Direction of Faulting in the Deep-Focus Spanish Earthquake of March 29, 1954[1]

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Abstract

An earthquake of magnitude 7.1 occurred off the south coast of Spain on March 29, 1954. The earthquake was remarkable in that it had a focal depth of about 650 km; no earthquake with focal depth greater than normal is known to have occurred in this area previously.

Using methods already established but here reviewed, the mechanism at the focus is investigated. The method defines two planes, without determining which is the fault. There are thus two possibilities. Under the first possibility the fault is approximately vertical and strikes north-south. The movement is vertical, such that the eastern side of the fault rises with respect to the western side. Under the second possibility the fault is approximately horizontal, and the movement is also horizontal, the material above the focus moving due east (that is, in the sense of the earth's rotation) with respect to the material below the focus.

Introduction

Detailed studies of the earth's seismicity have shown that earthquakes with deeper than normal focus ordinarily occur in well defined and very limited areas of the earth's surface. They are associated particularly with many of the circum-Pacific seismic zones, although earthquakes with intermediate focal depths are found in the Hindu Kush and in the eastern Mediterranean. The occurrence of a deep-focus earthquake outside of these established zones is a definitely unusual event.

Such an earthquake occurred on March 29, 1954, in the vicinity of Granada, Spain. No earthquake with focal depth greater than normal is known to have occurred in this area before, yet it is clear that this shock had a focal depth of about 650 km. It was, moreover, larger than any shock previously known in the vicinity, having had a Richter magnitude of 7.1, sufficient to cause property damage in Granada and Malaga despite the great depth of focus.

It seems desirable that such an unusual earthquake should be studied as extensively as possible. As a contribution to this study we here present the results of an investigation into the direction of faulting in the earthquake.

Method used

The method used in this research, which was developed in a series of earlier papers (Hodgson and Milne, 1951; Hodgson and Storey, 1953), is based on the premise that the earthquake is due to slipping along a fault. Fig. 1 provides a simple example. Suppose that FF represents, in plan, the trace of a vertical fault which undergoes displacement during an earthquake in the sense shown by the arrows. By the simple argument that points ahead of an arrow will be pushed by the impulse while points behind an arrow

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will be pulled, one sees intuitively that the area in the vicinity of the earthquake will be divided into four zones in which the initial motion will be alternately compressional and dilatational as shown in the figure. The boundaries between the zones are provided by the trace of the fault and by the line perpendicular to the motion couple. Conversely, given a suitable distribution of seismograph stations close to the epicentre, it should be possible to separate those recording an initial compression from those recording an initial dilatation by two lines at right angles; one of these lines will represent the trace of the fault.

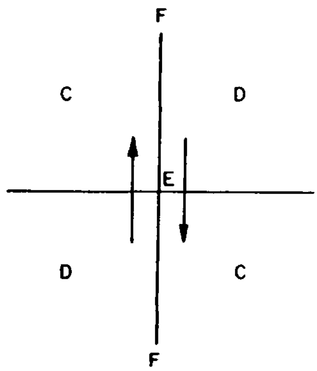

Fig. 1. Zones of compression and dilatation set up around the epicentre.

This very simple example serves to illustrate the principle, established rigorously by NAKANO (1923), that the volume surrounding an earthquake focus is divided into four sectors, alternately compressional and dilatational with respect to first motion. The boundaries of the sectors are defined by the fault plane and by a second plane, perpendicular to the displacement couple, called the *auxiliary* plane. In particular, if one were dealing with a homogeneous earth, its surface would be divided by these planes into four lunes, two of which would receive the initial motion as a compression, the alternate two receiving a dilatation.

Actually of course the earth is not homogeneous, and this simple distribution is complicated by the curvature of the seismic ray. In Fig. 2, for example, a station S lying to the right of the fault plane receives its initial impulse from a ray originating to the left of the fault. This difficulty is overcome by a device due to Byerly. Instead of plotting S in its true position it is plotted at the point S′, known as the extended position, the point where the tangent to the ray meets the earth. In this way the orientation relative to the planes is maintained, so that the expected separation of the earth's surface into lunes is achieved.

In practice the mapping is done on a stereographic projection, the point at the antipodes of the earthquake being used as the pole of projection and the corresponding diametral plane as the mapping surface. The epicentre becomes the centre of the map, and the extended position S′ of the station S plots into the point B, at the same azimuth as S but at a distance OB from the centre. OB is called the *extended distance*.

It is a property of the stereographic projection that circles on the globe project into circles on the map. The boundaries separating compressions from dilatations on the earth are circular, being the intersections of the sphere with the fault plane and the auxiliary plane. Hence the boundaries on the map must

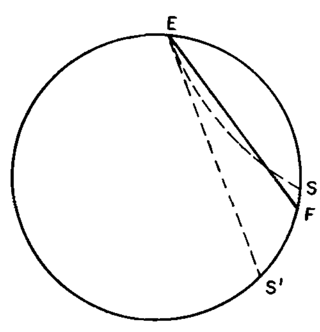

Fig. 2. Definition of Extended position.

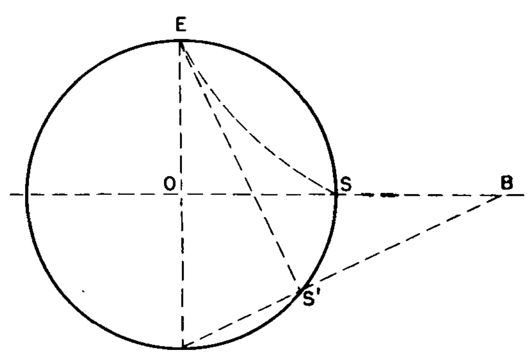

Fig. 3. Definition of Extended distance.

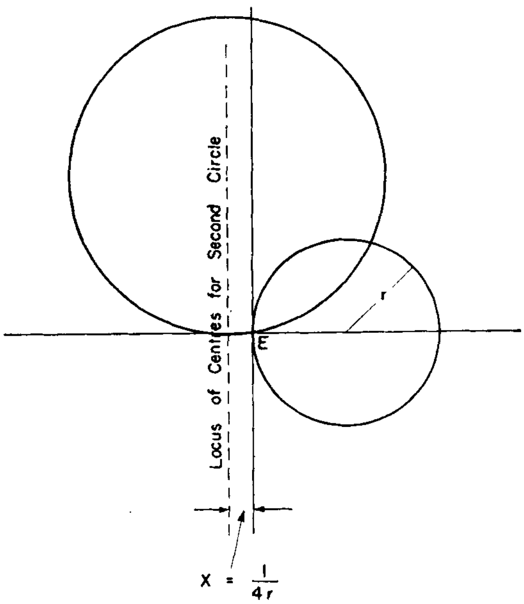

Fig. 4. A typical fault-plane solution.

also be circles. The technique of the research is thus to plot stations on the map at their extended distances and to separate those receiving initial dilatations from those receiving initial compressions by a pair of circles. One of these circles will represent the fault plane, the other the auxiliary plane. It may be shown that the diameters of the circles are equal to the tangent of the dip of the corresponding plane.

In drawing the solution circles it must be remembered that the circles represent orthogonal planes. There is therefore a limitation on their relative positions. This may be expressed as follows. Suppose that one circle of radius r is defined. Then the other circle must have its centre on a line drawn parallel to the tangent to the first circle and at a distance $1/(4r)$ from it.

A typical fault plane solution is shown in Fig. 4. The orthogonality relationship has been shown in the diagram.

In obtaining fault plane solutions one is frequently hampered by the poor distribution of data, owing, for example, to the presence of oceans or of uninhabited land areas. This difficulty has been overcome to some extent through the use of secondary phases. The extended distance of a station is a function of the angle at which the ray leaves the focus to reach the station. As will be apparent from Fig. 5, this angle is different for different phases, so that the extended distance of the station is different for the different phases. One well defined record can thus provide several points on a map.

Before using a secondary phase it is of course necessary to know whether it has suffered any phase change in the course of its path, by reflection, for example, at the surface of the earth or at the boundary of the core. A recent paper by INGRAM and HODGSON (1956) shows that for a focal depth of 0.10 R both PP and pP must have suffered a phase change on reflection, no matter what distance they may be recorded at. It is also assumed, in the light of work by BÅTH (1954), that P_cP does not suffer phase change on reflection at the earth's core.

It should be particularly noted in Figure 5

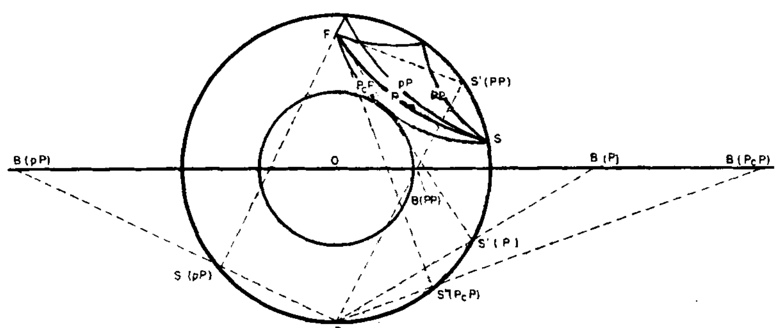

Fig. 5. The phases P_cP, P, pP and PP leave the focus at different angles. Their extended distances OB(P_cP), OB(P), OB(pP) and OB(PP) are thus quite different. Note that pP, arising from an upward-rising ray, has a negative distance.

Table 1. Data on Which Solution is Based

Station	Distance in Degrees from Epicentre	Azimuth in Degrees Epicentre to station	Phase Reported	Direction of Motion
Cartuja	0.1	90.0 W	P	C
Toledo	2.6	7.5 W	P	D
Alicante	2.7	61.5 E	P	C
Lisbon	4.6	68.8 W	P	D
Tortosa	4.7	39.3 E	P	(D)
Coimbra	4.8	50.0 W	P	D
Alger Univ.	5.5	91.5 E	P	C
Barcelona	5.9	44.5 E	P	C
Oropa	11.7	42.7 E	P	C
Paris	12.3	18.1 E	P	C
Pavia	12.3	46.1 E	P	(D)
Prato	12.7	54.6 E	P	D
Basel	13.0	35.0 E	P	D
Rome	13.0	64.6 E	P	D
Rocca di Papa	13.2	65.3 E	P	D
Bologna	13.3	52.1 E	P	D
Salo	13.3	46.8 E	P	D
Chur	13.5	41.4 E	P	D
Zürich	13.5	37.6 E	P	D
Strasbourg	13.9	32.2 E	P	D
Ravensbourg	14.2	38.2 E	P	D
Kew	14.3	7.6 E	P	D
Meszstetten	14.3	36.5 E	P	D
Karlsruhe	14.4	32.3 E	P	D
Stuttgart	14.6	34.4 E	P	D
Uccle	14.7	19.8 E	P	D
ReggioCalabria	15.0	81.1 E	P	D
Messina	15.1	80.3 E	P	D
Trieste	15.4	51.8 E	P	D
De Bilt	15.8	19.6 E	P	D
Rathfarnham	16.3	5.4 W	P	C
Witteveen	17.0	21.0 E	P	D
Durham	17.9	9.3 E	P	D
Prague	18.0	39.2 E	P	D
Vienna	18.2	46.3 E	P	(C)
Stara Dala	18.9	49.9 E	P	D
Aberdeen	19.9	2.0 E	P	D
Skalnate Pleso	20.7	47.7 E	P	D
Copenhagen	21.3	24.8 E	P	D
			P_cP	D
Athens	21.6	79.4 E	P	D
Bergen	24.0	10.4 E	P	D
Istanbul	25.4	71.4 E	P	(C)
M'Bour	25.6	148.8 W	P	C
Uppsala	26.4	23.9 E	P	D
Reykjavik	29.2	16.4 W	P	C
Helwan	29.7	93.8 E	P	(C)
Kiruna	33.4	16.0 E	P	D
Lwiro	49.5	135.5 E	P	D
Seven Falls	49.5	56.1 W	P	C
Shawinigan Falls	50.8	56.2 W	P	C
Ottawa	53.3	57.0 W	P	C
New York C.C.	53.6	62.9 W	P	(D)
			pP	(D)
Palisades	53.6	62.7 W	P	C
Philadelphia	54.6	63.5 W	P	C
			pP	C
Resolute Bay	54.9	18.9 W	P	C
Kirkland Lake	55.2	52.6 W	P	C
Morne des Cadets	55.6	97.8 W	P	C
State College	56.2	61.6 W	P	(D)
Washington	56.4	64.2 W	P	C
San Juan	57.5	90.7 W	P	C
Quetta	57.7	74.6 E	P	D
			pP	D
Cleveland	58.4	59.5 W	P	C
Cincinnati	61.5	60.8 W	P	C
Columbia	61.5	67.6 W	P	C
Chicago	62.5	56.8 W	P	C
			pP	C
Lincoln	69.0	54.2 W	P	C
			pP	C
			PP	D
Fayetteville	69.6	59.5 W	P	C
Kimberley	70.7	153.9 E	P	D
Balboa	73.5	91.1 W	P	C
Pietermaritzburg	73.6	149.6 E	P	D
Tananarive	73.6	129.9 E	P	D
College	74.4	14.8 W	P	C
Bozeman	74.7	43.7 W	P	C
Hungry Horse	74.7	40.3 W	P	C
Merida	74.7	75.1 W	P	C
			pP	C
Butte	75.5	42.8 W	P	C
Grahamstown	75.6	154.3 E	P	D
Salt Lake City	78.2	47.2 W	P	C
			pP	(D)
Victoria	79.3	36.0 W	P	C
			pP	(D)
Seattle	79.5	37.1 W	P	C
Vera Cruz	80.4	73.0 W	P	C
La Paz	80.7	118.6 W	P	C
			pP	C
			PP	(C)
Chihuahua	82.1	59.9 W	P	C
Oaxaca	82.4	74.6 W	P	C
Nelson	82.8	64.4 W	P	C
			pP	(D)
Tacubaya	82.8	71.1 W	P	C
Tucson	83.0	54.4 W	P	C
Boulder City	83.2	49.6 W	P	C
Mineral	84.1	42.4 W	P	C
			pP	C
Shasta	84.3	41.9 W	P	C
			pP	(D)
Montezuma	85.6	122.7 W	P	(D)
Fresno	85.7	46.1 W	P	C
			pP	C
Berkeley	86.3	44.0 W	P	C
			pP	C
			PP	D
			PPP	C
Mount Hamilton	86.3	44.6 W	P	C
			pP	C

Station	Distance in Degrees from Epicentre	Azimuth in Degrees Epicentre to Station	Phase Reported	Direction of Motion
Pasadena.....	86.5	49.0 W	P	C
			pP	C
Manzanillo....	86.9	68.6 W	P	C
Sapporo......	93.9	25.1 E	P	D
			P_cP	D
			PP	(D)
Hong Kong ..	96.4	55.5 E	P	D
			PP	(D)
Matsushiro ...	98.4	30.4 W	P	D
			PP	C
Djakarta.....	109.8	82.6 E	P	(C)
			pP	(C)
			PP	C
Honolulu.....	116.9	26.8 W	PKP_1	C
Riverview....	159.0	88.2 E	PKP_2	D
			PP	C
Christchurch..	173.1	155.0 E	PKP_1	D
			PP	(D)
Wellington ...	175.7	163.3 E	PKP_1	D
			PP	(D)

that the pP ray, which is generated by an upward rising ray, has a negative extended distance. This is true of any phase which derives from an upward rising ray, and applies not only to pP but also to P for stations close to the epicentre. This has the result of distorting the geographical position of stations close to the epicentre, so that they "pass through" the epicentre and appear at an azimuth opposite to their true one. This can be very confusing unless the reason for it is understood.

Tables of extended distances for the phases shown in Fig. 5 and for many others have been published (Hodgson and Storey, 1953; Hodgson and Allen, 1954 a, b; Hodgson, Allen and Cock, 1956). These tables have been used in the present problem.

Summary of available data

Questionnaires seeking information on the direction of motion were circulated to the seismograph stations of the world in January, 1955. The response to this appeal has been very satisfactory, and we take this opportunity to thank our collaborators for their help. The information from the returned questionnaire forms is given in Table 1, along with the distance and azimuth of each contributing station. These distances and azimuths were measured using a device developed for the purpose by this Observatory (Willmore and Hodgson, 1955). As a check on the computations, the distances and azimuths were measured independently by each of us.

In Table 1, C indicates that the phase in question was recorded as a compression, D that it was recorded as a dilatation. In plotting, pP and PP are shown with the opposite phase, to allow for the phase change on reflection, but the table gives the motion as actually recorded. Phase designations in parentheses are inconsistent with the published solution.

Fault plane solution

The data listed in Table 1 have been used to plot the fault plane solution diagram shown in Figure 6. Not all the data given in the table have been plotted; to do so would have made the diagram too confusing.

Examination of the diagram will show that a line striking N 2° E, passing between Rathfarnham and Aberdeen, separates compressions on the left from dilatations on the right. We shall presently show that this line of separation is not a straight line but the arc of a very large circle, and that a second very small circle exists, too small to show on this diagram. We shall require that the large circle be large enough to include the observation for Wellington. Since Wellington lies at an extended distance of 40.2 units, the radius of the circle is required to be something in excess of 60 units.

Fig. 6 affords an opportunity to observe the "passing through" of the pP phase. In the south-east quadrant of the diagram, for example, will be found the pP observations from many California and Mexico stations, agreeing in their phase designations with the direct P wave recorded at Lwiro, Tananarive and the South African stations. In the same quadrant will be found P observations from Lisbon, Coimbra and Toledo. These stations lie close to the epicentre and have passed through the origin to their opposite azimuth. Again it should be noted that the information from these stations agrees with that obtained directly and from the pP phases. Other examples of passing through will be found in the diagram; Alicante is plotted to the west of La Paz, Alger University and pP Quetta

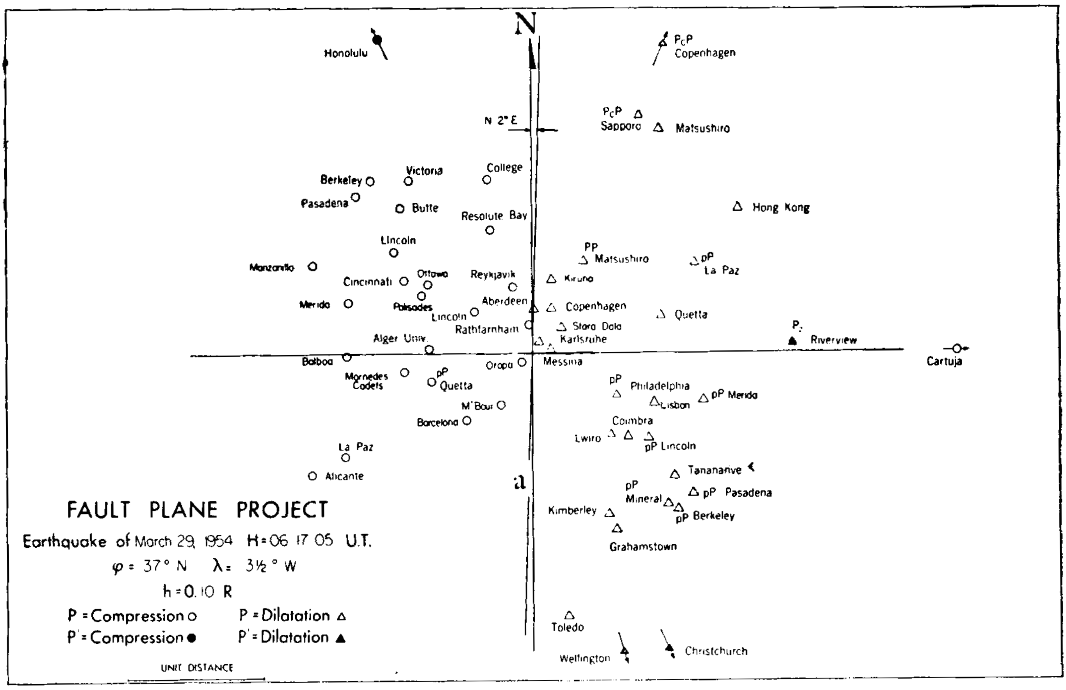

Fig. 6. Fault plane solution diagram. The notation is explained in the legend.

in the vicinity of Morne des Cadets, while Cartuja is plotted off the diagram to the right at a very large distance.

Figure 7 gives the fault plane diagram of the immediate epicentral vicinity on a very large scale. The line through the origin, striking N 2° E has been shown. This line is supposed to separate compressions on the west from dilatations on the east, but on this enlarged diagram it is possible to show a number of dilatations, lying very close to the epicentre, but to the west of it. These dilatations, as well as the compressions for Paris and Oropa, are all from stations which have passed through the origin because of their proximity to the epicentre.

The dilatations at Basel, Prato and Bologne have been separated from the compressions at Paris and Oropa by the small circle shown. This circle has its centre at a distance of 0.004 units from the main circle. According to the formula given earlier the main circle has a radius r given by

$$1/(4r) = 0.004$$

so that $r = 62$ units. We have already pointed out that this radius is sufficient to include the PKP observations at Wellington. The radius corresponds to a dip of about 89°.1.

The small circle represents a plane striking N 78°.5 W and dipping to the south-west at an angle of 3°.4.

The solution presented in Figures 6 and 7 account for all but 20 of 134 observations of motion. The number of observations available, and the numbers of inconsistent observations are summarized in Table 2. This percentage of inconsistencies is somewhat less than normal for a solution of this kind.

Table 2

	P	P_1'	P_2'	pP	PP	PPP	P_cP	Total
Total Number of Observations	100	3	1	17	10	1	2	134
Number of Inconsistent Observations . .	9	0	0	6	5	0	0	20

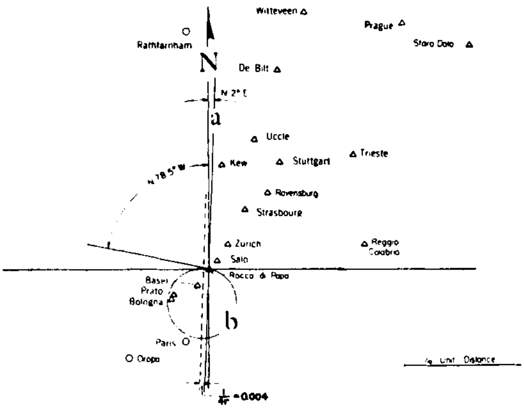

Fig. 7. Fault plane solution diagram of the immediate epicentre vicinity.

Fig. 8. Cross sections of the earth, through the focus, drawn to scale, showing the two geological possibilities.
a. If plane *a* represents the fault.
b. If plane *b* represents the fault.

Discussion

We have already seen that circle *a* represents a plane striking N 2° E and dipping toward the east at an angle of 89°.1. Circle *b* represents a plane striking N 78°.5 W and dipping to the southwest at an angle of 3°.4. For the purpose of this discussion it seems unwise to say more than that the one plane is vertical and strikes N—S while the other plane is essentially horizontal.

We have then to consider two possibilities. If plane *a* represents the fault, then the fault strikes north-south and is vertical. Plane *b*, under this assumption, will represent the auxiliary plane, which is, by definition, perpendicular to the motion vector. The auxiliary plane being horizontal the motion vector is vertical. The situation is shown, in section, in Fig. 8 a. The western block has dropped relative to the eastern one.

If, on the other hand, the horizontal plane represents the fault, then the vertical plane must represent the auxiliary plane and the motion vector must be horizontal. In this case the motion vector must act in an east-west direction, so that the motion will be as shown in Figure 8 b. Here the material above the focus has moved due east relative to the material below it.

Which of the two possibilities is the true one? This matter can only be solved through the use of S waves, a technique which has not yet progressed to a satisfactory point.

Fault plane solutions have been found for many deep focus earthquakes in the program carried out by this Observatory (HODGSON and STOREY, 1954; HODGSON, 1955, 1956 a, b) Most of these have been from earthquakes around the Pacific. In all cases they have shown large transverse components. Indeed this is the first solution obtained for an earthquake of more than normal depth in which there was virtually no transverse displacement. The present solution is therefore unique in the history of the program, further evidence of the unusual nature of this remarkable earthquake.

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