INITIAL MOTION OF THE FIRST LONGITUDINAL EARTHQUAKE WAVE RECORDED AT PASADENA AND HUANCAYO*

By Markus Båth

Introduction

The initial motion of the first longitudinal earthquake waves (P waves) recorded at a station is (1) upward or away from the epicenter (compression = *c*) or (2) downward or toward the epicenter (dilatation = *d*). The P waves do not change their phase during their propagation through the earth, and the first motion, obtained from seismograms, depends only on the earthquake mechanism. The directions of later waves (such as pP, P_cP, PP, etc.) depend both on the earthquake mechanism and the possible phase changes on reflections; also, their directions are generally more difficult to determine from seismic records, owing to the motion already existing when they arrive. When the earthquake mechanism has been established by means of the P waves, the direction of motion of the later waves could give some information about the earth's interior.

The determination of the geographical distribution of compression and dilatation for a given earthquake or for a large number of earthquakes at a given seismographic station is an old problem. The value of these distributions is to give tectonic information about the earthquake areas. Reference is made to a paper by Gutenberg (1941),[1] which in addition to a detailed study for California also contains several general views on this problem as well as references to earlier literature. A comprehensive bibliography has been given by Kawasumi (1937). The world distributions of compressions and dilatations have earlier been studied for a few stations: for Pasadena with material from 1931–1934 by Gutenberg and Richter (1935), see also Gutenberg and Richter (1938), p. 283; for Uccle by Somville (1925); for Zi-ka-wei, as well as for a number of other stations, by Gherzi (1924, 1928, 1937); for Helsinki by Vesanen (1942); for Rome by Filippo and Marcelli (1949). See also Gutenberg (1929), p. 193, where a few data for Pulkovo are given, obtained from Galitzin. Since this manuscript was completed, there has appeared a paper by Byerly and Evernden (1950), who have studied the first motion recorded at Berkeley. In a comparison of Berkeley and Pasadena the author finds very good agreement (about 90 per cent), and the few disagreements (almost exclusively along the American side of the Pacific) can be explained by the different positions of the two stations.

It is necessary to determine the first motion at a large number of stations in order to get the desired information both on the orientation of the fault planes and the directions of motion along the fault planes. The present paper gives the geographical distribution of compressions and dilatations for Pasadena and Huancayo. It is the author's hope that this work will be continued for many seismologic stations, since until that is done no very detailed information about the tectonics can be expected.

In researches of this kind it is important to get an accurate determination of the direction of motion and to have accurate information about the position of the epicenters. The location of epicenters was taken from Gutenberg and Richter (1949). To make the distribution as reliable as possible, only cases with clear beginnings

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[1] See References at the end of this paper.

were used. A small motion in one direction may often be followed by a much larger motion in the other. The P phase is often composed of several waves of different periods, the beginnings of which may be in opposite directions. An instrument sensitive to short periods will record the short waves, which will often not be recorded by instruments sensitive to longer periods—a fact of importance in the comparison of first motions recorded by different instruments. Larger shocks are more complicated than the smaller ones, but a special investigation showed that the magnitude of the shocks had no influence on the direction of the first motion. At stations situated on or near the extensions of fault planes one may expect interference phenomena between waves originating on the two sides of the fault planes, with ensuing complications.

Materials Used

The information on compression and dilatation for Pasadena (lat. 34° 08.′9 N, long. 118° 10.′3 W) and its auxiliary stations (Tinemaha, Haiwee, Riverside, Mount Wilson, Mount Palomar, Santa Barbara), and Tucson also, given in the Pasadena seismic bulletin for 1931–1949, was collected for the earthquakes tabulated by Gutenberg and Richter (1949). For 1947–1949 the epicenter determinations by Gutenberg at the end of each year in the Pasadena bulletin were used. Compression (*c*) and dilatation (*d*) in this bulletin have all been determined by Richter, and they have been given only in clear cases. Many instances have been checked directly from the records by the present author. The determinations depend mainly on the short-period Benioff reluctance transducer vertical seismometer. The directions at all the stations of the group are usually the same, except of course for local shocks, and except where the epicenter lies on or near a nodal line.

Compressions and dilatations for Huancayo have been determined by the author directly from the records for 1932–1945 and for the second half of 1949, which are on file at the Seismological Laboratory at Pasadena. The Huancayo station is situated in Peru at lat. 12° 02.′8 S, long. 75° 20.′4 W. It is equipped with a Wenner horizontal seismometer (N–S, E–W) and a Benioff reluctance transducer vertical seismometer. The directions of motion were determined from all three records whenever possible, which must be consistent if the determinations are correct. Only clear cases were used, and then only those tabulated by Gutenberg and Richter (1949).

The number of reliable cases obtained for Huancayo was naturally less than the number for Pasadena, owing to the difference in instrumental equipment at the two stations. For Huancayo most of the observations refer to South and Central America and the Atlantic Ocean; there are a few in North America and some observations of P′ for earthquakes in the East Indies and neighboring areas. Of importance for the number of observations is also the extent to which earthquake areas fall within the shadow zone 103°–143°. For Huancayo, these areas include the Aleutians down to Japan, the Pacific islands from New Zealand to New Guinea, and eastern Europe and western Asia. For Pasadena, the principal earthquake areas within the shadow zone are the East Indies, the Transasiatic Belt, and South Atlantic.

Results

The results are shown on maps, where a triangle means compression (*c*), a circle dilatation (*d*). A solid triangle or circle indicates deep shock (*ds*; depth $h > 300$ km.), a heavy open triangle or circle indicates intermediate shock (*is*; 70 km. $\leqq h \leqq$ 300 km.), and a light triangle or circle represents shallow shock (*ss*; $h <$ 70 km). When there are two or more observations for the same epicenter, confirming each other, only one sign is given. The directions to Pasadena and Huancayo, as the case may be, have been drawn on the maps.

In the following description only a few of the most important features of the distribution will be pointed out. The explanations given for a few of the cases are only tentative. For several cases, more than one explanation seems possible, and definite conclusions may be obtained only by using a large number of stations. The division into regions is the same as used by Gutenberg and Richter (1949). References to

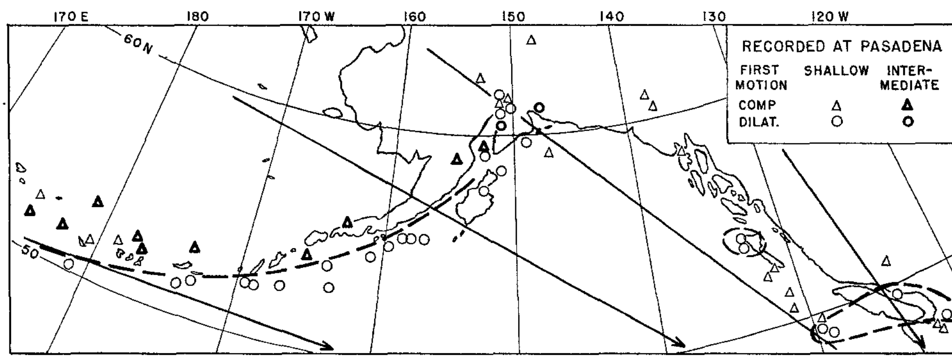

Fig. 1. Aleutian Islands, Alaska, British Columbia.

investigations of a few individual earthquakes have been made, but only when they include data about compression and dilatation.

Region 1: Aleutian Islands, Alaska (fig. 1).—Pasadena (*Pa*) has a very regular distribution with *d* for *ss* and *c* for *is*. Exceptions occur at the west end (westward from about 178° W) with *c* for *ss*, where the extension of the fault lines presumably passes through or near *Pa*. Complications occur about 151° W, where *is* change to *d* and *ss* show a mixture of *d* and *c*; the direction to *Pa* is here presumably about perpendicular to the faults, and the tectonic movements probably change their character (intersecting structures). At 59½° N, 152° W there is an *ss* and an *is* with opposite motions at *Pa*, which is a relatively frequent occurrence.

Huancayo (*Hu*) has *c* for the *ss* at 53° N, 165½° W (opposite to *Pa!*), 61¾° N, 151° W (opposite to *Pa*), 61¼° N, 150¾° W, and *d* for *ss* at 59¾° N, 149° W (same as *Pa*), and *d* for *is* at 61¼° N, 147½° W (same as *Pa*).

The distribution of *c* and *d* for the earthquake of July 22, 1937, at 64¾° N, 146¾° W has been studied by Adkins (1940). The *c* given for *Pa* was found, however, to be rather uncertain, indicating its position near a nodal line (this point is not given in fig. 1).

It does not seem possible to explain the regular occurrence of *d* for *ss* and *c* for *is* by a horizontal motion, nor by a common downward motion from the Pacific along a common surface, if this is assumed plane, but it could easily be explained if the dip of the surface is greater for *is* than for *ss*. This interpretation is confirmed by the fact that the *ss* at 53° N, 165½° W has *c* at *Hu*. It therefore seems to be evidence for a similar difference between *ss* and *is* in the Aleutians as between *is* and *ds* (deep shocks) in South America, pointed out by Benioff (1949). Moreover, there may naturally be a slight horizontal component of motion, westward for the south side, as is indicated by the *c* and *d* for *ss* at *Pa* for the western part of the region.

Region 2: Eastern Alaska, British Columbia (figs. 1 and 12; directions to *Hu* have not been given in fig. 12, as they deviate only little from straight lines).—The area is dominated by *c* at *Pa*. The line of epicenters from about 61° N, 138° W to 49° N, 129° W forms an angle of about 16°–18° with the direction to *Pa*, and its extension falls to the west of *Pa*. Assuming the faults to have the same general direction as the line of epicenters, the occurrence of *c* may be explained by a horizontal movement, southward of the land relative to the Pacific structure. From about 49° N, 129° W to 48° N, 122° W the trend of the earthquake belt has a different direction, and so

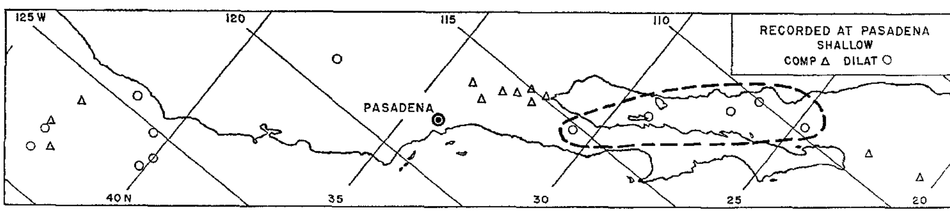

Fig. 2. California and Gulf of California.

presumably have also the directions of the faults, with the consequence that *Pa* is now on the Pacific side of their extension and gets *d*.

Hu has *c* for the *ss* at 53¾° N, 133¼° W and *d* for the *ss* at 47¼° N, 122½° W (both opposite to *Pa!*). Both *Hu* and *Pa* lie very near the extensions of the faults, especially for earthquakes along the eastern side of the Pacific, with ensuing complications of the distribution of *c* and *d*.

Region 3: California (figs. 2 and 12).—Of the earthquakes to the NW of *Pa*, some give *c*, others *d*, the reason being that the general trend of the faults is along the direction to *Pa*, and the fact that some earthquakes give *c*, others *d*, is due to minor local differences of the fault directions. The *d* at 41½° N, 124½° W has been added from a paper by Byerly (1938). This *d* seems unreliable from the seismograms at *Pa*, and in figure 3 in Byerly's paper *Pa* is seen to lie on the extended fault line. The *c* area to the southeast of *Pa* corresponds to the northward relative motion of the Pacific coastal regions. The first motion of the Nevada earthquake at 38¾° N, 118° W (December 21, 1932) has been studied by Byerly (1935), who found a very complicated pattern. There was *c* at *Hu*, but a mixture of *c* and *d* at the *Pa* station group. Gutenberg (1941) has made a very detailed investigation of the faulting in southern California, using the *c* and *d* at Pasadena and auxiliary stations.

Hu has *c* for the California shocks for which the motion could be determined.

Region 4: Gulf of California (fig. 2).—There is a clear distinction for *Pa* between *d*, at least from about 31° N, 116° W to about 24° N, 109° W, and *c* to the south of the latter point, all for *ss*. This distribution is most probably explained by a change in the direction of the fault lines (with regard to *Pa*), along which the continent moves southward relative to the other side. There are no reliable observations from *Hu* for this region.

It seems as if all earthquakes along the Pacific coast of North America fit into the same scheme of a southward relative motion of the continent, and that the fault lines lie along the lines of earthquakes. This is confirmed by the fact that Pulkovo (Galitzin, quoted by Gutenberg, 1929), Uccle (Somville, 1925), Helsinki (Vesanen, 1942), and Rome (Filippo and Marcelli, 1949) record *d* for these earthquakes.

Region 5: Mexico (fig. 3).—There is a regular but complicated distribution of *c* and *d* at *Pa* both for *ss* and *is*, presumably resulting from a corresponding distribution of the directions of the fault lines; the limits between the different areas are indicated on the map. We find for this as well as for several other regions that there is no definite connection between *c* and *d* for *ss* and *is* within the same area; nor is this to be expected.

In the region about 16° N and 91°–93° W, the limit for *ss* passes somewhat to the north of the corresponding limit for *is*. The *is* with *c* about 14½°–15° N, 91°–92° W, form a special group, surrounded on both sides by *is* with *d* at *Pa*. This group is also remarkable for giving exceptionally strong core reflections (P_cP, P_cS, . . .), at least at *Pa*. At 15½° N, 91½° W and 14¼° N, 91½° W we have two other instances of opposite motion at *Pa* for *ss* and *is* with the same epicenter.

On comparing *c* and *d* for *Hu* and *Pa* we find general agreement for this area except for the isolated *is* at 14½°–15° N, 91°–92° W and for some of the *ss* around 18°–19° N, 103°–104° W. For most of this region *Pa* and *Hu* are in about diametrically opposite directions. The clear cases of *is* in the area from about 16° N, 91° W to 19° N, 100° W with *d* at both stations are presumably due to mainly horizontal motions approximately parallel to a line between the points mentioned with eastward displacements on the north side. This therefore seems to be a continuation of the relative motion of the North American continent. The displacements may in addition have small vertical components.

A more thorough discussion of this case may be desirable. The definite indication of *d* for the *is* both at *Pa* and at *Hu* for the area mentioned (except at its western end) means that the extended fault lines do not pass near these stations, since a mixture of *d* and *c* would then be expected. The most consistent areas are obtained when the angle between the fault lines and the direction to a station is nearer to 45° than to either 0° or 90° (for dip slip depending on dip angle). The faults have most probably the same general direction as the trend of earthquake epicenters. The occurrence of *d* for the group under consideration both at *Pa* and at *Hu* could be explained either by a strike slip as indicated above or by a dip slip along fault planes of the proper dip angle. Of these two explanations the first mentioned seems the most likely, as it can also easily explain the two *ss* at 14¾° N, 92½° W and 14½° N, 91½° W with *c* at both stations, as well as the *is* at 15° N, 91½° W with opposite directions, simply by assuming somewhat different directions of the fault lines but the same general movement. These observations could not easily be explained by the other assumption. In accordance with this interpretation, Pulkovo (Galitzin, quoted by Gutenberg, 1929), Uccle (Somville, 1925), and Rome (Filippo and Marcelli, 1949) all have *c* for this area.

Region 6: Central America (fig. 3).—This region is an immediate continuation of the preceding one. The tentative conclusion about the dominant motion, obtained in the discussion of region 5, gets a strong support from the regular distribution of

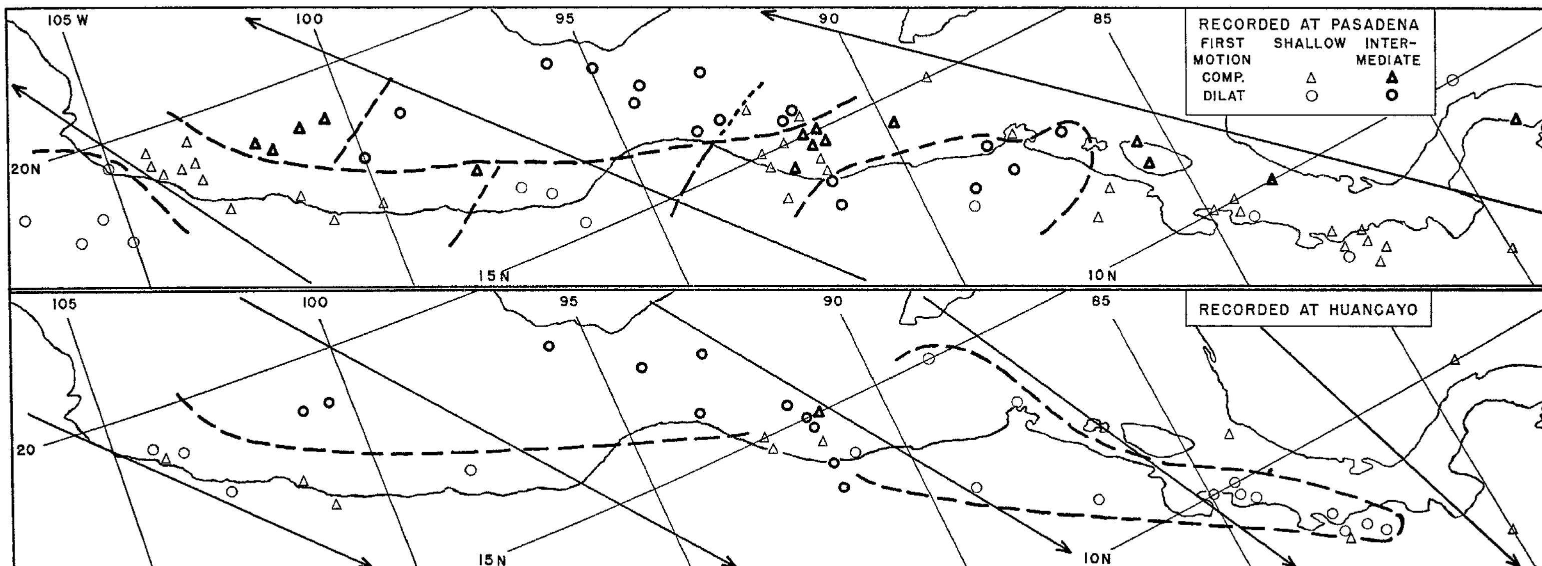

Fig. 3. Mexico and Central America.

c and *d* for *Hu*. The extension of the line from 14° N, 91° W to 7¾° N, 82¼° W with *d* at *Hu* (enclosed by a dashed line in fig. 3) passes to the east of *Hu*, whereas the extension of the line from 8° N, 83° W to 5° N, 82½° W with *c* at *Hu* passes to the west of *Hu*. This is all explained by a relative southward motion of the parts to the east of the fault lines. The first-mentioned section gives predominantly *c* at *Pa*, but also *d* on the SW side of the narrow belt. *Pa* is also near the extension of this line.

The occurrence of opposite motions for the same epicenter and the same depth range observed at only one or two stations does not necessarily mean that at the same hypocenter opposite motions occur at different times. Especially where there are faults of different directions close to each other an earthquake may at one time occur on one fault, at another time on another fault. In several cases, earthquakes with about the same hypocenter may be divided into two or sometimes more groups not only from the first motion but also from the whole appearance of the P phase.

Region 7: Caribbean (figs. 11 and 12).—By far the greatest number of the points in this region give *c* at *Pa*. The active region around 19° N, 68° W gives exclusively *c* at *Pa*. This area is complicated by a number of faults. The data for *Hu* are here rather scanty.

The *Pa* data and the few *Hu* data for the same shocks cannot be reasonably explained by horizontal motion. But a motion with a vertical component along a sloping fault plane may explain the observations. For a proper dip of that plane it is possible for *Pa* and *Hu* to have the same motion if they are either on the same side or on opposite sides of the fault trace. The Caribbean area has also the characteristic Pacific arc properties (see Gutenberg and Richter, 1949).

The apparently exceptional area about 14½°–15° N, 91°–92° W (region 5) seems to be the area where the Caribbean arc joins the Mexican and Central American earthquake belt.

Regions 8 and 9: South America (fig. 4).—In general, there is here a regular but complicated distribution of *c* and *d*.

Almost all the *ss* extending in an approximately N–S direction in the northwestern part of the region give *c* at *Hu*, but a mixture of *c* and *d* at *Pa*. They could be regarded as a continuation of the *c* area for *Hu* in region 6 and also explained by a continuation of the relative southward movement of the continent. It is worth mentioning that both Uccle (Somville, 1925) and Rome (Filippo and Marcelli, 1949) have *c* for this area. All these observations could be explained either by strike slip or by dip slip or by a combination of both, along a sloping fault plane in all cases. A dip slip or at least a component of dip slip seems probable, as it also well explains *d* for *is* at *Pa* (see below).

Most of the shocks mapped for these regions are *is*. They show a certain rather definite distribution of *c* and *d* both at *Pa* and at *Hu;* on the maps the different areas have been separated by dashed lines. It is obvious that the distributions of *c* and *d* for the two stations have a general resemblance to each other, the distribution for one station being a clear deformation of the distribution for the other. At *Pa* there is a strong preponderance of *d* for *is:* the central larger area and the southern smaller area. The area between is predominantly *c* for *is* at *Pa* and almost exclusively *c* at *Hu*. The *is* to the north of *Hu* show a mixture of *c* and *d* at that station, probably

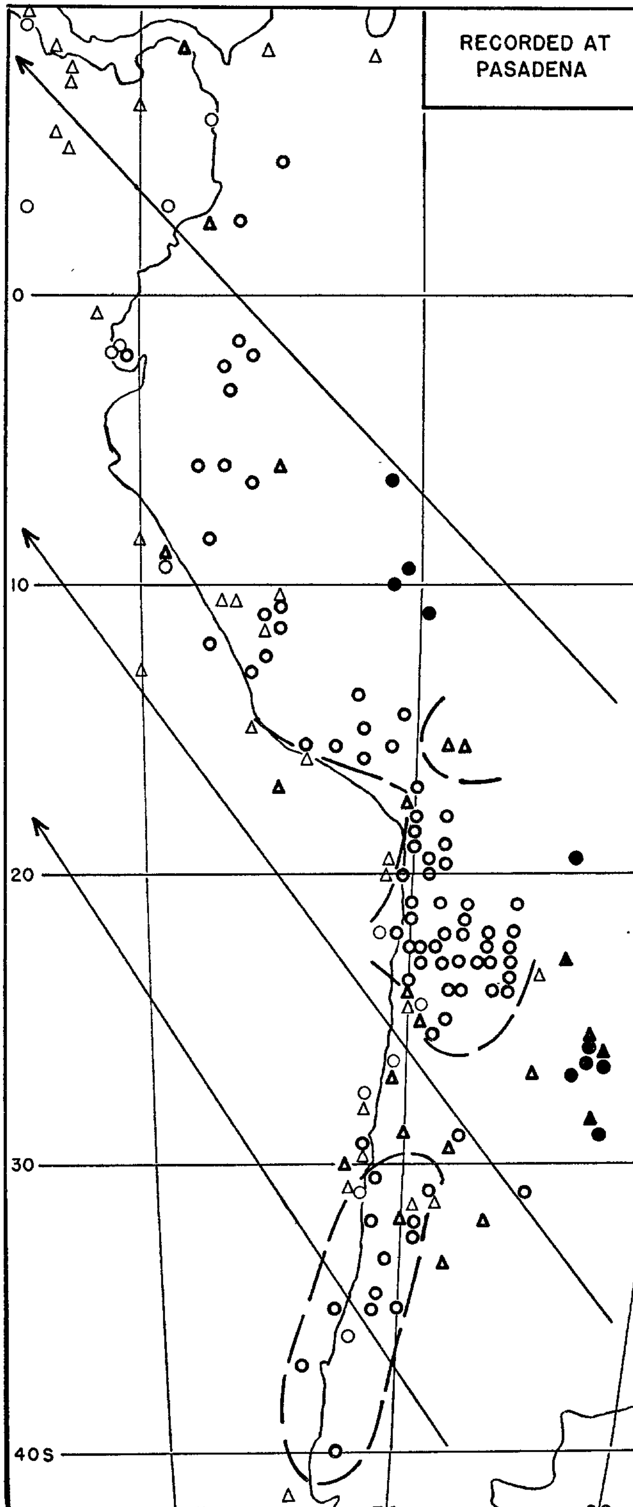

Fig. 4. South America (recorded at Pasadena).

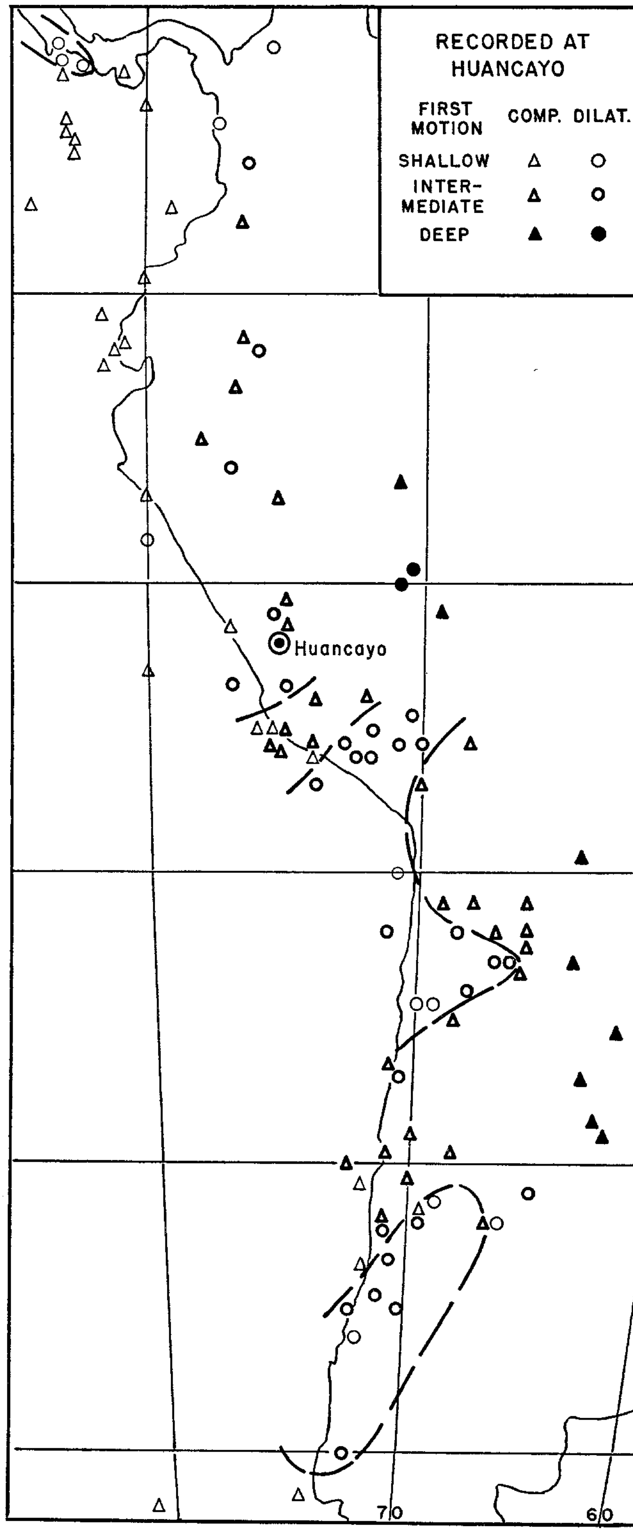

Fig. 4. South America (recorded at Huancayo).

because *Hu* lies on the same line as the epicenters. That the distributions of *c* and *d* to the south of *Hu* are analogous at the two stations is easily conceivable, since they are both in about the same azimuth. The distribution is, however, too complicated to be explained only from these data. The differences in the orientation of the fault planes and in the direction of the motions certainly account for the observed distribution.

Both the *is* at 21° S, 69° W and the *ss* at 33½° S, 71½° W have a small but clear *c* at *Hu*, followed by a strong *d*, and both are close to boundary lines. The *is* at 22½° S, 69° W (July 18, 1931) has a clear *d* at *Pa*, not *c* as given in the Pasadena bulletin.

For the deep shocks (*ds*) we find that the northern group (6°–11° S) gives *d* at *Pa*, and the southern group (19°–29° S) gives *c* at *Hu*. The last-mentioned *c* area forms a continuation of the corresponding *c* area for *is*.

The most important features of the *c* and *d* distribution in South America are summarized below. Two sections, A and B, are perpendicular to the west coast and are situated approximately at 10° S and 25° S, respectively.

SECTION A

	ss	*is*	*ds*
Pa	*c* and *d*	*d*	*d*
Hu	*c*	*c* (and *d*)	*c* and *d*

SECTION B

	ss	*is*	*ds*
Pa	(*c*)	*d*	*c* and *d*
Hu	—	*d* and *c*	*c*

The tendency in section A of a transition from *c* to *d* in passing eastward, earlier for *Pa* than for *Hu*, is easily explained from the positions of the stations in relation to the structures. The tendency in section B for a change from *d* to *c* in passing from *is* to *ds* is an indication of a larger dip angle for *ds* than for *is*, pointed out by Benioff (1949) by means of the spatial distribution of earthquakes in this region.

Region 10: Southern Antilles (figs. 11 and 12).—Owing to the distance, there are only two observations at *Pa*, both with *d*. *Hu* has more observations, mainly *c*, especially around 55°–60° S, 55°–60° W.

Region 11: New Zealand.—There are only three observations at *Pa* with two *d* for *ss* (41° S, 175¾° E and 41° S, 175½° E) and one *c* for *is* (37½° S, 178° E). *Hu* has *d* for the *ss* at 41° S, 175¾° E. As the number of observations for *Hu* is relatively small at the more distant parts of the Pacific Ocean and adjacent areas, they have all been collected on a single map of smaller scale (fig. 13). For *Pa* there are many more observations, and in general the distribution of *c* and *d* is here far more complicated than on the American side of the Pacific.

Regions 12 and 13: Kermadec, Tonga, Samoa, and the Fiji Islands (figs. 5 and 13).—There is a sufficient number of observations for *Pa* only. The distribution of *c* and *d* is extremely complicated but nevertheless has certain general properties. The two dashed curves in figure 5 mark the limits between areas of *c* and *d* for *ds* and *is*, respectively. The larger number of *ds* enables us to give the corresponding limit in greater detail than for *is*. For *ds* there are alternating tongue-like sections of *c* and *d*. There is no correlation between the depths of *ds* and the corresponding distribution

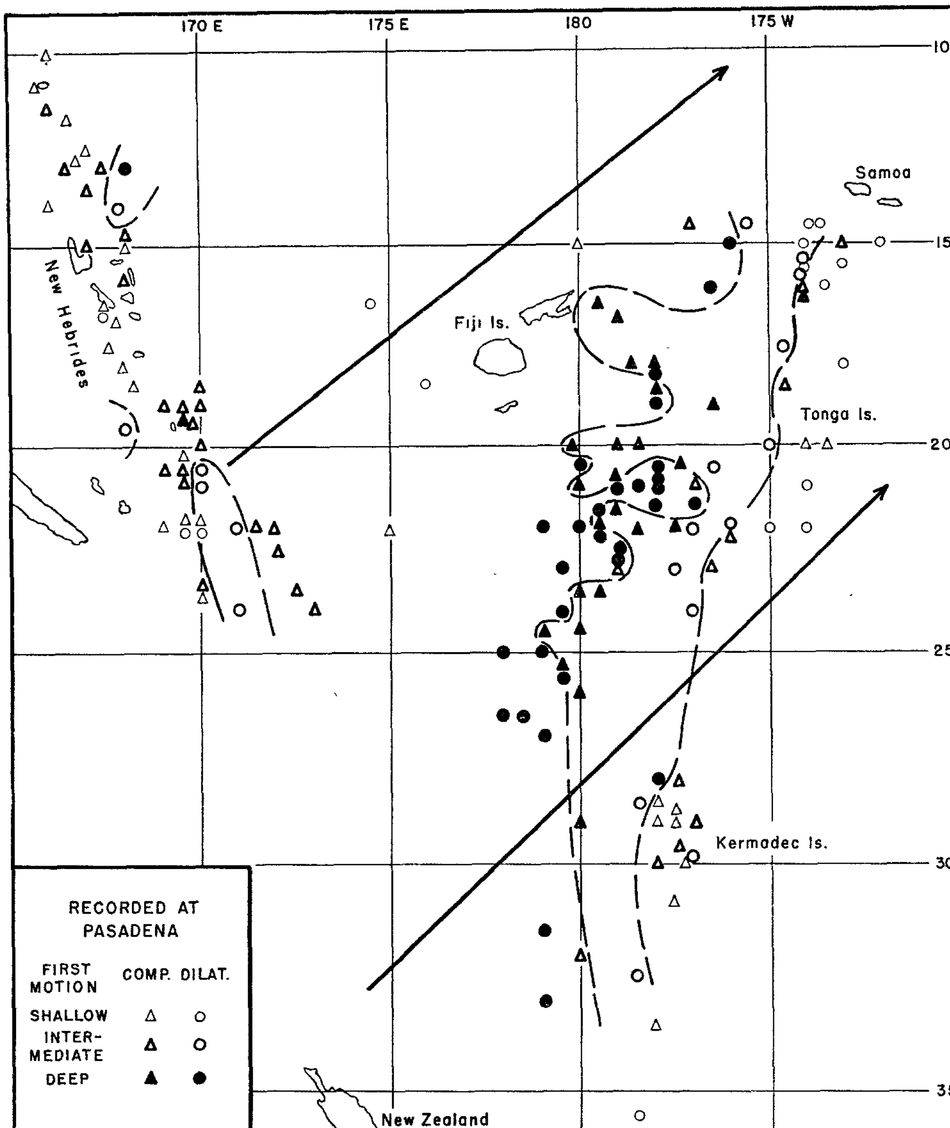

Fig. 5. Kermadec, Tonga, Samoa, and Fiji Islands, and New Hebrides.

of *c* and *d*. Proceeding from west to east, we have first a *d* area for *ds*, followed by a *c* area for *ds;* after that comes correspondingly a *d* area for *is*, and finally a *c* area for *is*. There is also a tendency for the occurrence of *c* for *is* within the *d* area for *ds*. There is no similar distribution for *ss*. For *ss* we find a definite *c* area about 28°–31° S, 177°–178° W and an equally definite *d* area about 14°–18° S, 172°–174° W (Samoa Islands).

The fact that the general trend of the earthquake belt does not deviate much from the direction to *Pa* certainly contributes to the complicated distribution.

Region 14: New Hebrides (figs. 5 and 13).—The general trend of the earthquake belt is here nearly perpendicular to the direction to *Pa*. The distribution is simple for *Pa* with almost exclusively *c* for *ss* and a very large proportion of *c* for *is* (the few cases with *d* are marked by dashed lines to clarify the picture).

The only clear cases at *Hu*, the *is* at 20½° S, 169½° E and 19° S, 169½° E, have also *c*.

The observations are readily explained by the relative downward motion of the Pacific side (east side) along a vertical fault plane or a fault plane with a dip angle >

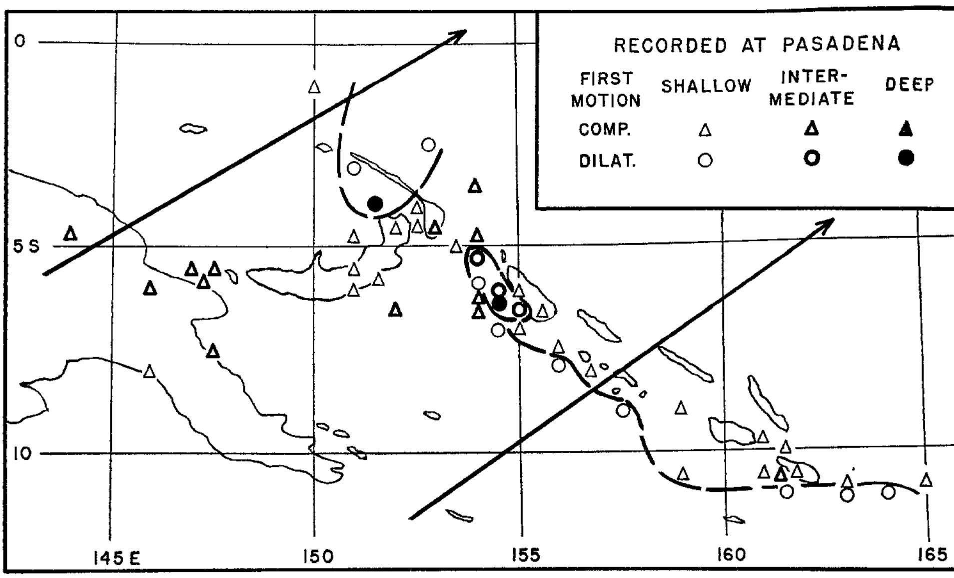

Fig. 6. Solomon Islands to New Britain and New Guinea.

25°. The exceptional cases with *d* may possibly be due to a smaller dip angle. Some of the *is* with *d* have smaller depth than neighboring *is* with *c*, as for example the *is* at 22° S, 171° E and 24° S, 171° E compared with the *is* to the east of them, and likewise for the *is* at 19½° S, 168° E. In other parts there is no similar difference in depth.

This is clearly a region in which *ss* and *is* within the same area have the same motion at *Pa*. Region 1 is an example of the opposite.

Regions 15 and 16: Solomon Islands to New Britain and New Guinea (figs. 6 and 13).—These regions form a natural continuation of the preceding one, with a slight change of direction of the earthquake trend. There is still a definite preponderance of *c* both for *ss* and *is* at *Pa*. The areas with *d* are marked by dashed lines. The *is* with *d* within the enclosed area around 5°–7° S, 154°–155° E are at approximately the same depth as the neighboring *is* with *c*. The few cases for *Hu* have also *c*. The New Guinea shocks (mainly observations of *is*) all have *c* at *Pa*.

The most probable explanation for *c* and *d* seems to be the same as for region 14.

Regions 17 and 18: Caroline Islands, Marianas Islands, and Bonin Islands (figs. 7 and 13).—These regions are characterized by very complicated patterns of the *c* and *d* distribution at *Pa* both for *ss* and for *is*. The pattern is more regular for *ds* with mostly *c;* the exceptional cases of *ds* with *d* at *Pa* have been marked by dashed lines in figure 7. There is no general difference in depth for *ds* with *d* and *ds* with *c* at *Pa.*

The trend of the earthquake belt in region 18 is nearly perpendicular to the direction to *Pa.* The fault lines may also be assumed to be approximately perpendicular to the direction to *Pa.* The great-circle arc through *Pa* perpendicular to the earthquake belt of region 18 passes approximately through the point 33° N, 138° E. If the motion were pure strike slip, we should get *c* on one side and *d* on the other side of this point. The mixture of *c* and *d* is easy to explain if we assume motions with dip-

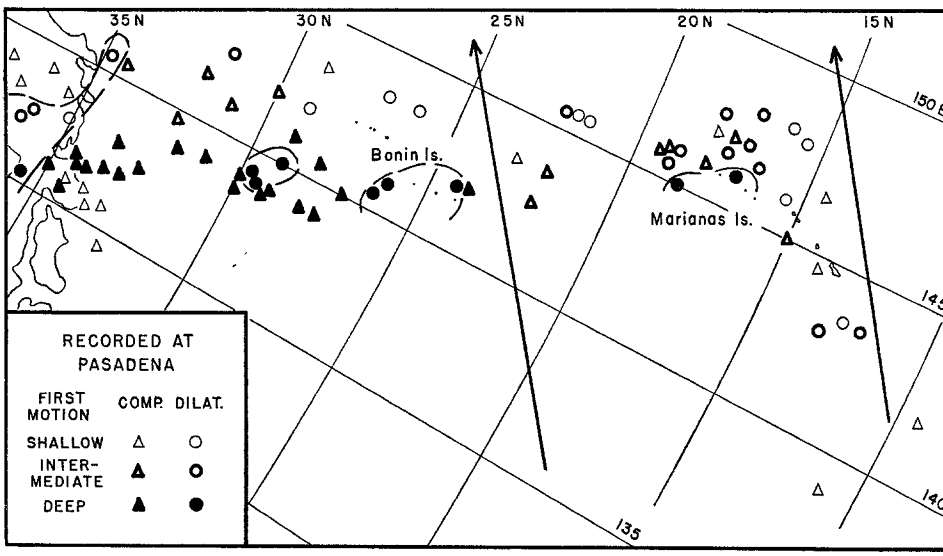

Fig. 7. Caroline, Marianas, and Bonin Islands.

slip components, for if the dip of the fault plane is such that the P wave leaves the focus at about right angles to this plane, such a mixture is to be expected. For a distance of 85° (= the approximate distance from region 18 to *Pa*) the angle of the P wave with the earth's radius at the focus varies from 22° for 100 km. depth to 32° for 700 km. depth. Assuming a motion of the Pacific structure toward and underneath the continental side (western side here), the dip angle could be about 22°–25° for *is,* but the preponderance of *c* for *ds* leads to the conclusion that the dip angle is greater for *ds* (anything > 30°). We are here obviously led to the same conclusion as for the Aleutians (region 1).

Regions 19 and 46: Japan to Kamchatka, and Manchuria to Sea of Okhotsk (figs. 8 and 13).—The *ss* and *is* again show a complicated pattern of *c* and *d* at *Pa.* To clarify the picture, the areas with *d* for *ss* and *is* have been surrounded by dashed lines in figure 8. It should be emphasized that this is the only purpose of these dashed lines, and they do not indicate any other limits or structures. The *ds* show a very simple picture with *c* at *Pa,* almost without exception. This indicates that the fault-dip angle is here relatively far from its critical value. There are no obvious relations in detail between the boundaries between *c* and *d* and the depths of the

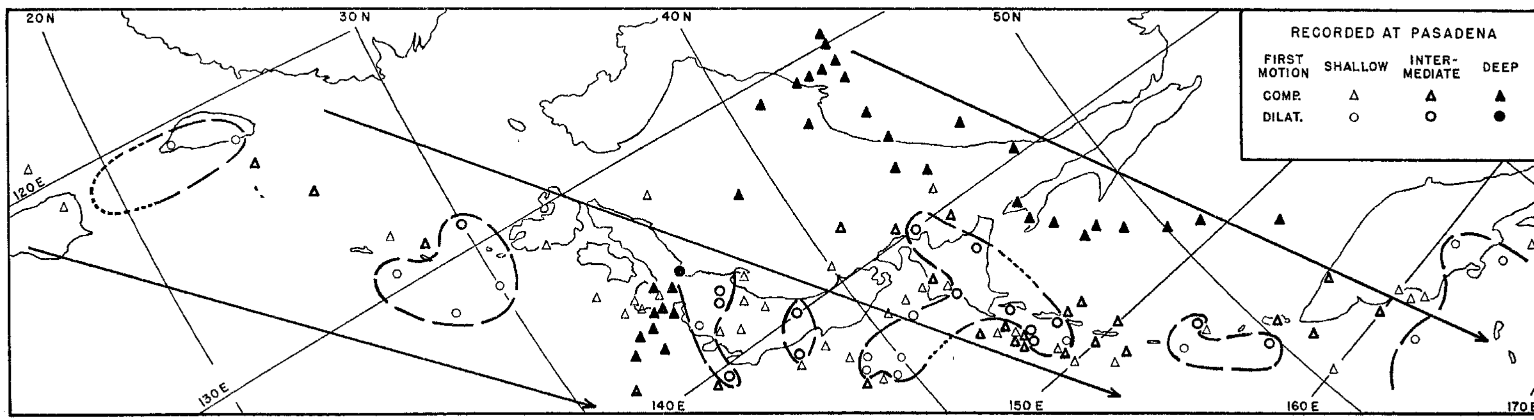

Fig. 8. Japan to Kamchatka, Manchuria to Sea of Okhotsk, Riukiu Islands, Formosa, and Philippine Islands.

hypocenters. There seems, however, to be a general tendency for a transition from *d* to *c* in passing from shallow to deeper shocks for a station situated on the Pacific side of an arc structure (this occurs in regions 1, 8, 18, 19, and 46).

Uccle (Somville, 1925) and Helsinki (Vesanen, 1942) record mainly *c*, but also *d*, for shocks in Japan and neighboring regions.

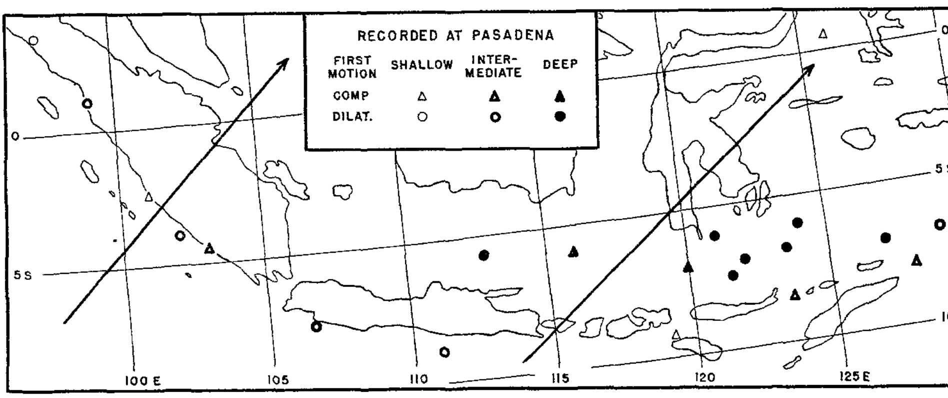

Fig. 9. Celebes and Sunda arc.

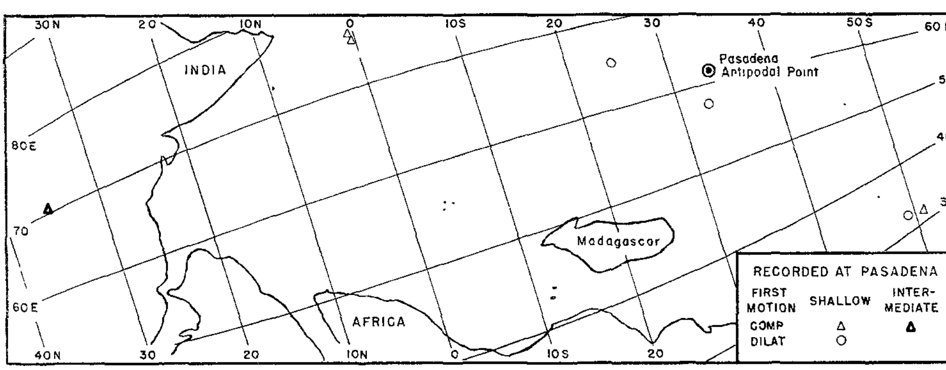

Fig. 10. Indian Ocean.

Several Japanese seismologists have made detailed studies of the distributions of *c* and *d* for individual Japanese shocks, together with theoretical considerations. Reference to some of this literature will be found in papers by Kawasumi (1937) and Gutenberg (1941).

Regions 20, 21, and 22: Riukiu Islands, Formosa, and the Philippine Islands (figs. 8 and 13).—Region 20, for which we have the largest number of observations, is dominated by *c* both for *ss* and *is* at *Pa;* the areas with *d* are marked with dashed lines.

The trend of the earthquake belts in region 20 is a continuation of region 19. The direction in both these regions is not very different from the direction to *Pa*, which at least in part explains the complicated pattern of *c* and *d*. There are obviously alternating areas of *c* and *d*, with *c* predominating. The *ss* at 18° N, 121° E (December 29, 1949) has *c* at *Pa* instead of *d* as given in the Pasadena seismic bulletin.

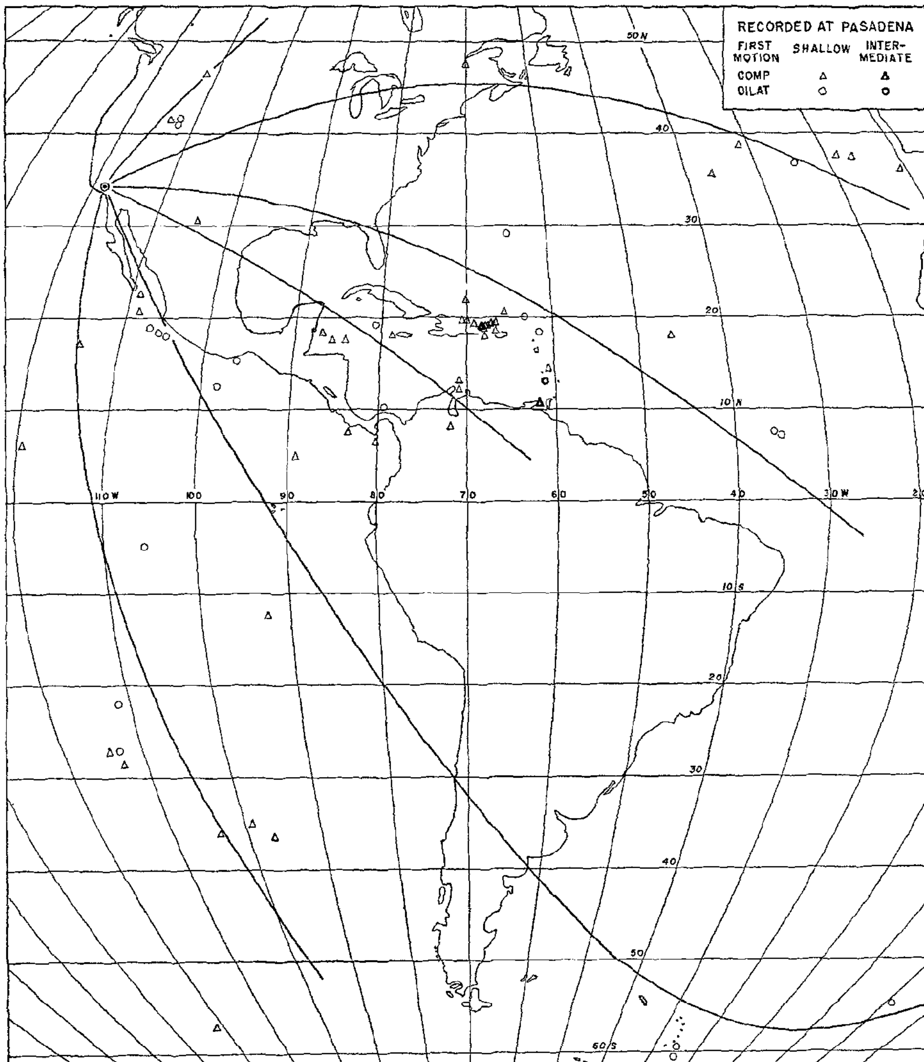

Fig. 11. Observations at Pasadena for North America, Caribbean, Southern Antilles, Atlantic Ocean, Eastern and Southeastern Pacific.

Regions 23 and 24: Celebes and Sunda arc (figs. 9 and 13).—For regions of greater distance than about 105° the first motion refers to P′ (PKP) and for even larger distances to P″ (PKIKP). The distant observations for *Hu* (fig. 13) are in general too few to allow detailed conclusions regarding the distribution of *c* and *d*. For *Pa* the regions 23 and 24 have mostly *d* for *is* and especially for *ds*. The *ds* at 6¾° S, 123¾° E with *d* at *Pa* has been investigated in detail by Koning (1941). The occurrence of both *c* and *d* for the *ds* in region 24 cannot be explained from differences in depth. The earthquake belt along Sumatra is nearly perpendicular to the direction to *Pa*.

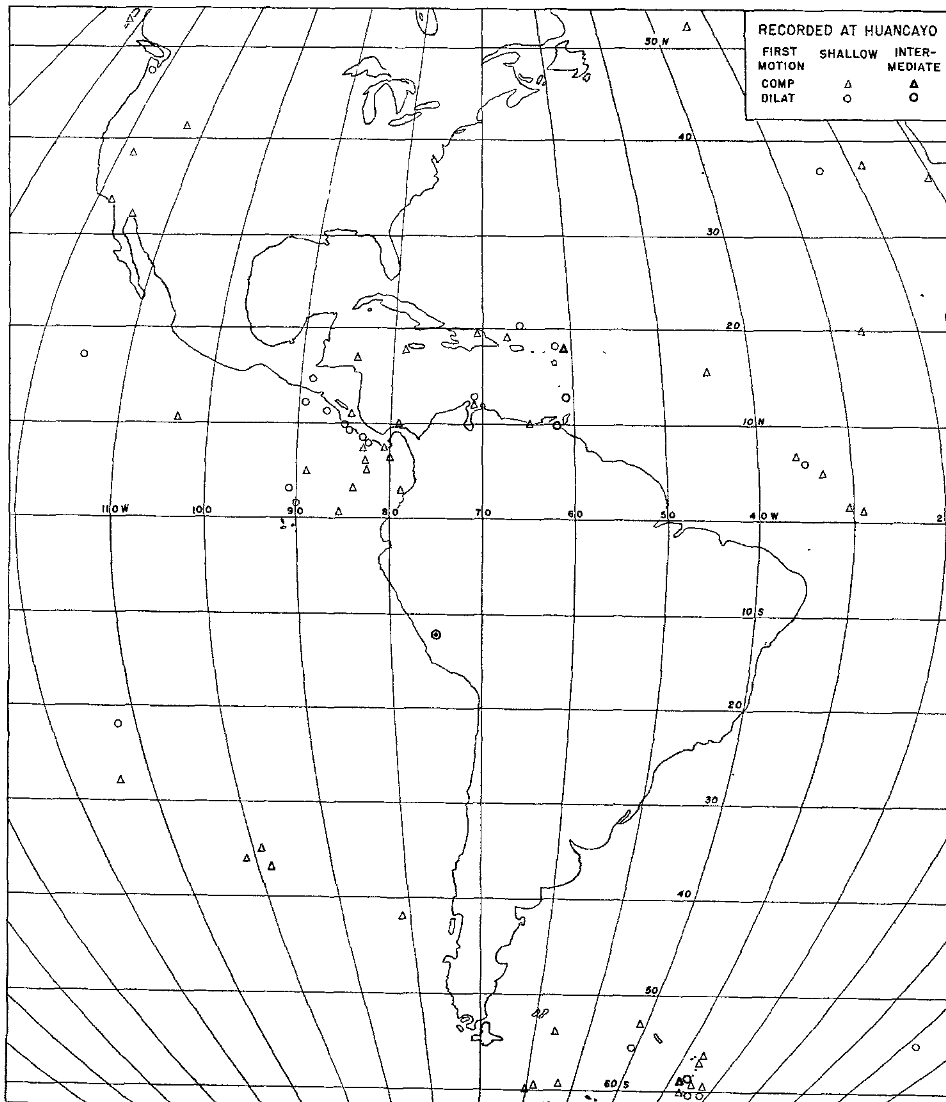

Fig. 12. Observations at Huancayo for North America, Central America, Caribbean, Southern Antilles, Atlantic Ocean, Eastern and Southeastern Pacific.

The regions studied hitherto are those which surround the Pacific Ocean and are naturally those for which we have most observations at *Pa* and *Hu*. For other parts of the world there are generally only scattered observations, and their description can therefore be made short.

Region 25: Andaman Islands to Burma (fig. 13).—*Pa:* no observations. *Hu:* a few *ss* with *c*.

Region 26: Szechuan, Southern Tibet (fig. 13).—*Pa: d* for *ss* at 27¼° N, 100¼° E. *Hu: c* for *ss* at 24½° N, 70¼° E.

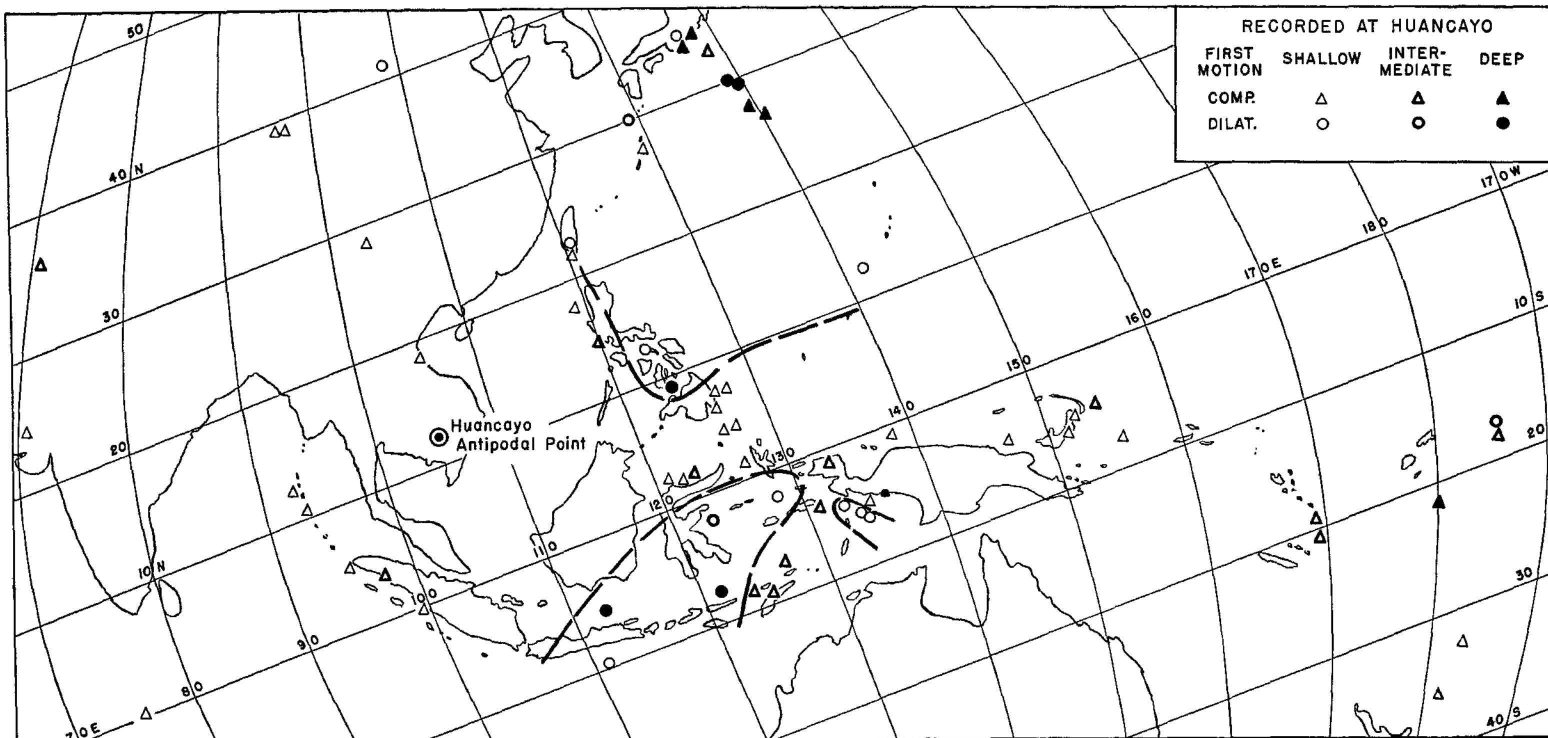

Fig. 13. Observations at Huancayo for southwestern Pacific and the East Indies.

Region 27: Kansu to Sinkiang (fig. 13).—*Pa* and *Hu: c* for *ss* at 39¼° N, 96½° E.

Region 28: Mongolia.—*Pa: c* for *ss* at 47° N, 90° E and 45¾° N, 90¼° E; *d* for *ss* at 47° N, 90° E. *Hu:* no observations.

Regions 29 and 30: Iran-Urals and Asia Minor–Levant–Balkans.—*Pa* has *d* for *ss* at 35½° N, 27° E. *Hu:* no observations.

Regions 31 and 32: Western Mediterranean and Atlantic Ocean (figs. 11 and 12).—*Pa* has *c* for *ss* in region 31. The distribution of *c* and *d* for the *ss* at 37½° N, 18½° W (November 25, 1941) has been studied in detail by Filippo (1950). The *Pa* record has for this case actually a small *c* followed by a sharp *d; Hu* has a clear *c. Pa* and *Hu* have both *c* and *d* for the Atlantic *ss; Hu,* predominantly *c. Pa* has *d* for an *is* at 39°.2 N, 15°.2 E and *c* for a *ss* at 64½° N, 2° W.

It is worth mentioning that both Uccle (Somville, 1925) and Rome (Filippo and Marcelli, 1949) have *c* for Mid-Atlantic shocks.

Region 33: Indian Ocean (figs. 10 and 13).—Only a few observations exist. The *ss* in the vicinity of the antipodal point of *Pa* have *d.*

Region 34: North America (figs. 11 and 12).—There are a few scattered *ss,* mainly with *c,* but some with *d,* at *Pa.* The *ss* at 30¾° N, 104½° W with *c* at *Pa* has been investigated in detail by Byerly (1934).

Regions 35–38: Brazilian Shield, central and western Europe, Africa, Australia.—*Pa* and *Hu:* no observations.

Region 39: Pacific Basin.—*Pa: d* for *ss* at 19½° N, 155¼° W; *c* for *ss* at 20½° N, 155¼° W and *ss* at 19½° N, 155° W (Hawaii). *Hu: d* for *ss* at 20½° N, 155¼° W.

Region 40: Arctic belt.—*Pa: c* for *ss* at 77° N, 9° E and 79¾° N, 2° E; *d* for *ss* at 74¾° N, 14° W. *Hu:* no observations.

Region 41: Eastern Siberia.—*Pa: c* for *ss* at 46½° N, 127° E. *Hu:* no observations.

Region 42: Baffin Bay to Bering Sea.—*Pa:* exclusively *c* for the Baffin Bay earthquakes (three observations); also *c* for *ss* at 67½° N, 136° W. *Hu:* exclusively *c* for the Baffin Bay earthquakes (five observations).

Regions 43 and 44: Southeastern and eastern Pacific (figs. 11 and 12).—There are mainly *c* at *Pa* and at *Hu.* No definite conclusions are possible.

Regions 45–50.—No observations except for region 46 (see region 19).

Region 51: Rumania.—*Pa: c* for *is* at 45¾° N, 26½° E. *Hu:* no observations.

Summary and Outlook

This study is concerned with the initial motion of the P waves at Pasadena and Huancayo. The results have been given in maps. In order to make the distribution more obvious, some boundary lines have been drawn. These boundaries are generally not to be taken as geometrical lines, but rather as transition zones. The appearance and positions of these lines can clearly be given in more or less detail, depending on the number of earthquakes used. For an earthquake well within an area of either compression or dilatation we can expect a clear first motion of P, whereas for earthquakes within mixed areas and for earthquakes on or in the vicinity of boundary lines we generally cannot.

As a general conclusion, we find that compressions and dilatations have certain definite geographical distributions, indicating that the general tectonics are the same within relatively large areas. Furthermore, these distributions are independent of time, throughout the period for which seismic records are available, and presumably the distributions change only with geological time. The distributions we have obtained in particular for Pasadena and Huancayo are also to be taken as reliable results. On the other hand, it should be strongly emphasized that the efforts made to explain some of the observed distributions in terms of tectonics are highly tentative. In order to arrive at more definite results regarding the general tectonics of the earthquake regions, we need the detailed distributions of compression and dilatation for a large number of stations. The author would like to use this opportunity to suggest strongly that these distributions be determined for the seismic stations over the world. In such work we have to bear in mind that only cases which are certain beyond doubt should be used. Naturally, the notations "compression" and "dilatation" refer to the motion of the ground and not to the motion of the seismograph pendulum. When such distributions have been determined for a large number of stations, they could be brought together to give more definite information. I should also like to suggest that the initial motion of P waves should be given in seismic bulletins whenever it can be determined with reliability, but only then. Directions determined only from records of horizontal seismographs may naturally be used also, once the location of the epicenter is known approximately.

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California Institute of Technology,
Pasadena, California.
(Division of the Geological Sciences, contribution no. 569.)