The 1992 Nicaragua earthquake: a slow tsunami earthquake associated with subducted sediments

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THE 1992 Nicaragua earthquake was a 'tsunami earthquake'; that is, it generated tsunamis[1] disproportionately large for its surface-wave magnitude, M_s. The moment magnitude, M_w, determined from long-period (~250-s) surface waves[2], was 7.6, significantly larger than the 20-s M_s of 7; this M_s–M_w disparity is also characteristic of tsunami earthquakes[3,4]. The Nicaragua earthquake is the first tsunami earthquake to be captured by modern broadband seismic networks, allowing us to present here seismograms of sufficiently high quality to make inferences about the rupture mechanisms. We conclude that the Nicaragua earthquake was a slow thrust earthquake which occurred on the subduction interface between the Cocos and North American plates, and because of the absence of sediments on the trench floor offshore of Nicaragua, the slip propagated up-dip all the way to the ocean

bottom, exciting large tsunamis. The occurrence of slip on a plate interface filled with soft subducted sediments caused the rupture process to be slower than in ordinary subduction-zone thrust earthquakes. Our results reinforce the idea that tsunami warning systems using long-period (≥100-s) waves[5–7] are necessary to reduce the hazard from this type of earthquake.

Figure 1 shows the mainshock epicentre, the aftershock area, the mechanism determined from long-period surface waves and the source time function determined from long-period body waves. The surface-wave magnitude, M_s, determined with data from 11 IRIS stations is 7. The epicentre is near a previously identified seismic gap[8]. The mechanism is thrust which is consistent with subduction of the Cocos plate beneath Nicaragua. A seismic moment, M_0, of 3.7×10^{27} dyn cm ($M_w = 7.6$) was obtained. The seismic moment could be considerably larger or smaller than this value if the dip angle, which is not well determined, was reduced or increased, respectively. This solution is similar to the Harvard centroid moment tensor (CMT) solution[1]. The difference is partly due to the difference in the dip angle and the period of the wave used. The long-period centroid location is closer to the trench than the epicentre, suggesting that the rupture propagation was up-dip toward the trench.

The anomalous character was readily identified on the high-quality seismograms. For example, Fig. 2 shows a long-period wave, indicated by an arrow, on the displacement seismogram recorded at the Pasadena TERRAscope station. For ordinary earthquakes, this long-period wave is buried under much larger short-period waves and is not visible. The appearance of this wave is a direct manifestation of deficiency in short-period energy. Figure 3 compares long-period Rayleigh waves from the Nicaragua earthquake recorded at station KON (Norway) with those from the 28 June 1992, earthquake in Landers, California ($M_s = 7.5$, $M_w = 7.3$) recorded at station MAJO (Japan). The two seismograms are plotted to the same scale, so that the amplitude can be compared directly. These stations are located at about the same distance from their respective epicentres and in the azimuth where the Rayleigh-wave radiation is maximum. The difference in the spectrum is evident. The very-long-period Rayleigh waves (up to a period of 500 s) for the Nicaragua earthquake are much larger than those for the Landers earthquake, for both R_1 and R_2. In contrast, short-period surface waves are larger for the Landers earthquake than for the Nicaragua earthquake. This observation demonstrates the disparity between M_s and M_w, and indicates that the Nicaragua earthquake is a slow earthquake.

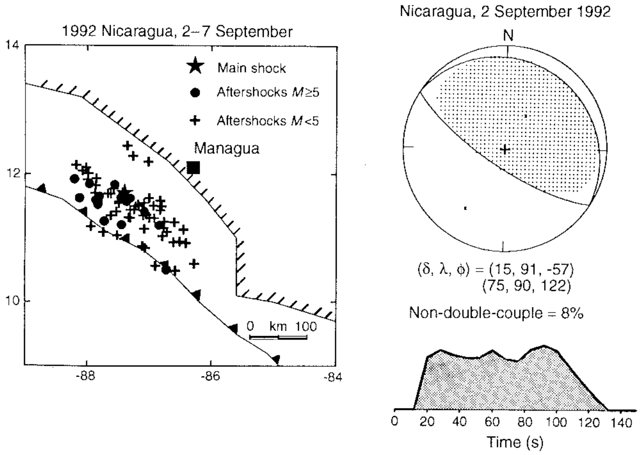

FIG. 1 Location of the main shock and the aftershocks of the 2, September 1992 Nicaragua earthquake (left), the mechanism determined with long-period surface waves from 11 stations (upper right), and the source time function determined with long-period body waves (lower right). The non-double-couple component of 8% is commonly found in this type of inversion, and should be considered insignificant. The body-wave solution was obtained using the first 150 s of P and SH waves from six stations, with the mechanism constrained to be the same as that determined with surface waves.

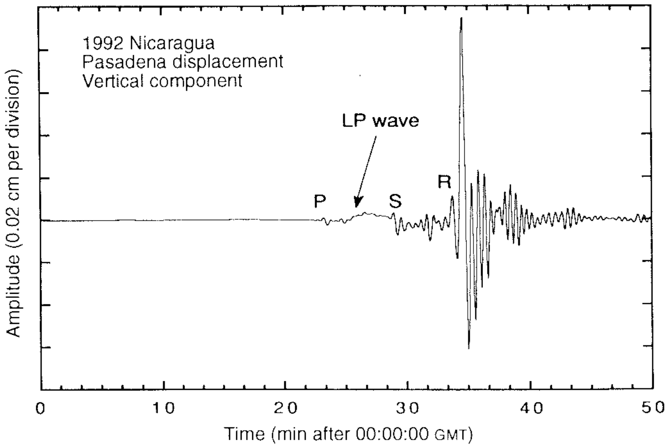

FIG. 2 The displacement seismogram recorded at the Pasadena TERRAscope station. Note the large long-period wave indicated by an arrow.

We examined seismic excitation at periods longer than 200 s by comparing the observed normal-mode amplitude with that computed for the source mechanism shown in Fig. 1. No evidence for enhanced seismic excitation was found beyond a period of 200 s. Thus, the Nicaragua earthquake is anomalous over a period range of up to 200 s.

The Nicaragua earthquake has very long source duration. The centroid origin time of the Nicaragua earthquake is ~50 s after the origin time determined by the National Earthquake Information Center (NEIC) using short-period waves. Inversion of body waves, shown in Fig. 1, also indicates a source duration of 80–100 s although the details of the source function could not be resolved. These observations suggest that the overall source duration is ~100 s. The broadband response of modern seismic networks is essential for determining source duration.

Because submarine slumping has been suggested as a cause of some tsunamis[9–11], we tried a slump model to interpret the Nicaragua earthquake data. We used a horizontal single force, instead of a moment tensor, as a kinematic representation of slumping, but a single-force model simply could not fit the data. Thus we conclude that the primary source of the Nicaragua earthquake is a slow thrust fault on the subduction interface, although some slumping could have accompanied the earthquake. Whether the size of the Nicaragua earthquake determined from long-period waves is large enough to explain the observed

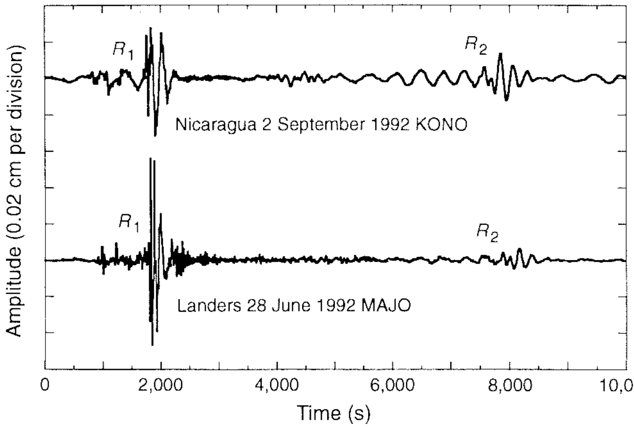

FIG. 3 Comparison of the long-period surface waves (displacement) from the Nicaragua earthquake ($M_S = 7.0$, $M_w = 7.6$) with those from the Landers earthquake ($M_S = 7.5$, $M_w = 7.3$). Note the large long-period (up to 500 s) waves seen on the record of the Nicaragua earthquake, for both R_1 and R_2.

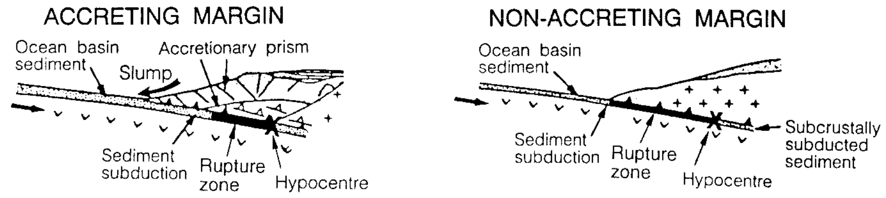

FIG. 4 Schematic diagrams showing the two types, accreting and non-accreting, of plate margin[20]. The Nicaragua earthquake occurred on a non-accreting margin where the sediments are completely subducted. The slow rupture extending all the way to the trench floor causes tsunamis. In accreting margins, thrust earthquakes may not rupture to the trench floor, but occasional sediment slumping on the accretionary prism may cause very large tsunami earthquakes.

tsunami is unresolved at present. The excitation and progagation of tsunamis are strongly affected by the coastal topography, focusing and defocusing of tsunami energy, and the details of the sea-floor deformation.

Among tsunami earthquakes, the 1896 Sanriku, Japan, and the 1946 Unimak Islands. (Aleutian Islands) earthquakes are most anomalous[3]. The Sanriku earthquake was felt only moderately along the Sanriku coast, but very large tsunamis hit the coast $\sim$30 min later and drowned more than 22,000 people; presumably, because of the absence of strong shaking, they did not expect large tsunamis. The magnitudes of these earthquakes determined at short period are only 6.8 to 7.5 (refs 3, 12), but they excited some of the largest tsunamis in history. The source spectral amplitude of these events increases beyond 200 s (ref. 3). Compared with these earthquakes the Nicaragua earthquake is not very anomalous; it is comparable to other tsunami earthquakes such as the 1960 Peru[13,14], 1963 Kurile Island (October 20)[14,15] and 1975 Kurile Island earthquake[14,15].

Several mechanisms have been proposed for tsunami earthquakes. When tsunami earthquakes were first recognized, slow slip on the subduction interface was intuitively thought to be the cause of their deficiency in short-period energy[3]. It was later suggested that a secondary steeply dipping fault in the accretionary prism was responsible for some tsunami earthquakes[15]. Vertical displacement on a steep fault is considered more favourable for tsunami excitation. Theoretically, a shallow vertical dip-slip fault does not excite seismic waves efficiently but it generates tsunamis well; such a fault could thus be the source of tsunami earthquakes[16]. The moderate tsunami earthquakes 1960 Peru, 1963 Kurile Island and 1975 Kurile Island were all caused by slow slip on a basal decollement in the accretionary prism[14]. As shown above, the 1992 Nicaragua earthquake is similar to these events.

In contrast, the mechanism of the very anomalous tsunami earthquakes such as the 1896 Sanriku and 1946 Unimak Island earthquakes is unknown at present. A slump model has been suggested for these events[10], but seismic data are limited both in quality and quantity, and cannot resolve their mechanism. In fact, a fault model is preferred for the 1946 Unimak Island earthquake[17]. In the Sanriku region, and along the Aleutian Islands, large-scale slump features are seen on the sea floor[18]. A large volume of sediments near the trench may occasionally collapse in slumping and cause large tsunamis. During the 1989 earthquake in Loma Prieta, California, tsunamis were excited by a slumping caused by shaking[19].

Unlike the trenches along the Sanriku coast or the Aleutian Islands, the mid-American trench off Nicaragua does not have a large volume of sediments or a well-developed accretionary prism[20]. This is surprising, because most tsunami earthquakes were previously thought to be associated with sediments in the accretionary prism. We suggest that the absence of sediments allowed the slip to propagate all the way to the ocean bottom. A large volume of soft sediments on the trench floor would prevent this.

Two types of tsunami earthquakes may then be suggested (Fig. 4). The first occurs in trenches with large amounts of sediment and an accretionary prism. Although the rupture of the individual thrust earthquake may not reach the ocean bottom, occasional slumping there may be the cause of large tsunami earthquakes. The second occurs in subduction zones without large amounts of sediment. In these subduction zones, the sediments are completely subducted, and the plate interface is filled with soft sediments[20,21]. The slip can extend to the surface, breaking through a relatively weak plate interface filled with sediments. The shallow depth and soft low-velocity sediments on the interface are responsible for efficient tsunami generation and slow rupture propagation, respectively. The 1960 Peru, 1963 and 1975 Kurile Islands, and 1992 Nicaragua earthquakes are of the second type, although the details in the rupture geometry (such as up-dip or rupture propagation) and the trench geomorphology may be different between these events. The truly large tsunami earthquakes (such as the 1896 Sanriku and 1946 Unimak Islands earthquakes) apparently belong to the first type, but direct evidence for this is not yet available. In future, however, the broadband capability of modern seismic networks will help seismologists to identify anomalous earthquakes such as slow earthquakes and tsunami earthquakes, and understand their relationship to the regional variation of subduction process.

Regardless of the mechanism, an important diagnostic feature of tsunami earthquakes is the difference between M_s and M_w. Unfortunately, most of the existing systems use an M_s threshold for issuing tsunami warmings. Long-period magnitudes such as M_w and mantle magnitude (a magnitude determined with mantle waves at a period of $\sim$100 s)[22,23] are more diagnostic of the tsunami potential of earthquakes[3,4,22,23]. As is evident in Figs 2 and 3, with the use of M_w, the Nicaragua earthquake would have been easily diagnosed as a tsunami earthquake. In fact, its seismic moment was quickly estimated at long period at Papeete and reported to warning agencies within an hour of the earthquake origin time (E. Okal, personal communication) Several tsunami warning systems using long-period waves have been proposed for both teleseismic and local tsunami warning purposes[5-7]. Systematic use of such a system could reduce the hazards posed by tsunamis. ☐

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