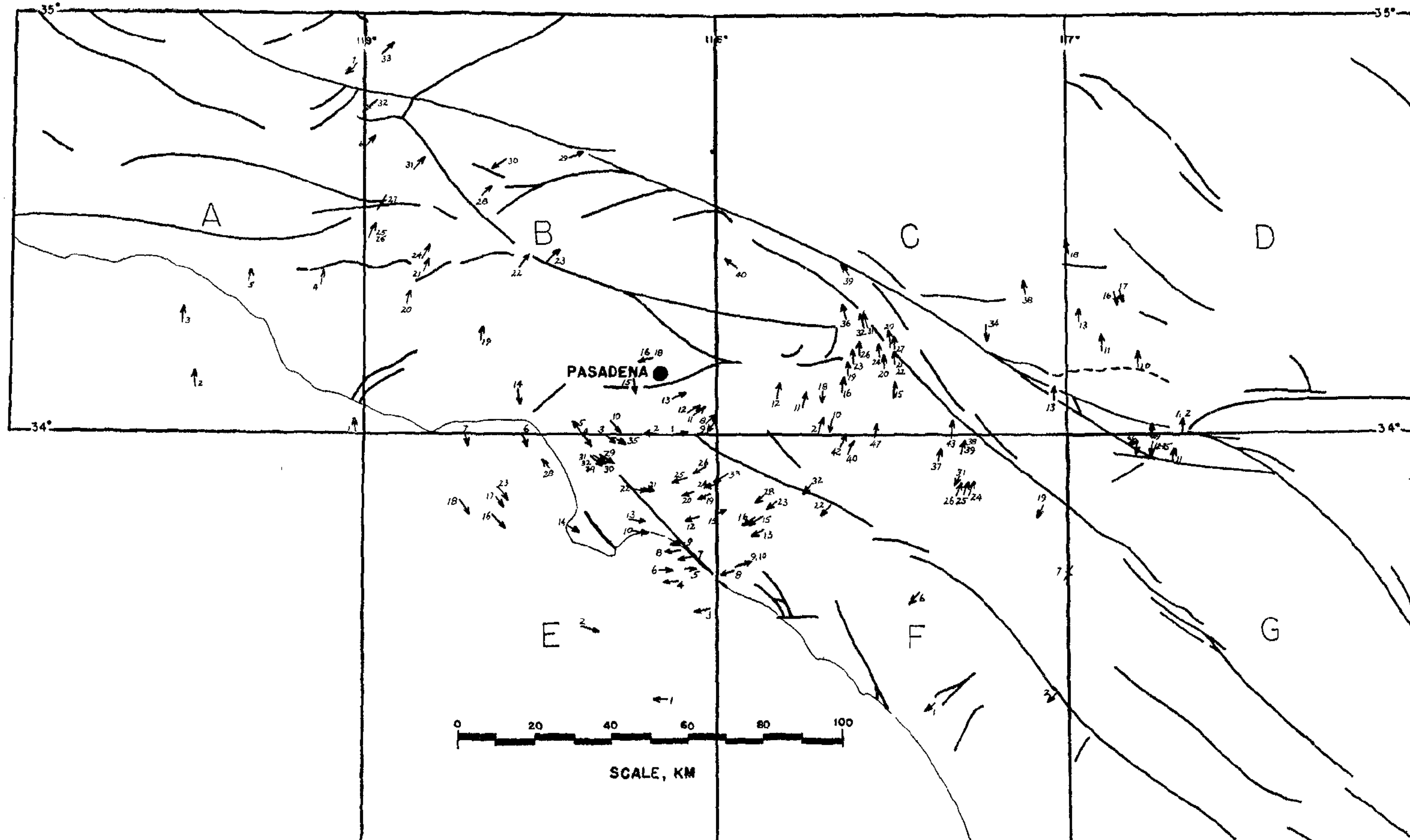

Fig. 7. Distributions of initial SH motions recorded at Pasadena and plotted at epicenters on fault map of southern California. Displacement directions are indicated by arrows; zero displacement, by +. Shocks are identified by numbers.

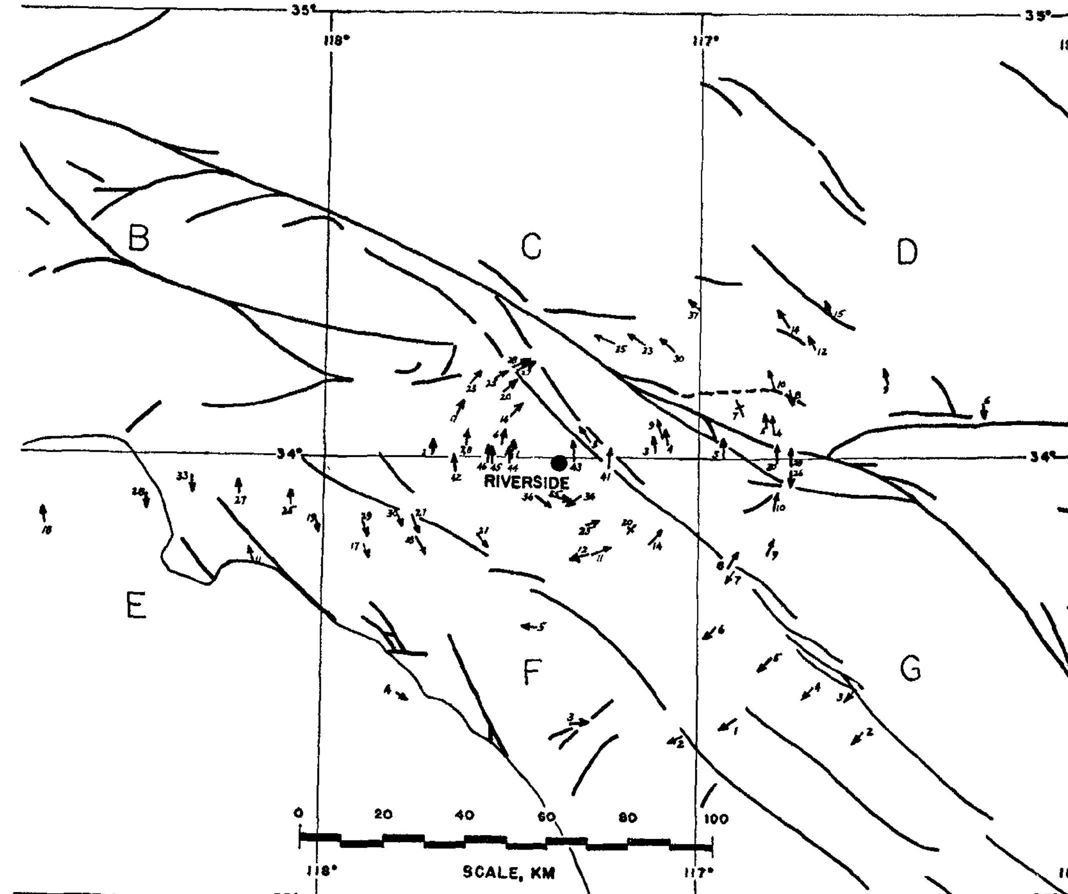

Fig. 8. Distributions of initial SH motions recorded at Riverside and plotted at epicenters on fault map of southern California. Displacement directions are indicated by arrows; zero displacement, by +. Shocks are identified by numbers.

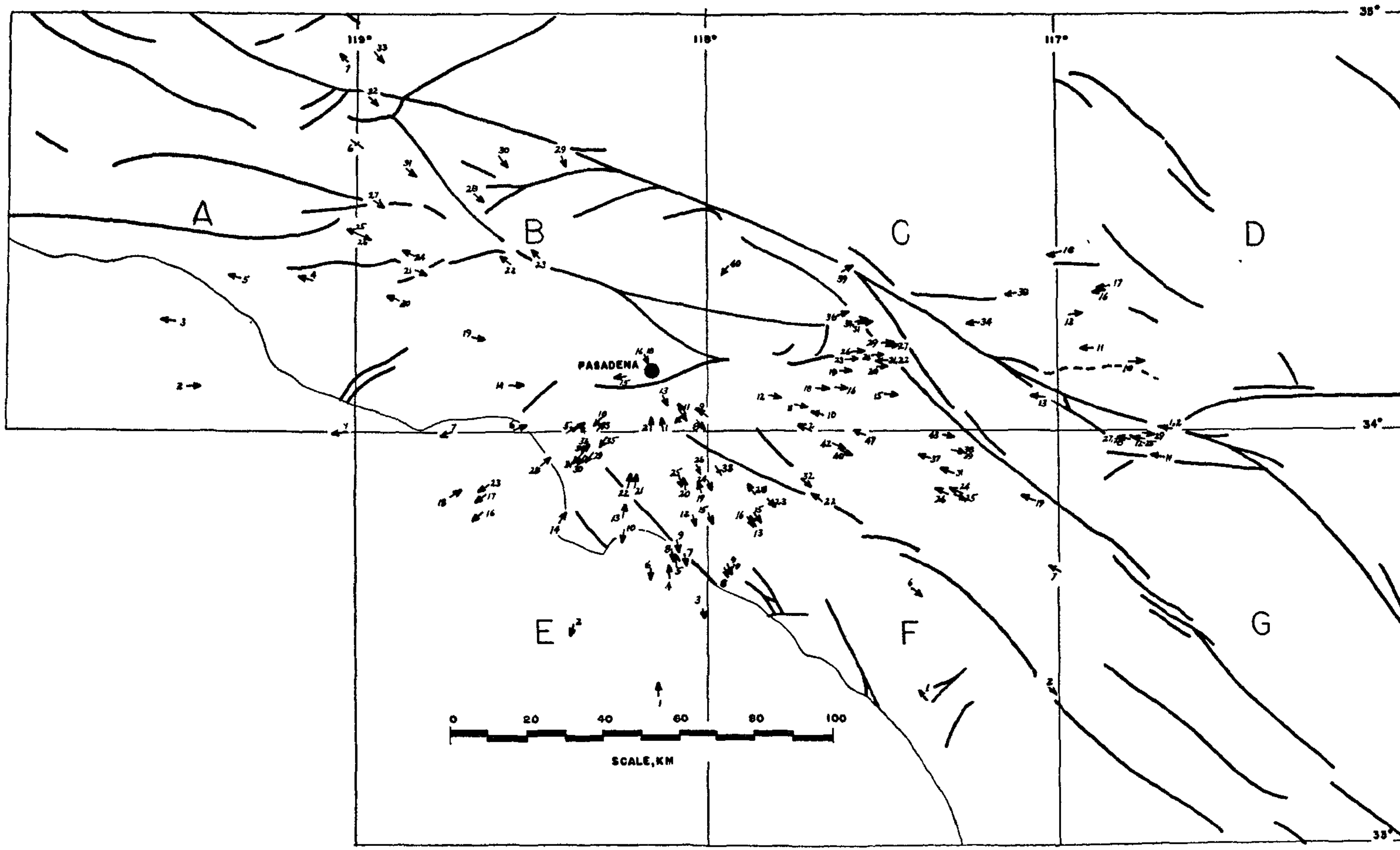

Fig. 9. Distributions of the component u of the initial SV motions recorded at Pasadena and plotted at epicenters on fault map of southern California. Displacement directions are indicated by arrows; zero displacements, by +. Shocks are identified by numbers.

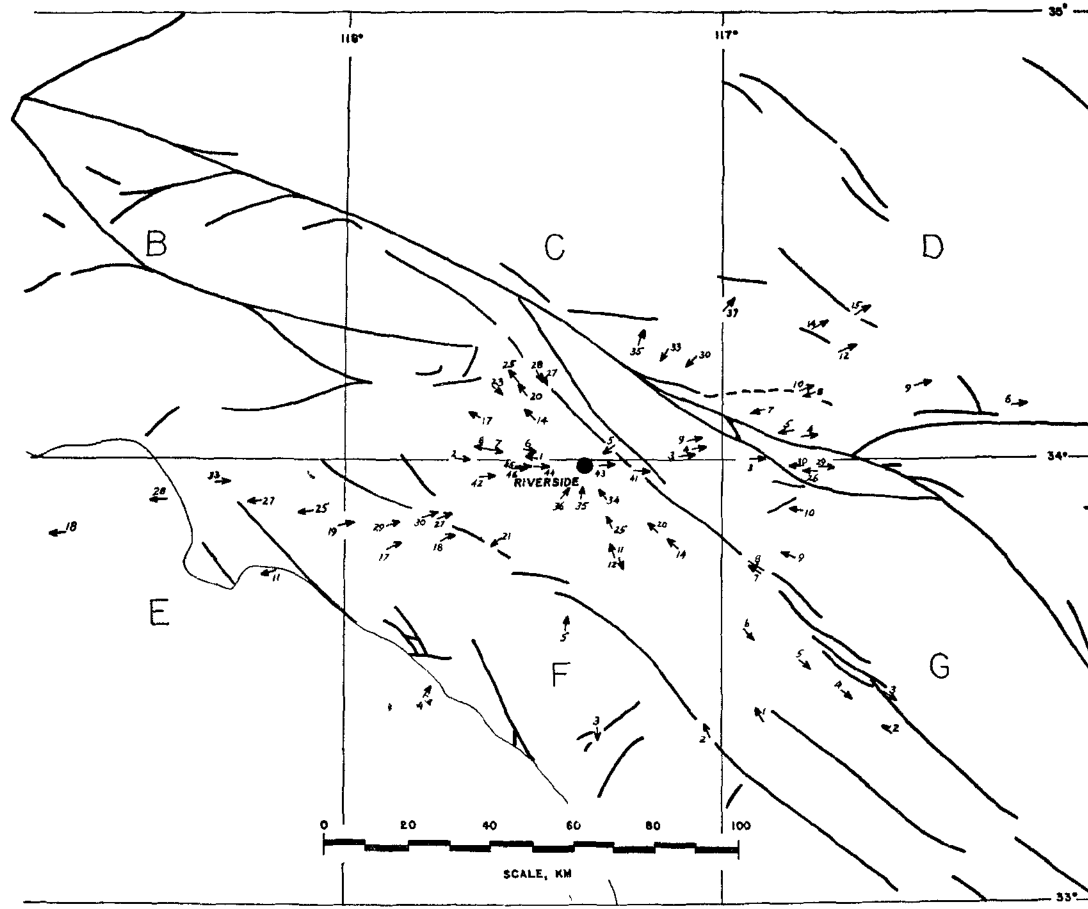

Fig. 10. Distributions of the component u of the initial SV motions recorded at Riverside and plotted at epicenters on fault map of southern California. Displacement directions are indicated by arrows; zero displacements, by +. Shocks are identified by numbers.

However, initial shear motions on seismograms from 14 aftershocks of an earthquake at 130 km. epicentral distance indicated, with few exceptions, the same SV and SH displacement directions. Since the smaller of these aftershocks show the same motions as the larger ones, it appears that initial displacements of even the more distant shocks were measured.

Third, response of seismographs to ground transients. In his discussion of the responses of mechanical seismographs to harmonic transient impulses, Berlage (1930) demonstrates that the initial phase of 0.5-second transients (an average in this study) is recorded quite accurately by 0.8-second torsion instruments. His results can be used only as approximations for torsion-seismograph responses to actual transients, however, since ground transients are not likely to be harmonic. Response of electromagnetic seismographs to transient inputs, is difficult to interpret.

Fourth, anistropy in the upper crustal layers. According to Stonely (1949), who follows the method of Rudzki (1911), anistropy in continental structures results in different SV and SH velocities. However, anistropy in the upper crust of southern California is too small to appear on seismograms, since, regardless of ray azimuths, initial amplitudes of shear waves on three-component seismographs were observed to arrive within 0.2 second of each other.

Fifth, variations in wave paths and depths of focus. In southern California, variations in focal depths do not alter incidence angles or corresponding SV determinations to any significance. Some of the direct waves traversing the Los Angeles Basin to be recorded in Pasadena pass through large thicknesses of sediments overlying older rocks. Wave paths can only be surmised, since precise thicknesses and velocities of the sediments are not known. Initial directions of SV and SH motions are probably only slightly affected, though the magnitude of SV and the ratio SV/SH are undoubtedly altered.

It appears from the foregoing that direct SV vibrational directions may be uncertain, and values of SV/SH may be doubtful, but that direct SH vibrational directions are probably reliable.

Distributions of Observed SH and SV Motions

Striking consistencies of motion within local regions appear in initial directions of SH vibrations observed in Pasadena and Riverside (figs. 7 and 8), indicating that strongly preferred directions of horizontal fault components exist in southern California and that SH waves are apparently polarized.

Considerably less consistency characterizes directions of SV vibrations (Figs. 9 and 10) although some uniformity occurs in several very localized regions. Discrepancies of SV motions may be due to the fact that vibrational directions of SV waves are known to be functions not only of horizontal fault components and ray azimuths, but also of vertical fault displacements. SV data indicate discordant vertical movements along faults in the same vicinity. Polarization of the SV waves is suggested but not clearly shown. It is plausible that the entire shear wave may be approximately plane-polarized.

The SH and SV motions of small faults may be analyzed by comparing observations with theoretical vibration directions and corresponding fault movements (figs. 2–6). Small fault displacements over limited fault surfaces can be considered as linear movements, but the assumption (p. 157) of a straight-line path must be modified since direct rays between the source and the surface are refracted.

Refractions through the crustal layers result in a difference in incidence angles between the surface and the source. Energy losses of direct SV or SH waves from refractions at discontinuities in the crust are negligible for the approximate angles involved (Gutenberg, 1944*b*, fig. 1, p. 95).

Direct rays originating at normal depths of focus usually travel from a layer of low velocity to an overlying layer of higher velocity. For the direct waves recorded, incidence angles at the source are calculated to be 70 degrees or less. However, a recorded direct wave traversing the basin may leave the source at a larger incidence angle.

It can be concluded that, except for the influence of sediments upon rays traversing the basin, the theoretical illustrations of figures 2–6 represent observed SH and SV motions originating from faults, and data can be compared to these illustrations to determine possible related fault types.

The tectonic interpretations of the data that follow are based on comparison of the SH and SV data with figures 2–6, and comparison with Gutenberg's (1941) observations of impulses of compressional waves occurring earlier (1934–1940) but in the same region as those involved in this study (1941–1949). Compressional impulses were not recorded in this investigation.

Fault types consistent with observed longitudinal and transverse wave impulses are described in the following paragraphs. Shocks are designated on figures 7–12 by numbers, increasing from south to north in each lettered region.

Region C: shocks between Pasadena and Riverside.—Shocks between Pasadena and Riverside show northerly SH motions, suggesting that both stations are situated on fault blocks moving relatively northward. SV motions suggest that both stations are situated on the downthrown fault blocks for some shocks and on the upthrown blocks for others. SV/SH ratios, though of questionable reliability, suggest a wide range of fault dips.

Of seven shocks in this group recorded at both Pasadena and Riverside, all indicated northerly SH displacements, four indicated the same SV directions, and three indicated opposite SV directions. Two showed similar SV/SH ratios, five were markedly dissimilar, and differences in ratios were not consistent at the two stations.

According to Gutenberg (1941), initial impulses of compressional waves from this epicentral region usually arrive at Pasadena as compressions and at Riverside as dilatations.

Faulting of an approximately east-west-trending reverse or thrust type is consistent with the SH and P impulses and agrees, generally, with SV and SV/SH data. The San Andreas type of motion, a northwesterly-trending right-handed transcurrent type of movement is not indicated by the SH displacements recorded at Riverside. The San Andreas fault, lying north of this region, probably defines the northerly limit of the apparent reverse or thrust type of movement.

Region E–F: south of Pasadena.—Shocks south of Pasadena usually show southerly SH motions at both Pasadena and Riverside, indicating predominantly southerly displacement of the fault blocks on which the stations are situated. About 75 per

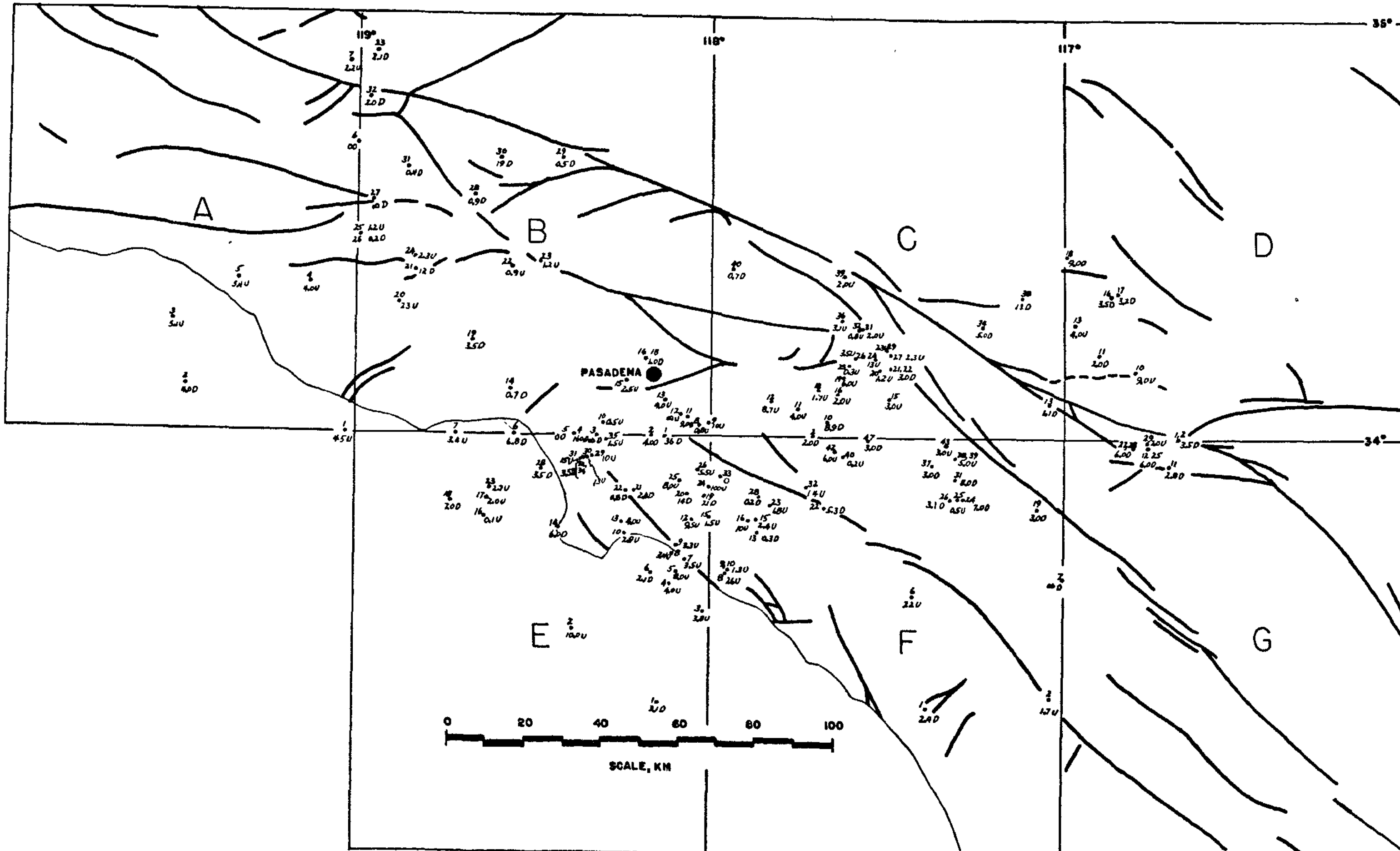

Fig. 11. Distributions of the component w of the initial SV motions and amplitude ratios of SV/SH waves received at Pasadena and plotted at epicenters on fault map of southern California. Numbers above location refer to shock number. Numbers below location give ratios of SV/SH, and "U" or "D" indicates initial up or down motion.

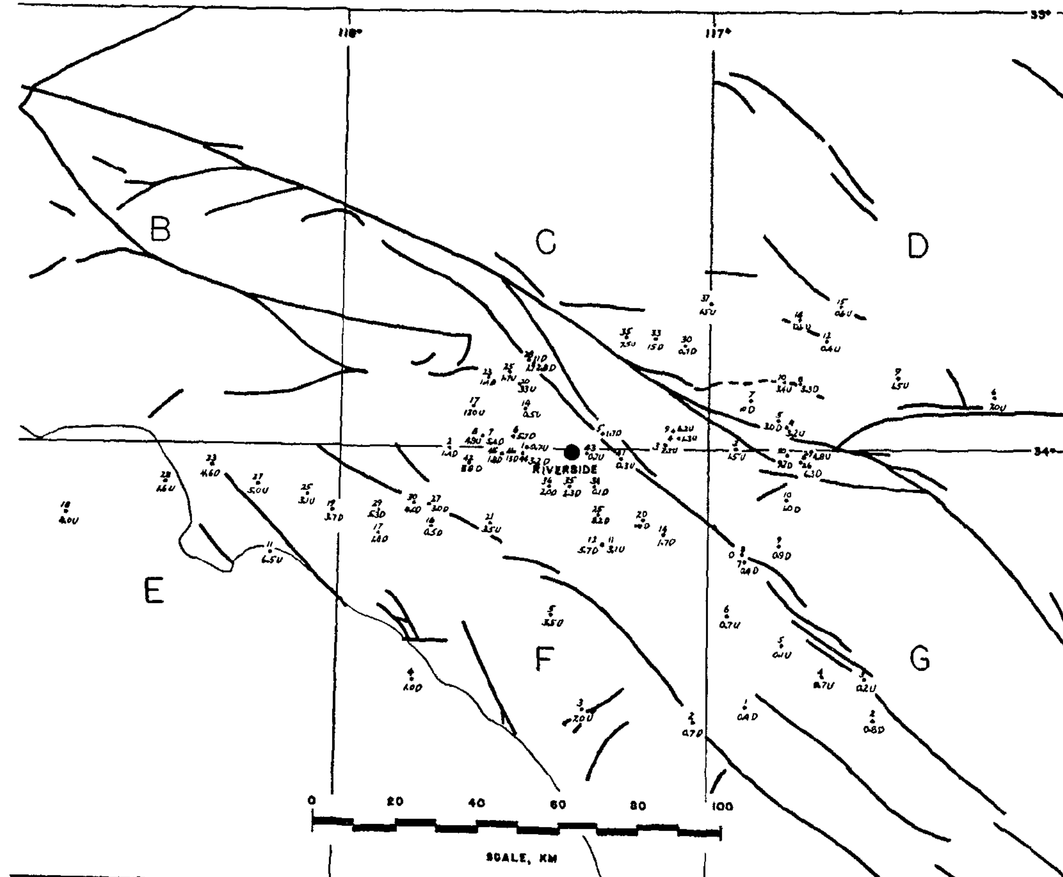

Fig. 12. Distributions of the component w of the initial SV motions and amplitude ratios of SV/SH waves received at Riverside and plotted at epicenters on fault map of southern California. Numbers above location refer to shock number. Numbers below location give ratios of SV/SH, and "U" or "D" indicates initial up or down motion.

cent of the SV waves recorded at Pasadena arrived as up motions; the relatively few recorded at Riverside arrived mostly as down motions. Ratios SV/SH varied markedly.

Gutenberg (1941) noted that longitudinal waves from these epicenters usually arrive as dilatations at Pasadena and as compressions at Riverside.

A slightly north-of-east-trending reverse or thrust movement is the fault type most consistent with the data. The Norwalk fault may be one such displacement. Several scattered shocks suggest a few San Andreas types of motion. Due east-west reverse or thrust faults are not substantiated by some of the P data at Riverside, nor are the SH data at that station consistent with the northeasterly-trending left-handed transcurrent movement. The data generally do not confirm vertical, horizontal, or normal faulting.

Region E: southwest of Pasadena.—Shocks southwest of Pasadena were studied only at the Pasadena station. SH motions indicate southerly displacements of the fault blocks on which Pasadena is situated. Although these waves probably traversed the sediments of the Los Angeles Basin, no effect of the sediments on SH motions is evident. SV motions are inconsistent; the data are too erratic to permit determination of possible effects of the sediments on SV vibrational directions.

As shown by Gutenberg (1941), longitudinal waves in this region usually arrive as dilatations at Pasadena, and as compressions at Riverside.

Faulting consistent with both the compressional and shear wave data includes northeasterly-trending reverse movements and northwesterly-trending displacements of the San Andreas type.

Region A–B: northwest of Pasadena.—Shocks northwest of Pasadena were studied only on Pasadena records. Most of the SH motions have northerly components. SV values and SV/SH ratios are inconsistent.

Gutenberg (1941) shows that most longitudinal waves in this region arrive at Pasadena as dilatations, a few as compressions; at Riverside, as either dilatations or compressions.

The data suggest more than one type of faulting, some consistent with east-west-trending reverse or thrust faults, some with northwesterly-trending left-handed transcurrent faults.

Region C–D–F–G: east and northeast of Riverside.—Shocks east and northeast of Riverside show SH motions with northerly components at Riverside. At Pasadena, both northerly and southerly motions are indicated by the limited data from this region. SV and SV/SH data are erratic at both stations.

According to Gutenberg (1941), most longitudinal waves in this region are recorded at Riverside as compressions, some as dilatations; at Pasadena, they usually arrive as compressions.

The San Andreas type of faulting is consistent with most of the data; some data indicate reverse or thrust types of movement. Data recorded from a group of aftershocks near Cabazon, where the San Andreas fault strikes approximately east-west for a short distance, suggest reverse or thrust faulting. Transcurrent and reverse fault types may well coexist in the region east of Riverside.

Region F–G: southeast of Riverside.—Shocks southeast of Riverside were studied only at the Riverside station. Most of the SH motions show southerly components, but several show northerly motions, particularly in the northern part of this region. Most of the SV waves from shocks at epicentral distances of more than 50 km. indicate consistent initial down motions, and the corresponding SV/SH ratios are small.

According to Gutenberg (1941), longitudinal waves in this region usually arrive at Pasadena as compressions; at Riverside, as either compressions or dilatations.

The data are consistent with the San Andreas type of movement; the rays from such fractures have approximately followed the general line of faulting toward the two stations, and the data reveal variations to be expected accordingly. Primarily horizontal faulting in northwesterly and southeasterly directions is further indicated by the rather unusual consistency in the SV motions and the small SV/SH ratios.

Fault Patterns in Southern California

Crustal structures and fault movements in southern California have been discussed by Gutenberg (1941, 1943) and by Wood (1947). Particularly interesting are Gutenberg's (1941) conclusions that impulses of longitudinal waves from shocks south of the Transverse Ranges are consistent with the San Andreas type of movement, with northwesterly-trending right-handed transcurrent types of displacements, the southwesterly block moving relatively northwest. Left-handed motions were rarely evidenced along such faults.

Two types of faults appear to prevail in the vicinity of the Los Angeles Basin in southern California, according to surface geologic mapping.[1] They are a northwesterly-trending movement of the San Andreas type, and an east-west-trending essentially vertical type of displacement. The agreement of such a fault pattern with the seismic data obtained in this study, and with earlier studies by Gutenberg (1941), suggests that present-day faulting may be very similar to that of the recent geologic past.

Fault types, as they agree with the seismic data, may be located regionally as follows:

1. Along the San Andreas fault and northeast and southeast from Riverside, transcurrent displacements trending northwesterly occur. In addition, east-west-trending reverse or thrust faults may exist east of Riverside. In this region, where the San Andreas fault briefly strikes east-west, displacements may have large vertical components instead of being primarily horizontal. Initial motions of a series of aftershocks from this region are consistent with reverse or thrust movements.

Southwest of the Los Angeles Basin, reverse, thrust, or San Andreas types of displacements may occur.

2. In most of the Los Angeles Basin, reverse or thrust faults trending about east-west appear to prevail. The inconsistency of SV and SV/SH data suggests that fault-plane dips vary. Some may be low-angle, many may be high-angle dips. SV data suggest northerly fault dips from some shocks, southerly fault dips from others.

3. In the Transverse Ranges northwest of Pasadena, both east-west-trending reverse faults and northeasterly-trending transcurrent faults occur. Most of the transcurrent faults appear to be left-handed, with the northwest block moving southwest. According to the data, the northwest-trending right-handed San Andreas movement is uncommon in this region.

[1] Oral communication, Dr. J. P. Buwalda.

Possible Stress Distributions in Southern California

Although the actual source of stresses in southern California is not known, Gutenberg (1941) suggests that shearing stresses resulting from differences in the Pacific and continental structures in the crust may produce the faulting observed. Observations of fault patterns and seismic data permit also a general postulation of regional compressive stress distributions.

All the fault types mentioned in this paper could have been produced by a maximum principal stress acting in a north-south direction. The strikes of both the transcurrent and the thrust faults are in agreement with principal stresses directed very roughly north-south, east-west, and vertical, although these directions may vary appreciably in mountainous regions.

The over-all fault pattern could be produced by the following approximate stress distribution based on the analysis of Anderson (1942). Stress distributions in southern California, generalized and roughly consistent with the seismic data, may be postulated as:

1. In the region of the San Andreas fault northwest and southeast of Riverside, and possibly also in the region southwest of the Los Angeles Basin:

$$\sigma_n > \sigma_v > \sigma_E$$

where σ_n is the north-south principal stress, σ_E the east-west, and σ_v the vertical principal stress.

2. East of Riverside where the San Andreas fault strikes east-west for a short distance, and in the Transverse Ranges northwest of Pasadena:

$$\sigma_n > \sigma_E \sim \sigma_v$$

3. In most of the Los Angeles Basin as far east as Riverside, and particularly in the region between Riverside and Pasadena:

$$\sigma_n > \sigma_E > \sigma_v$$

Variations in the strikes of these faults suggest that in this region σ_n may not be very much larger than σ_E.

These oversimplified stress distributions are undoubtedly altered by complications at depth. The angles between the northwesterly-trending and northeasterly-trending transcurrent faults (e.g., the San Andreas and Garlock faults) are usually larger than this simple picture indicates. Furthermore, although this stress distribution explains thrust faults, reverse faults may involve additional stresses.

The assumed stress picture postulates complementary systems of faults. Surface geology indicates that one set of the complementary systems is probably considerably more active than the other, again indicating that other crustal stresses may also be active.

The over-all fault pattern in southern California, however, is essentially consistent with a stress distribution in which a north-south principal stress direction is a maximum, and in which, in some areas, $\sigma_E > \sigma_v$, in others $\sigma_E \sim \sigma_v$, and in still others, $\sigma_E < \sigma_v$.

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