MECHANISMS OF EARTHQUAKES AND PLATE MOTIONS IN THE EAST PACIFIC

Donald W. FORSYTH

Department of Earth and Planetary Sciences, Massachusetts Institute of Technology, Cambridge, Mass. 02139, USA

Received 10 July 1972
Revised version received 18 September 1972

Mechanisms of earthquakes occurring on plate boundaries have been used to determine the relative motions of lithospheric plates in the east Pacific. By using both P-wave first motions and the radiation pattern of Rayleigh waves in the focal mechanisms determinations, the uncertainty in strike is held to about ± 10°. On the Chile fracture zone and the fracture zone at 4°S on the East Pacific Rise, the direction of motion is not parallel to the trend of epicenters. This supports the hypothesis that these fracture zones are composed of series of en-echelon transform faults.

Two regions were found on the East Pacific Rise, in which the slip directions probably are due to local tectonic activity, rather than motion between the Pacific and Nazca plates.

1. Introduction

Studies of seismicity, the focal mechanisms of earthquakes, bathymetry, and magnetic anomalies have been used to determine the relative motion between pairs of lithospheric plates. According to plate tectonic theory, transform faults should parallel the direction of motion between plates [1]. The orientation of the transform fault, and also the direction of motion, can be inferred from the location of earthquakes occurring in the fault zone. On the Galapagos Rift zone and on the Pacific-Antarctic ridge, the trends of epicenters in fracture zones agree with the direction of relative motion deduced from magnetic and bathymetric data. However, on the East Pacific Rise and the Chile Ridge, the strikes of active transform faults inferred from the gross distribution of earthquake epicenters do not agree with the poles of relative motion derived by Hey et al. [2] and by Herron [3] from bathymetry and magnetic anomalies. To resolve the apparent discrepancy between seismic and shipboard data, I have examined the focal mechanisms of events occurring on the ridge system in the east Pacific.

As shown by the map of seismicity in fig. 1, the Chile fracture zone at 36°S is apparently a long, ESE-trending, transform fault between the Chile Ridge and the East Pacific Rise. The loci of epicenters in the fracture zone and in the one at about 41°S 85°W form small circles about a point at 48°N 84°W [2], which, according to plate theory, is the position of the pole of relative motion between the Antarctic and Nazca plates [4].

There are three apparent fracture zone trends between the Nazca and Pacific plates shown in fig. 1: at 4°S, the trend is ENE; at 9°S, nearly east—west; and at 27°S, the trend is slightly south of east. These three fracture zone azimuths suggest the Nazca—Pacific pole of relative motion is located near 20°N 110°W. However, based on an examination of the available bathymetric and magnetic data, Herron has suggested that the fracture zone at 4°S [3] and the Chile fracture zone [5] are both series of en-echelon transform faults rather than single long faults. If this were the case, the overall trend of epicenters would not represent the true direction of motion in the fracture zones. Herron estimates the location of the Antarctic—Nazca and Nazca—Pacific poles to be 72°N 116°W,
and 58°N 93°W, respectively. The hypothesis of en-
echelon faulting can be tested by determining the fo-
cal mechanisms of earthquakes on these transform
faults. The slip vector of an earthquake describes the
motion which took place between the two blocks on
opposite sides of the fault surface. Therefore, the hori-
izontal component of the slip vector of events occur-
ing on plate boundaries should be parallel to the di-
rection of motion between the plates.

2. Focal mechanisms determination

The remote location and relatively small size
($m_B = 5.2$ to $6.4$) of the earthquakes examined in this
study make it difficult to achieve adequate coverage
in observations of the long period P-wave first-motion
polarities. The distribution in azimuth is poor, lim-
ited mainly to stations north and east of the events.
In most cases, variation in distance was also limited.
However, by combining the first motion observations
with the fitting of theoretical radiation patterns to
the observed azimuthal distribution of Rayleigh wave
amplitudes, accurate determinations of the focal me-
chanisms were obtained.

Rayleigh waves are seismic surface waves whose
amplitude is dependent on the strike and dip of the fault
plane and the direction of the slip on the fault. For
example, at long periods a plot of amplitude as a
function of azimuth for a strike-slip source yields
a four-lobed pattern, with the nodes on the direction
of the strikes of the fault and auxiliary planes (exam-
ple in fig. 2). A dip-slip event gives a two-lobed radia-
tion pattern. By measuring amplitudes in several dif-
ferent directions from the event, the source geometry
can be determined. The method employed was as fol-

do.

The long period vertical component of seismograph
records of WWSSN stations were digitized at intervals
of about 1.4 sec. Records from 20 to 25 stations were
Fourier-analyzed for each event, except for the March
7, 1963 earthquake for which only 13 records were
available. Using the amplitude equalization method
[6], the amplitude spectral densities observed at each
station were then corrected for instrument response,
geometrical spreading on the spherical earth, and at-
tenuation. In correcting for the attenuation, I assum-
ed a $Q$ value of 125 [7] and a group velocity of 4.0
km/sec for the periods of 50 and 67 sec used in subse-
quent analysis. The solutions were found to be insen-
sitive to reasonable variations in $Q$. The next step was to
generate theoretical radiation patterns and use a stati-
tical test to compare their fit to the observed ampli-
tudes. Using the oceanic earth model of Anderson [8],
the radiation patterns were computed according to for-
mulas given by Saito [9] for the excitation of surface
waves in a layered earth. The least squares fit of each
theoretical pattern to the observed data was computed.
Then an F-test was performed comparing the fit of the
best model with the fit of all other models. In this
way, a range of possible models was defined, with lim-
its set at the boundaries of the 95% confidence region
in the three-dimensional space of the fault parameters,
strike, slip and dip. The radiation pattern is also de-
pendent on the depth of the source. Tests on the fit of
radiation patterns to data from events with an appre-
Fig. 2. Focal mechanism of the Oct. 12, 1964 earthquake. In the left-hand figure, dots indicate observed amplitudes of 67-sec Rayleigh waves as function of azimuth. The amplitude is proportional to the distance from the center of the figure. Smooth, continuous line is the theoretical radiation pattern. Figure on the right is a Schmids net projection of the lower focal hemisphere showing the distribution of P-wave polarities. Solid circles represent compressions, open circles are dilations.

ciable degree of thrust or normal faulting showed that the depth was less than 15 km at the 95% level of confidence. A depth of 5 km below sea bottom (the base of the crust) was arbitrarily assigned to each event. Although variation of a few km in depth affects the quality of the fit, the best-fitting source mechanism is usually not significantly altered. The effects of finiteness of the source are neglected, as the wavelengths of the surface waves used in this study are much greater than the source dimensions of small earthquakes.

The last step in determining the focal mechanism was to find a solution to the first-motion data within the range of possible models defined by the Rayleigh wave data. One such solution is shown in fig. 2, with the Rayleigh wave amplitude distribution showing the four lobe pattern characteristic of strike-slip events. The complete data for all events will be presented elsewhere. The uncertainty in strike of the fault planes, as defined by region of uncertainty in the Rayleigh wave solution, ranged from ± 7° to ± 15°, with the average uncertainty about 10°. Table 1 lists the fault parameters for each event. Also included are the azimuth of the horizontal component of slip and spreading directions computed from poles of rotation given in the literature.

3. Relative motion

As shown in fig. 3, all but one of the events studied are characterized by predominantly strike-slip motion. Solution 2 gives normal or tensional faulting on the Galapagos Rift zone in the only part of the east-central Pacific ridge system that has a well-developed central rift valley [2] and appreciable seismic activity along the ridge crest (see fig. 1). Event 1 lies on a fracture zone just north of the Galapagos Islands which was identified by Herron and Heirtzler [10] on the basis of seismicity and an offset in magnetic anomalies. Although the fault cannot be identified topographically [11], the slip vector of event 1 suggests that the fault trend is north—south, parallel to the Panama and Ecuador fracture zones farther east, rather than north-east as was previously proposed [10]. The slip vectors of solutions obtained by Molnar and Sykes [12] in the Panama fracture zone region are also north—south.
Table 1
Focal mechanisms and slip directions.

<table>
<thead>
<tr>
<th>No.</th>
<th>Date</th>
<th>Lat.</th>
<th>Long</th>
<th>Fault parameters</th>
<th>Horizontal slip directions</th>
<th>Plate boundary</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>26 June 1969</td>
<td>2.01</td>
<td>-90.48 c</td>
<td>175 80 -160</td>
<td>1 + 6 g,j,h</td>
<td>COC-NAZ</td>
</tr>
<tr>
<td>2</td>
<td>20 Sept. 1969</td>
<td>1.78</td>
<td>-101.03 c</td>
<td>204 60 -75</td>
<td>37 e</td>
<td>COC-NAZ</td>
</tr>
<tr>
<td>3</td>
<td>9 Sept. 1969</td>
<td>4.43</td>
<td>-105.93 c</td>
<td>100 80 -165</td>
<td>103 105 g,j,h</td>
<td>NAZ-PAC</td>
</tr>
<tr>
<td>4</td>
<td>6 Nov. 1965</td>
<td>-22.13</td>
<td>-113.76 b</td>
<td>52 60 166</td>
<td>45</td>
<td></td>
</tr>
<tr>
<td>5</td>
<td>3 Nov. 1965</td>
<td>-22.34</td>
<td>-113.98 b</td>
<td>65 85 165</td>
<td>64</td>
<td></td>
</tr>
<tr>
<td>6</td>
<td>7 March 1963</td>
<td>-26.87</td>
<td>-113.58 d</td>
<td>110 82 -8</td>
<td>108 101 g,j,h</td>
<td>NAZ-PAC</td>
</tr>
<tr>
<td>7</td>
<td>18 Nov. 1970</td>
<td>-28.72</td>
<td>-112.74 c</td>
<td>119 80 -6</td>
<td>118 100 g,j,h</td>
<td>NAZ-PAC</td>
</tr>
<tr>
<td>8</td>
<td>12 Oct. 1964</td>
<td>-31.4</td>
<td>-110.8 b</td>
<td>249 87 167</td>
<td>68 e</td>
<td></td>
</tr>
<tr>
<td>9</td>
<td>29 Dec. 1966</td>
<td>-32.66</td>
<td>-111.79 b</td>
<td>50 60 -160</td>
<td>60 e</td>
<td></td>
</tr>
<tr>
<td>10</td>
<td>6 Oct. 1964</td>
<td>-36.2</td>
<td>-110.9 b</td>
<td>268 58 -12</td>
<td>82 85 h,g,j,h</td>
<td>NAZ-ANT</td>
</tr>
<tr>
<td>11</td>
<td>19 April 1964</td>
<td>-41.7</td>
<td>-84.0 b</td>
<td>271 62 -11</td>
<td>86 79 h,g,j,h</td>
<td>NAZ-ANT</td>
</tr>
<tr>
<td>12</td>
<td>21 Jan. 1967</td>
<td>-49.71</td>
<td>-114.9 b</td>
<td>108 90 172</td>
<td>108 109 k,j,h</td>
<td>ANT-PAC</td>
</tr>
</tbody>
</table>

a) Choice between fault plane and auxiliary plane made on tectonic considerations. Strike is in degrees east of north. Dip angle is measured downward from horizontal line whose azimuth is 90° west of the strike. Slip angle is measured counterclockwise from a horizontal line on the fault plane. b) ISC Bulletin location. c) USCGS location. d) Location by Sykes [16].

e) Choice of fault plane uncertain. f) Degrees east of north. g) Hey et al. [2]. h) Herron [3]. i) Hey et al., Galapagos triple junction. j) Hey et al., Easter Island triple junction. k) Le Pichon [17].

On the Pacific-Antarctic Ridge, the slip direction of event 12 is parallel to the trend of epicenters and to the strike of the Eltanin fracture zone, a major fracture zone at 56°S. Solutions 1 and 12 are both in agreement with the relative motion between plates given in the literature (table 1). Solutions 3 and 10 strongly support the interpretation of the fracture zones at 4°S and 36°S as series of en-echelon transform faults. The sense of motion is consistent with transform faulting, and the slip directions differ by 20–25° from the trends of the epicenters. The difference in strike is significant at the 99% level for both events. Apparently the Nazca plate is moving away from the Antarctic plate in a direction slightly north of east at the Chile fracture zone, rather than ESE as implied by the trend of epicenters. At the site of event 11 on the Nazca-Antarctic plate boundary, the slip direction derived from the pole given by Herron [3], which infers the en-echelon fault pattern on the Chile fracture zone, differs by less than 10° from the direction given by the pole of Hey et al. [2], which does not infer such a pattern (see event 11, table 1). The observed horizontal component of the slip vector has an uncertainty of about 10° and lies between the two computed slip directions. Thus, solution 11 is consistent with either of the two postulated spreading poles and does not provide an additional test of the hypothesis of en-echelon faults.

Mechanism 3 indicates the Nazca plate is moving N 103°E with respect to the Pacific plate, in agreement with previous determinations from the first motions alone [13]. Only two of the other solutions on the East Pacific Rise, events 6 and 7, agree with this direction of motion. A magnetic anomaly profile crossing the ridge crest between the position of events 6 and 7 at 28°S shows that sea-floor spreading has proceeded there at a half-rate of 9 cm/yr for the last 5 my [3]. This spreading rate is consistent with those measured elsewhere on the Nazca-Pacific plate boundary and suggests that events 6 and 7 reliably represent the direction of motion between these plates. The other events farther north and south along the ridge lie in regions of complex seismicity which do not appear to be simple transform fault zones. Further evidence that these are not simple transform faults are the components of thrust and normal faulting in events 4 and 9, respectively. These areas may be sites of non-rigid behavior of the plates due to the high spreading rates, they may possibly be short-lived mini-plates caught between the two larger oceanic plates, or the spreading axis may be in the process of shifting. A recent ship crossing of the ridge north of the Easter Island fracture...
zone showed that there may be a double spreading axis active in this zone (Herron, personal communication), as indicated in fig. 3. The anomalous zone north of the Chile fracture zone may be involved in the evolution of the unstable ridge-ridge-transform fault triple junction [14] at the intersection of the Nazca, Antarctic and Pacific plates.

The slip vectors determined in this study confirm the relative motions of the plates deduced from magnetic and bathymetric data. More detailed surveys will be required to determine the tectonic processes involved in the regions of anomalous slip.

Acknowledgements

This research was sponsored by the Office of Naval Research under contract N00014-67-0204-0048.

A computer program written by Yi-Ben Tsai was used to compute theoretical radiation patterns. I thank Donald Weidner for helpful suggestions and Frank Press for critically reviewing the manuscript.

References