The 1976 August 16, Mindanao, Philippine earthquake ($M_S = 7.8$) – evidence for a subduction zone south of Mindanao

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Received 1978 June 26

Summary. The Philippine earthquake of 1976 August 16, is one of the largest to have occurred world-wide in recent years ($M_w = 8.8$; $M_s = 7.8$; seismic moment, $M_0 = 1.9 \times 10^{28}$ dyne-cm). It is, however, associated not with the Philippine Trench, which is the dominant tectonic feature along the eastern Philippine Islands, but with a much less prominent trench system in the Moro Gulf, North Celebes Sea, south of Mindanao. In this area most of the seismicity is at depths greater than 500 km, associated with the westward dipping Benioff zones of the Sangihe and Mindanao arc systems. This event, however, has a shallow focus and caused a locally destructive tsunami. The focal mechanism of the mainshock determined in this study from long-period surface and body waves indicates a predominantly thrust mechanism with strike N33° W, dip 22° NE and rake +68°. A significant amount of directivity, which can be seen in the observed surface wave seismograms, is explained very well if the source rupture propagates 160 km unilaterally in an azimuth of 300° from the mainshock hypocentre, with rupture velocity 2.5 km/s. The largest aftershock ($M_s = 6.8$) occurred outside the main aftershock area 12 hr following the mainshock and apparently resulted from motion on a subsidiary fault since the P-wave first motion data indicate strike-slip motion for this event. Bathymetric data indicate the presence of a trench striking north—south in the region of the Moro Gulf, and seismic reflection profiling indicates disturbed sediments east of the trench showing evidence for subduction. In addition, the geological structures mapped on the island of Mindanao are consistent with this mode of deformation. The only other known large earthquake in the region on 1918 August 15 ($M_s = 8.0$) probably occurred along the same subduction zone, on an adjacent segment, to the south of the recent event. The 1976 August 16 Philippine earthquake thus represents the first clear seismic evidence for a north-east dipping subduction zone beneath Mindanao in the Moro Gulf, North Celebes Sea.

Introduction

The Philippine earthquake of 1976 August 16 (origin time 16h 11m 0.7.35 UT; location
6.26° N, 124.02° E; depth = 33 km ('normal'); \( m_b = 6.4 \) (USGS); \( M_w = 8.8 \); \( M_s = 7.8 \) (this study); is one of the largest earthquakes to have occurred world-wide in recent years. It occurred in the Moro Gulf, North Celebes Sea, south of Mindanao, the largest island in the southern Philippine archipelago (Figs 1 and 8). The earthquake caused a locally destructive tsunami which was primarily responsible for the large loss of life (5000 deaths), according to Wallace et al. (1977), who state that six out of every seven casualties resulted from the tsunami, while the damage and loss of life due to the effects of shaking were small.

Although the dominant tectonic feature of this region, the Philippine Trench, lies along the eastern Philippine Islands, this event was not associated with it, but with a less prominent though important bathymetric feature called the Cotabato Trench (Hamilton 1974a, b; Hamilton 1977) which strikes in a north–south direction in the North Celebes Sea (Fig. 8). Most of the background seismicity of the North Celebes Sea occurs at depths in excess of 500 km, and is associated with the west-dipping Benioff zones of the Sangihe and Mindanao arc systems (Hamilton 1974b; Cardwell & Isacks 1978). Some shallow seismicity was evident, however, prior to the 1976 August 16 event. It is shown as a diffuse zone in this area by Hamilton (1974b) and Tarr (1974). Hypocentral locations of these early events do not define any fault plane or Benioff zone associated with the Cotabato Trench; however, the data are of poor quality. The relocated aftershock hypocentres, based on the presently available data also fail to indicate a planar pattern. The previous major event in the region with \( M_s = 8.0 \) occurred on 1918 August 15. A relocation of that earthquake for this study indicates that it probably was associated with a more southerly segment of the same subduction zone.

In this study, long-period surface waves were used to constrain the mechanism of the 1976 August 16 Philippine earthquake, as well as determining its seismic moment and source directivity. These data indicate that the earthquake has an oblique thrust mechanism with one shallow plane, the fault plane, dipping to the north-east beneath the island of Mindanao. Thus, the Philippine earthquake is the first seismic evidence for a north-east dipping subduction zone in the Moro Gulf.

Seismological data

Relocation of the mainshock of the 1976 August 16 Philippine earthquake and relative locations of aftershocks, with respect to the main event, were made in this study using P-wave first arrival time data, taken from the Earthquake Data Reports (EDR) of the USGS. All P-wave readings for stations in the distance range 0 to 50° with residuals less than 3.0 s were used in the relative locations. The resulting epicentres are plotted in Fig. 1. The majority of the aftershocks plotted lie to the north-west of the mainshock location, suggesting a unilateral propagation of the earthquake rupture, extending 160 km to the north-west. We will show later that this rupture propagation is consistent with the long-period surface wave data. It is also worth noting that the maximum tsunami damage occurred along the coastal area at the north-west end of the aftershock pattern (Wallace 1977, private communication), suggesting that the direction of source rupture propagation affected the propagation of the tsunami and its resulting effect along the coastline.

The P-wave first motion data for the mainshock are shown in Fig. 2. By use of these data alone, only one plane, that dipping to the west, is constrained. This is the typical situation for events which have a dominant thrust or normal component and for which few, close-in, azimuthally well-distributed P-wave first motion data are available (Abe 1972). However, long-period surface wave data can be used to provide a constraint to the other plane.
Figure 1. Map of south-west Mindanao, Philippines, showing the aftershock zone of the 1976 August 16 earthquake (hatched area). The open circles are aftershocks which occurred in the 12-hr period following the mainshock (before the main aftershock). The closed circles represent later aftershocks up to 1.5 month. All aftershocks have $m_b > 4.5$. The locations of the mainshock and main aftershock are shown together with their respective focal mechanisms (see Figs 2 and 3 for details). Locations of earlier earthquakes with $M > 8.0$ are shown (stars). The solid square represents the relocation of the 1918 event (this study), indicating a shift to the east for the epicentre. The hatched zone represents the coastal zone along which tsunami damage from the 1918 event was the greatest (Masó 1918).

The surface waves $G_3$ (Love waves) and $R_3$ (Rayleigh waves) which were recorded by the World-Wide Standardized Seismographic Network (WWSSN) long-period seismographs and equalized to a propagation distance of $360^\circ + 90^\circ$, are shown in Fig. 5. The equalization method is discussed by Kanamori (1970). Using a filter described in Kanamori & Stewart (1976), short-period (less than 60 s) surface waves have been removed. The Rayleigh waves indicate a two-lobed radiation pattern, while the Love wave radiation pattern is four-lobed. These patterns are consistent with the mechanism shown in Fig. 2. The theoretical radiation patterns of Love and Rayleigh waves for a shallow dipping thrust fault mechanism are shown in Kanamori (1970). These data will be discussed in detail in the section on surface wave analysis. Note that the solution shown in Fig. 2 has a small amount of left-lateral strike-slip motion on the north-east dipping plane, so that the mechanism is described as oblique thrust. Agreement in the strike of this plane is provided by the strike of the aftershock zone (north–north-west trending). Aftershock hypocentres, although all less than 75 km in depth, are too diffuse to indicate support for either fault plane.

Twelve hours following the mainshock, a large earthquake occurred outside the main aftershock area (date 1976 August 17; origin time 04$^h$ 19$^m$ 27.3$^s$ UT; location 7.2$^\circ$ N,
Figure 2. The $P$-wave first motion data for the Philippine earthquake of 1976 August 16, indicating shallow thrust faulting to the north-east. A small amount of left-lateral strike-slip motion is included. The fault plane is constrained by the strike of the aftershock zone (see Fig. 1) and the surface-wave data. All data used in this plot were read from the WWSSN seismograms, in this study. An equal-area projection of the lower focal hemisphere is shown.

Figure 3. The $P$-wave first motion data for the main aftershock ($M_s = 6.8$) of the 1976 August 16, Philippine earthquake, indicating left-lateral strike-slip motion on the preferred fault plane which strikes N 80° E. All data used in this plot were read from the WWSSN seismograms, in this study. The smaller open and closed circles represent less reliable readings.
Figure 4. WWSSN long-period seismograms for the 1976 August 16, Philippine earthquake. The upper record is the vertical component from Bulawayo, Rhodesia (BUL). This station is in an azimuth of maximum radiation for Rayleigh waves. Note that only odd numbered Rayleigh wave multiples can be seen clearly. Even numbered multiples have very low amplitudes. Similarly for the lower trace, which is the east–west component from Godhaven, Greenland (GDH). This station is naturally rotated with respect to SH energy from the source region, and is close to a maximum in radiation for Love waves. Note that only odd numbered Love wave multiples can be seen clearly. These observations are consistent with the implied directivity to the north-west in the source rupture propagation.

The WWSSN long-period seismograms for the 1976 August 16, Philippine earthquake show relatively large amplitude, multiple surface waves. These are seen clearly in Fig. 4, where two such seismograms are illustrated. The upper record is a WWSSN long-period vertical seismogram for Bulawayo, Rhodesia (BUL). This station, lying close to a maximum in the two-lobed radiation pattern indicated in Fig. 5, shows clear multiple Rayleigh waves for R3, R5 and R7. Earlier arrivals of R1 and R2 cannot be seen due to the large amplitude
arrivals in this part of the seismogram. Rayleigh-wave multiples $R_4$ and $R_6$ have very low amplitudes. The larger amplitudes of $R_5$ compared with $R_4$, and $R_7$ compared with $R_6$, suggest that significant directivity may be present in the rupture propagation. This suggestion is further enhanced by the observed Love waves appearing on the east–west component of the WWSSN station Godhaven, Greenland (GDH). This component is almost naturally rotated, with respect to the arrival of $SH$ wave radiation from the earthquake source (back azimuth, $\phi_{SE} = 2.5^\circ$), so it is ideal for observing Love waves. It also lies close in azimuth to a maximum in the Love wave four-lobed radiation pattern, shown in Fig. 5, so large amplitude multiple Love waves are expected and are seen in the lower seismogram of Fig. 4. Note that only the odd numbered Love wave multiples are clearly observed. Even numbered multiples show very small amplitudes, by comparison. This amplitude asymmetry is consistent with the directivity observed for Rayleigh waves.

![Seismograms](https://academic.oup.com/gji/article/57/1/51/716416)

**Figure 5.** Azimuthal plots of equalized seismograms for $R_3$, $G_3$, and synthetic seismograms computed for the fault geometry shown in Fig. 2 with a unilateral propagation (160 km), rupture velocity of $v_r = 2.5$ km/s and rupture azimuth of $\phi_r = 300^\circ$. A seismic moment of $10^{28}$ dyne-cm was used in the synthesis. In the observed patterns one asterisk indicates that $R_3$ and $G_3$ were equalized to $R_3$ and $G_3$ distances. Two asterisks indicate that $R_3$ and $G_3$ were equalized to $R_3$ and $G_3$ distances. The amplitude scale is for the trace amplitude on a WWSSN long-period instrument (15–100) with a magnification of 1500.
Since short-period ($T < 60$ s) surface waves are severely affected by structural heterogeneities during propagation, only long-period signals are used in the present study to determine the overall seismic radiation pattern, the seismic moment $M_0$ and the amount of directivity.

In order to match the overall radiation pattern shown in Fig. 5, we first computed synthetic surface waves for a point double-couple source, located at a depth of 33 km. With the constrained west dipping plane of the focal mechanism shown in Fig. 2 remaining fixed, we varied the slip angle, $\lambda$, until good agreement in the overall radiation pattern for both Love and Rayleigh waves was found. The best fitting solution is that given in Fig. 2. The method of synthesis, the velocity and the $Q$ structure are described by Kanamori (1970) and Kanamori & Cipar (1974). The same filter which we used on the observed data in Fig. 5 was applied to the synthetic records so that a direct comparison could be made. In Fig. 6, the maximum trace amplitudes of the observed Love and Rayleigh wave data are plotted as solid circles, as a function of azimuth. Although the overall agreement is satisfactory, the point source amplitudes are clearly too large in the azimuth range 0 to 180° for Rayleigh waves and 70 to 240° for Love waves. However, as discussed earlier, the aftershock zone extends to the north-west of the mainshock epicentre, a distance of 160 km, and so a point source modelling of the earthquake rupture appears inappropriate.

Source Model

\[ S = 22^\circ, \quad \phi_f = 327^\circ, \quad \lambda = +68^\circ \]

\[ M_0 = 1.9 \times 10^{28} \text{ dyne-cm} \]

Point Source

Unilateral 160-0 km $v_r = 3.0$ km/sec $\phi_f = 327^\circ$

Unilateral 160-0 km $v_r = 2.5$ km/sec $\phi_f = 300^\circ$

Figure 6. Equalized station peak to peak amplitudes for observed $R_3$ and $G_3$ data, plotted as a function of azimuth (solid circles). Curves represent the various fault models used in this study. The preferred model is that indicated by the solid line.
To obtain a better fit of the maximum trace amplitudes of Love and Rayleigh waves shown in Fig. 6 we included the source finiteness in the modelling procedure. The asymmetry in amplitude of the observed radiation pattern can then be explained by directivity (Ben-Menahem 1961). In the first case, we chose the fault geometry shown in Fig. 2, i.e. \( \delta = 22^\circ, \phi_f = 327^\circ \) and \( \lambda = +68^\circ \) (\( \delta \) = dip angle; \( \phi_f \) = strike of the fault measured clockwise from north; \( \lambda \) = slip angle; sign conventions are given in Kanamori & Stewart (1976)) and included the source finiteness, with the rupture extending 160 km in an azimuth, \( \phi_f = 327^\circ \), the same as the fault azimuth, with a rupture velocity, \( u_r = 3.0 \) km/s. As seen in Fig. 6, this model gave a much better fit to the observed data than the point source case. However, the synthetic amplitudes in the Rayleigh-wave case were still too large in the azimuth range 30 to 150°. As a result, in the second case, using the same fault geometry, we reduced the rupture azimuth to \( \phi_f = 300^\circ \) and the rupture velocity to \( u_r = 2.5 \) km/s. This then reduced the Rayleigh-wave amplitude in the azimuth range 30 to 150° to give a slightly better fit. In view of the quality of the observed data, it was not felt that further modelling would be appropriate. Thus these values represent our preferred mechanism. This result suggests the rupture propagated in an up-dip direction, a result that has been suggested for other large thrust events at subduction zone boundaries (Sykes 1971; Kelleher, Sykes & Oliver 1973; Kelleher et al. 1974). From a comparison of the maximum trace amplitudes of the observed and synthetic records for this final model, Figs 5 and 6, a seismic moment, \( M_0 = 1.9 \times 10^{28} \) dyne-cm is obtained from both Love and Rayleigh waves. It is important to note that this realistic fault geometry explains the overall radiation patterns of surface waves and the amplitude ratio of Love to Rayleigh waves very well.

In order to supplement the WWSSN data, seismograms from the ultra-long period instruments at the Seismological Laboratory, California Institute of Technology and the Seismographic Station of the University of California at Berkeley were used. The Caltech

\begin{figure}
\begin{center}
\begin{tabular}{|c|c|}
\hline
\textbf{Pasadena} & U.L.P (No. 33) \( (T_p = 35, T_g = 100) \) \\
\hline
\textbf{Obs} & \begin{tabular}{c}
\begin{tabular}{c}
19° 51′

cm
\end{tabular}
\end{tabular} \\
\hline
\textbf{Syn} & \begin{tabular}{c}
\begin{tabular}{c}
-19° 51′

cm
\end{tabular}
\end{tabular} \\
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\begin{center}
\begin{tabular}{|c|c|}
\hline
\textbf{Berkeley} & U.L.P \( (T_p = 100, T_g = 300) \) \\
\hline
\textbf{Obs} & \begin{tabular}{c}
\begin{tabular}{c}
19° 48′
\,cm
\end{tabular}
\end{tabular} \\
\hline
\textbf{Syn} & \begin{tabular}{c}
\begin{tabular}{c}
-19° 48′
\,cm
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\caption{Observed and synthetic Rayleigh waves (R,) at Pasadena and Berkeley (ultra long-period instruments). The records are filtered in two pass bands as shown \( (T_p \) is the short-period cut-off, \( T_g \) the long-period roll-off). Note the agreement of the phase.}

Figure 7.
instrument (PAS, No. 33) has a peak response at 150 s and records very long-period surface waves. The UC Berkeley instrument is peaked at 90 s and also records very long-period surface waves well. Fig. 7 shows the observed data for both instruments, filtered at a low pass cut-off, $T_0 = 60$ s and a high pass roll-off, $T_m = 900$ s and also at $T_0 = 100$ s and $T_m = 300$ s. Synthetic seismograms have been computed for the fault mechanism shown in Fig. 2 and with source finiteness, discussed earlier, included (see final model in Fig. 6). The same filter was applied to the synthetic records. The agreement of the waveforms is very good. A seismic moment, $M_0 = 1.4 \times 10^{28}$ dyne-cm was found in all cases which, although a little smaller than the WWSSN data estimate, is still in agreement with it, considering all the uncertainties involved. We will use, in the later discussion, the moment of $1.9 \times 10^{28}$ dyne-cm obtained from the WWSSN data.

It is possible to interpret the above results in terms of the average dislocation of the fault, $\bar{D}$, and the average stress drop, $\Delta \sigma$. If we assume, from Fig. 1, a fault width, $w \approx 80$ km then by using a fault length, $L = 160$ km, also from Fig. 1 and, e.g. Aki (1966) and Kanamori & Anderson (1975), we have $\bar{D} = M_0/\mu Lw = 3.0$ m and $\Delta \sigma = 8\mu \bar{D}/3\pi w = 17$ bar where $\mu = 5 \times 10^{10}$ dyne/cm$^2$ is used.

**Tectonic setting**

The Philippine earthquake of 1976 August 16 occurred in an area called the Moro Gulf in the North Celebes Sea, south of the island of Mindanao. The major tectonic feature in the region, the Philippine Trench, lies approximately 400 km to the east of the mainshock epicentre (Fig. 8). It is clear that this event is not directly associated with it. However, the influence of the westward dipping Benioff zones of the Sangihe and Mindanao arc systems (Hamilton 1974b; Cardwell & Isacks 1978) are seen as contributing to the seismicity of the region, albeit at depths in excess of 500 km. The shallow seismic events prior to the Philippine earthquake and the relocated aftershock hypocentres are diffuse and do not define any fault plane or Benioff zone. Thus this event offers the only seismic evidence for the existence of a subduction zone dipping to the north-east, beneath the island of Mindanao in the North Celebes Sea. However, no evidence exists for this subduction zone extending deeper than the rupture indicated by the Philippine earthquake.

Several large earthquakes have occurred in this region in the past. Masó (1910) lists 'violent and destructive earthquakes' in the time period 1599 to 1909 and Repetti (1946) catalogues earthquakes in the period 1589 to 1899 for the Philippines. However, since most of the locations they presented are based on felt reports or tsunami damage data, the association of such events with any tectonic feature must be considered tenuous. For example, two of the largest events in this area listed by the previous authors, are those which occurred on 1897 September 20 and 21. Their epicentral locations, given by Gutenberg (1956) ($6^\circ$N, $122^\circ$E), are shown in Fig. 1. However, if we look closely at Masó (1910), he states that the tidal wave generated by the event on 1897 September 21 'claimed hundreds of victims on the western shores of Basilan', the large island south of Zamboanga, shown in Fig. 1. It is quite possible, from this fact and the felt area, that the event occurred outside of the Celebes Sea and may be attributed to the south-east dipping subduction zone associated with the Sulu Trench (Fig. 8), although this portion of the Sulu Trench has little evidence for seismic activity.

The earthquake of 1918 August 15, magnitude 8.25 (Gutenberg & Richter 1965) listed by Geller & Kanamori (1977) as $M_s = 8.0$, $m_b = 7.6$, on the other hand clearly lies in the North Celebes Sea. Gutenberg & Richter (1965) relocated the epicentre at $5.5^\circ$ N, $123.0^\circ$ E. It is plotted in Fig. 1 as one of the stars. In this study, we relocated the event by computer,
using the International Seismological Summary (ISS) readings. All P-wave readings for stations in the distance range 0 to 90° and with residuals less than 3.5 s were used in the relocation. The hypocentre was constrained at 10 km depth in order to obtain a solution. The resulting epicentral location (5.7° N, 123.5° E) is indicated by the solid square in Fig. 1. This location, which has an associated error of 15 km, may then imply that the earthquake is located along the subduction zone, south-east of the mainshock. The maximum tsunami damage for this event, shown in Fig. 1 as the hatched coastal region (from Masó 1918) is consistent with this location.

It is possible, then, that both the 1918 and 1976 earthquakes represent rupture of successive segments of the north-east dipping subduction zone in the North Celebes Sea.

Figure 8. A bathymetric chart of the Moro Gulf, North Celebes Sea region, south-west of Mindanao (after Mammerickx et al. 1976). The solid line ABCDEF represents the ship track along which seismic reflection profiling data were taken (profile from Lamont-Doherty Geological Observatory, RV Vema Cruise #28). The dashed line XY represents an anonymous seismic reflection data profile. Note the bathymetry shown, indicating the presence of the Cotabato Trench of depth 4700 m striking north-north-west in the vicinity of the mainshock rupture. The star represents the mainshock epicentre, the solid ellipse, the aftershock zone of the Philippine earthquake.
The seismic reflection profile data (see Fig. 8 for location). CT represents the location of the Cotabato Trench. Note from Fig. 8 that each letter represents a change in orientation of the profile. The relative motion vectors at the bottom of the figure represent the direction of subduction, i.e. to the north-east (Warren Hamilton 1977, private communication).

Figure 9. The seismic reflection profile data (see Fig. 8 for location). CT represents the location of the Cotabato Trench. Note from Fig. 8 that each letter represents a change in orientation of the profile. The relative motion vectors at the bottom of the figure represent the direction of subduction, i.e. to the north-east (Warren Hamilton 1977, private communication).
Although less prominent than the Philippine Trench (maximum depth ≈ 9500 m), the Cotabato Trench (maximum depth ≈ 5700 m) striking north–south in the region of the Philippine earthquake, curves west–north-west to east–south-east paralleling the southern Mindanao coastline and eventually trends north–south again in the region west of the West Sangihe Ridge (Fig. 8). The trench topography is seen also in the seismic reflection profile, ABCDEF (Figs 8 and 9). Note that the profile changes direction at each letter. In Fig. 9, the Cotabato Trench (CT) can be seen at the three localities where the profile crosses it. The sense of motion of the subduction is shown at the bottom of Fig. 9. Note the relatively undisturbed sediments in the Celebes Basin between D and E and their downwarping between E and F. Profile XY represents a seismic reflection profile (anonymous). From X to the midpoint of the profile, the sediments are again undisturbed, but from the midpoint to Y, i.e. on the eastern or landward side of the trench, severe warping of the sediments can be seen.

One unusual aspect of the tectonic deformation of the Philippine earthquake sequence is the occurrence of the main aftershock \( (M_s = 6.8) \), 12 hr after the mainshock. It is unusual because the mechanism for this event appears to be pure strike-slip (Figs 1 and 3). The sense of motion, left-lateral displacement if we choose the plane striking N 80° E, can be interpreted as tear faulting close to the north-west edge of the aftershock zone – the result of block movement to the north-east of the Moro Gulf relative to the western arm of Mindanao. Some other recent earthquakes also show significant variation in the mechanism of their largest aftershock compared with their respective mainshock fault plane solution.

![Figure 10](https://academic.oup.com/gji/article/57/1/51/716416)

Figure 10. A schematic tectonic map of Mindanao, indicating the major features of the island. Note that the structures in the eastern part of Mindanao lie parallel to the Philippine Trench, i.e. in a north–south direction, while those in southern Mindanao, trend north–north-west, an influence of the north-east dipping subduction zone shown on the map. The star and ellipse represent the mainshock and aftershock pattern locations respectively, for the Philippine earthquake (after Ranneft et al. 1960).
Such an example is suggested for the 1976 February 4, Guatemala earthquake, in which the mainshock ($M_s = 7.5$) was associated with N66°E left-lateral strike-slip faulting on the Motagua fault (Kanamori & Stewart 1978), while the main aftershock ($m_b = 5.8$) may have occurred on the Mixco fault, a north–south trending normal fault (Person, Spence & Dewey 1976). Similarly, for the 1976 July 27, Tangshan earthquake, China, the mainshock ($M_s = 7.7$) was primarily a strike-slip event, with some associated thrust faulting following 11 and 19 s afterwards, while the main aftershock ($M_s = 7.2$), occurring 15 hr after the main event represented an oblique dip-slip fault motion on a plane, perpendicular to the mainshock rupture plane (Butler, Stewart & Kanamori 1978). Such complexity, although unusual, may be more common than is presently recognized.

The dominant offshore features also influence the structural trends on land. For example, in eastern Mindanao they are dominated by the north–south strike of the Philippine Trench (Fig. 10). Parallel to the trench in order east to west, lie the Pacific Cordillera, the Philippine Fault, the Agusan–Davao Trough and its seaward extension, the Sangihe Trough and the Central Cordillera with its widespread Tertiary volcanism (Krause 1966; Ranneft et al. 1960). Deep and intermediate earthquakes, which are distributed along the west dipping Benioff zone, project to the surface along the trend of the Sangihe and Agusan–Davao Troughs, suggesting that subduction may have been concentrated in that region until subsequent development of the Philippine Trench, which now hosts most of the shallow seismicity (Caldwell & Isacks 1978; Hamilton 1974b).

West of the Central Cordillera, in southern Mindanao, the Mindanao Lineament, a depressed zone of high-angle reverse faults, deformation and volcanoes, strikes north–north-west, separating the northerly structural trends to the east and the north-westerly trends of folds and faults in the Cotabato (Tiruray) Highlands (Gervasio 1966). The Cotabato Highlands stand 22 000 feet above the adjacent floor of the Celebes Sea. They consist of discontinuous belts of Miocene sedimentary strata, intrusive andesite porphyry and basalt which have been tilted and block faulted along north–north-west trending faults. Terraced shorelines, steep mountain fronts, deeply dissected fluvial terrace deposits and hour-glass valleys imply recent uplifting of the Highlands region (Ranneft et al. 1960).

The 1976 Philippine earthquake occurred in the Moro Gulf, directly west of the Cotabato Highlands, at the edge of the Celebes Sea. It is shown here that it represented thrust movement on a fault plane dipping, at shallow angle, to the north-east, toward the Cotabato Highlands block. Thus the 1976 event may contribute to the Pleistocene and Recent pattern of uplift in the Cotabao Highlands and to the subduction of the Celebes sea-floor beneath the island of Mindanao.

**Conclusions**

The source mechanism of the 1976 August 16, Philippine earthquake is oblique thrust, with the fault plane dipping to the north-east (strike N33ºW, dip 22º and rake +68º, see Fig. 2). The seismic moment, $M_0 = 1.9 \times 10^{28}$ dyne-cm is calculated from long-period multiple surface-wave data, after accounting for the directivity of the source rupture by propagating the rupture unilaterally a distance of 160 km in an azimuth of 300º from the mainshock hypocentre, with a rupture velocity of 2.5 km/s.

The source parameters cited above imply that significant tectonic deformation, predominantly thrusting to the north-east, occurred in this region at the time of the earthquake. Bathymetric data, as well as seismic reflection profile data, and the events, epicentre argue for the source of this event being along a relatively new (Oligocene or younger, Heezen & Fornari 1975) and developing subduction zone boundary, located in the Moro Gulf region, between the North Celebes Basin and the island of Mindanao.
Acknowledgments

We would like to thank the personnel of all the WWSSN stations who were kind enough to send us seismograms. We thank the Seismographic Station at UC Berkeley for supplying copies of their ultra long-period seismograms for the Philippine earthquake. We thank Robert E. Wallace and Warren Hamilton for useful discussions. We are grateful to the Lamont-Doherty Geological Observatory, Palisades, New York for providing Fig. 9 and J. Mammerickx and the Geological Society of America for allowing us to use Fig. 8.

This research was supported by a grant from the National Academy of Sciences, through WDC-A for seismology, the Division of Earth Sciences, National Science Foundation, NSF Grants (EAR76-14262 and EAR77-13641). Contribution No. 3113, Division of Geological and Planetary Sciences, California Institute of Technology, Pasadena, California 91125.

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