THE LARGE NORMAL-FAULTING MARIANA EARTHQUAKE OF APRIL 5, 1990
IN UNCOUPLED SUBDUCTION ZONE

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Abstract. A large, Ms = 7.5, shallow earthquake occurred beneath the Mariana trench on April 5, 1990. From the relocated aftershock distribution, the fault area is estimated to be 70 x 40 km². A tsunami observed on the Japanese islands verifies that the depth of the main shock is shallow. For waveform analysis, we use long-period surface waves and body waves recorded at global networks of GDSN, IRIS, GEOSCOPE and ERIOS. The centroid moment tensor (CMT) solution from surface waves indicates normal faulting on a fault whose strike is parallel to the local axis of the Mariana trench, with the tension axis perpendicular to it. The seismic moment is 1.4 x 10²⁰ Nm (x 10²⁷ dyn.cm) which gives Mw = 7.3. Far-field P and SH waves from 13 stations are used to determine the source time function. Since the sea around the epicentral region is about 5 km deep, body waveforms are contaminated with water reverberations. The inversion results in a source time function with a predominantly single event with a duration of 10 sec, a seismic moment of 2.1 x 10²⁰ Nm, and a focal mechanism given by strike = 198°, dip = 48°, slip = 90°. The short duration indicates a small area of the rupture. The location of the main shock with respect to the aftershock area suggests that the nodal plane dipping to the west is preferred for the fault plane. The Mariana earthquake is considered to have occurred in an uncoupled region, in response to the gravitational pull caused by the downgoing Pacific plate.

Introduction

A large shallow earthquake occurred on April 5, 1990 just beneath the Mariana trench where the Pacific plate is subducting beneath the Philippine Sea plate. This is the largest shallow event ever recorded in the region; the last event with a similar magnitude was on September 22, 1902 with Ms = 7.5 [Abe and Noguchi, 1983]. Since that event is very old for studying the focal mechanism, the 1990 Mariana earthquake provides us with a good opportunity to study the seismotectonic characteristics of this region. In this paper, we analyze waveform data to estimate the source process. This earthquake also caused a tsunami that was observed on the Japanese islands as well as the Pacific islands. The unusual behavior of the tsunami and the implication for hazard assessments of tsunami potential is described elsewhere [Satake et al., 1992].
master event. It occurred at 14:57:20.1 (UT) on April 6 (mb = 5.9) near the southern end of the aftershock area. The results were almost same as the NEIC locations (Figure 1). The length of the aftershock area is a little shorter, about 65 km. The aftershocks are distributed in the N-S direction with a sparse region in the central part. The main shock is located in the southern cluster. Almost the same distribution is obtained for a master event near the northern end. This pattern of the aftershock activity suggests an inhomogeneous distribution of stress drop or strength on the fault plane.

The pP phases were reported on NEIC for 14 aftershocks. The pP-P times range from 10 to 15 sec. Since the sea depth in the epicentral area is 5 km or so, it is probable that pwP phases were misread to pP phases. We consulted seismograms recorded at Dodaia Micro-earthquake Observatory and its satellite stations at Kanto area in Japan. The epicentral distances are about 25°. Clear phases are observed 10 to 15 sec after the P wave arrival. For example, the event of the 22:52:59.9 (UT) on April 5 shows clear phases 4 and 13 sec after the P wave arrival. If we assume that the thickness of the water layer as 5 km and the source depth as 25 km, the phases arriving 4 and 13 sec after P wave correspond to pP and pwP phase, respectively. This suggests that the pP phases reported by NEIC are pP phases. This misreading results in overestimation of the focal depth. We calculated the source depth using the pP-P times of NEIC by assuming that the phases are pP and got the depth range of 12 to 34 km for 12 aftershocks with an average of 23 km and a standard deviation of 6 km. The fault width is estimated to be 40 km when the fault dip is 42° which is derived from following body wave analysis.

Surface Wave Analysis

We performed a Centroid Moment Tensor (CMT) inversion [Dziewonski et al., 1981; Kawakatsu, 1989] using long-period surface waveforms (mainly R1 and G1) recorded at 19 stations of the IRIS, ODSN GEOSCOPE [Romanowicz et al., 1984] and ERIOS [Takano et al., 1990] networks. The stations used were COL, HRV, BCAO, CAY, COR, SCCZ, PAS, KIP, PPT, CTAO, SLR, CMB, KEV, KMI, SSB, INU, MAJO, KONO and TSK. The data were deconvolved to displacements and bandpass filtered between the frequency range from 3 to 7 mHz. Combining the data from these stations, we have a good azimuthal coverage.

The final solution for the moment tensor elements is given in Table 1. The centroid location is 15.288°N and 147.397°E for a depth of 10 km. The inversions were performed for the selective depths of 10, 20 and 33 km. The smallest variance of the solution was obtained for the depth of 10-20 km. The double-couple component that is expressed as the ratio of the minimum eigenvalue to the maximum is only 8 % and negligibly small. The moment of the best double couple is 1.4 x 10^20 Nm which gives MW = 7.3. The best double couple indicates almost pure normal-faulting with the strike almost parallel to the local trench axis. The tensional axis is perpendicular to the trench and the compressional axis is almost vertical. These stresses are typical of outer rise normal fault events. The dip of the westward dipping plane is 30°. Though the solution is very similar to that obtained by Harvard and GEOSCOPE groups, the uncertainty is not small because of difficulty in determining the dip angle for shallow events. We will get a steeper dip from the following analysis of body waves.

Body Wave Analysis

For body wave analysis, we used P and SH waves recorded at 13 stations at epicentral distances ranging from 30° to 100°. The arrival times were read directly on the broadband channel. All the records were deconvolved to displacements. We applied a multiple deconvolution method developed by Kikuchi and Kanamori [1991]. By minimizing the difference between the observed and synthetic waveforms, we determined the mechanisms of subevents. For the computation of Green's functions, we assumed a structure consisting of a water layer 5 km thick and an oceanic crust 10 km thick near the source region.

We computed Green's functions by assuming source depths of 6, 10, 14, 16, 20, 25 and 30 km, and derived source mechanism for each depth with a source time function of triangular shape. The residual error was minimized for the case of 16 km. Fixing the depth at 16 km and using a point source with the same mechanism as that obtained from the above analysis, we first made only one iteration. The seismic moment is obtained to be 2.1 x 10^20 Nm. The source time function is shown in Figure 2 (a) and the synthetic waveforms are shown in Figure 3. They show water reverberation similar to the observation, although the details are different. The difference may be due to our simplified water layer (uniform depth) or due to real complexity of the source process. If the latter case is true, more iterations should reveal the complex source process. We made five iterations. The seismic moment is obtained to be 3.0 x 10^20 Nm. Figure 2 (b) shows the

![Fig. 2. Source time function for single event model (a) and five subevents model (b).](image-url)
source time function. Residual reduction (49%) is not significantly different from that of the single event (53%) and it cannot be determined whether the source process is complex or not. The seismic moment from the single event is closer to that from the surface wave analysis. We prefer the single event solution for simplicity. The final source parameters are:

strike = 197.5°, dip = 47.8°, slip = 90.2°; strike = 17.2°, dip = 42.2°, slip = -90.2°. The mechanism is pure normal faulting.

**Stress Drop**

We can derive the stress drop $\Delta \sigma$ for the largest subevent from the seismic moment $m$ and duration $2\tau$. In the present model, the source time function of triangular shape is assumed, and half the duration $\tau$ corresponds to the rise time of 5 sec. We call $\Delta \sigma$ a local stress drop to distinguish it from an average stress drop over the entire fault. The local stress drop is estimated by the relation $\Delta \sigma = 2.5 m / (\nu \tau)^3$ where $m$ is the moment and $\nu$ is the rupture velocity [Fukao and Kikuchi, 1987]. Using $\nu = 3.0$ km/s, as was used by Fukao and Kikuchi [1987], we obtain $\Delta \sigma = 150$ MPa (1.5 Kbars) for $\tau = 5$ sec and $m = 2.1 \times 10^{20}$ Nm. This stress drop is much higher than the average stress drop of 3.2 MPa over the fault plane of 70 x 40 km$^2$.

Figure 4 shows the relation between the duration and seismic moment of the largest subevent in large shallow earthquakes of the world. The data are taken from Kikuchi and Fukao [1987] for interplate thrust events and Sugi et al. [1987] for intraplate normal-faulting events. It is indicated that the local stress drop for intraplate earthquakes is one order of magnitude higher than that for interplate earthquakes. Sugi et al. [1987] interpreted this in terms of different nature of fault interface. The Mariana event shows the highest value among the intraplate shocks. This suggests that the Mariana earthquake was caused by rupture of almost intact material.

**Discussion and Conclusion**

In the Mariana region, the Pacific plate is subducting northwardly beneath the Philippine Sea plate. The seismicity indicates that the slab is subducting vertically. The deepest depth of the trench in the world and the steepest dip of the Wadati-Benioff zone are the characteristic feature of the Mariana region. At the Mariana trench, the convergence rate is as low as 4 cm/year [Seno, 1977], and the age of the subducting slab is very old, about 150 Ma [e.g. Ruff and Kanamori, 1980]. Uyeda and Kanamori [1979] interpreted this in terms of different nature of fault interface. The Mariana event shows the highest value among the intraplate shocks. This suggests that the Mariana earthquake was caused by rupture of almost intact material.

![Diagram](image_url)
and Seno [1984], the subducting and overlying plates in the Mariana region are purely uncoupled, that is, the Pacific plate is subducting aseismically without causing large underthrusting earthquakes. There is no evidence of a similar size or larger underthrusting event during historic times. The 1977 Sumba earthquake is another example of an outer rise normal faulting event in an uncoupled region. It is the largest earthquake in the Sunda arc ever recorded. These show that the largest earthquakes in the uncoupled zone are outer rise normal fault events.

The shallow Mariana earthquake of 1990 occurred beneath the Mariana trench where the Pacific plate is aseismically subducting. Waveform analyses and aftershock distribution reveal that this event represents pure normal faulting on a fault with strike=197.5°, dip=47.8° and slip=90.2°. The seismic moment is 2.1 x 10²⁰ Nm. The duration of the rupture is 10 sec and the local stress drop is as high as 150 MPa. The Mariana earthquake is considered to have occurred in the uncoupled region, in response to the gravitational pull caused by the downgoing Pacific plate.

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