The Sanriku-oki, Japan, earthquake of December 28, 1994 (Mw 7.7): Rupture of a different asperity from a previous earthquake

Yuichiro Tanioka, Larry Ruff

Dept. of Geological Science, University of Michigan, Ann Arbor

Kenji Satake

Seismotectonics Section, Geological Survey of Japan, Tsukuba

Abstract. Fault geometry, depth, and slip distribution of the Sanriku-oki earthquake of December 28, 1994 (Ms 7.5) are estimated from seismic waveforms, geodetic measurements, and tsunami waveforms, and compared with those of the 1968 Tokachi-oki earthquake (Mw 8.2), the most recent large earthquake in the epicentral region. Seismic wave inversions indicate a shallowly dipping thrust type mechanism and the focal depth of 22-28 km, representing an underthrust event at the subduction interface. The source time function has an initial stage of 20 s followed by a main pulse of 30 s duration, a shape similar to that of the 1968 Tokachi-oki earthquake. Joint inversion of geodetic and tsunami data shows that the region of the largest slip, 1.7 m, corresponds to a region of relatively small slip for the 1968 Tokachi-oki earthquake. Furthermore, the joint inversion shows that the region of the largest asperity of the 1968 earthquake had essentially zero slip during the 1994 Sanriku-oki earthquake. These results indicate that the dominant asperities ruptured by the 1994 Sanriku and 1968 Tokachi-oki earthquakes are different. The result of the joint inversion also shows that the aseismic zone near the Japan trench was not ruptured by the 1994 earthquake.

Introduction

A large earthquake occurred off the Sanriku, Honshu, coast along the Japan trench on December 28, 1994. The NEIS Preliminary Determination of Epicenters (PDE) provides the source parameters: origin time, 12:19:23.0 GMT; epicenter, 40.525°N, 143.419°E; depth, 27 km; and magnitude, Ms 7.5. This earthquake caused significant damage including three fatalities in the Hachinohe area, Japan. The earthquake generated a tsunami which was recorded at tide gauge stations along the Pacific coast in northern Japan.

Many large earthquakes have occurred due to the subduction of the Pacific plate along the Japan trench. The most recent one in the 1994 epicentral region was the 1968 Tokachi-oki earthquake (Mw 8.2) (Figure 1), which has been extensively studied by using seismic waves [*Kikuchi and Fukao*, 1985; *Mori and Shimazaki*, 1985; *Schwartz and Ruff*, 1985] and tsunami waveforms [*Satake*, 1989]. All these results suggest that little slip occurred in the southernmost part of the aftershock area. The 1994 event occurred in the southern part of the 1968 aftershock area. The epicenters of the two earthquakes are also very close, less than 30 km apart. The seismicity of this region has been also studied by using ocean bottom seismometers (OBS) [*Hirata et*

al., 1985; *Nishizawa et al.*, 1992; *Suyehiro and Nishizawa*, 1994]. The results suggest that a 50-km-wide aseismic zone exists along the Japan trench. *Byrne et al.* [1988] suggest that the primary cause for this type of aseismic zone is the stable slip properties of the unconsolidated or semiconsolidated sediments in that zone.

The purpose of this paper is to answer two key questions: did the 1994 Sanriku-oki event rerupture the largest asperity of the 1968 Tokachi-oki earthquake? Did the 1994 event rupture the aseismic zone near the Japan trench? In order to do so, we determine the source process of the 1994 Sanriku-oki earthquake from seismic, tsunami, and geodetic data.

Seismological Analysis

Data and Method

We performed the Centroid Moment Tensor (CMT) inversion [*Dziewonski et al.*, 1981; *Fukushima et al.*, 1989] using long-period surface waves recorded at 18 IRIS stations (AFI, ANMO,
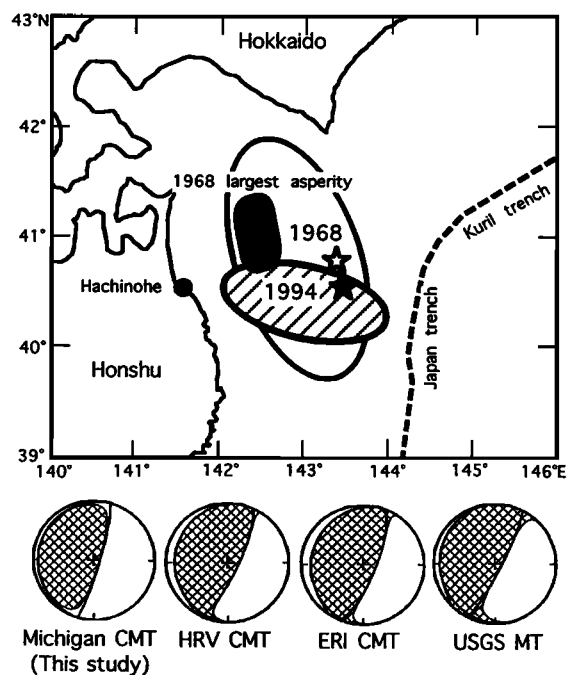

Figure 1. (top) The aftershock area of the 1994 Sanriku-oki earthquake (shaded ellipsoid) and the 1968 Tokachi-oki earthquake (open ellipsoid). Open star and solid star are the epicenters of the 1968 and 1994 earthquakes, respectively. The largest asperity of the 1968 event is schematically shown. (bottom) Four different solutions of the focal mechanism of the 1994 event.

ANTO, BGIO, CMB, COR, ESK, FFC, HRV, KEV, KONO, NWAO, PAB, PAS, PMG, RAR, SNZO, and TATO) to estimate the overall focal mechanism and seismic moment. We also performed the Moment Tensor Rate Function (MTRF) inversion [*Ruff and Miller*, 1994] using 15 P waves (AFI, ANMO, CCM, CMB, COL, COR, CTAO, ESK, FFC, HNR, HRV, KONO, PAS, PMG, and TUC) and 1 SH wave (COL) recorded at IRIS stations. We performed this to estimate the focal mechanism and the best depth of the earthquake. We then reinverted the seismograms at the above best depth and focal mechanism to estimate the source time function. The average P and S wave velocities from the ground surface to the hypocenter are assumed to be crustal values of 6.7 km/s and 3.9 km/s, respectively. The details of the analysis will be discussed below. We compare these estimates with those from Harvard CMT, Earthquake Research Institute (ERI) CMT, U.S. Geological Survey (USGS) moment tensor inversions. Comparison of focal mechanisms determined in the different frequency bands is used to check the complexity of earthquake source process [e.g. *Tanioka et al.*, 1995b].

Focal Mechanism and Depth

The focal mechanism of the 1994 Sanriku-oki event from our CMT inversion has a nodal plane dipping shallowly to the west (strike=180°, dip=9°, rake=75°) as shown in Figure 1. The focal mechanisms from the Harvard, ERI, and USGS moment tensor inversions, also shown in Figure 1, and from our MTRF inversion, shown in Figure 2, indicate basically the same geometry. All of these five different determinations indicate a shallow thrust-type fault motion, representing a plate interface event. The consistency among these five estimates over a wide frequency range suggests that the focal mechanism did not vary during the entire rupture process.

The best depth from the MTRF inversion is 22 km (Figure 2). The USGS depth is 7 km. The centroid depth by Harvard and ERI is 27.7 and 22.2 km, respectively. Except for the USGS estimate, there appears to be a fairly good agreement that the best overall depth lies between 22 and 28 km. *Suyehiro and Nishizawa* [1994] found from the OBS observations that the upper depth of the seismic coupling zone is about 15 km. *Tichelaar and Ruff* [1993] found that the maximum depth of the seismic coupling zone in northern Honshu is 37-43 km. If this entire width of the plate interface ruptures uniformly, the average depth for such an earthquake would be 26-29 km. This is
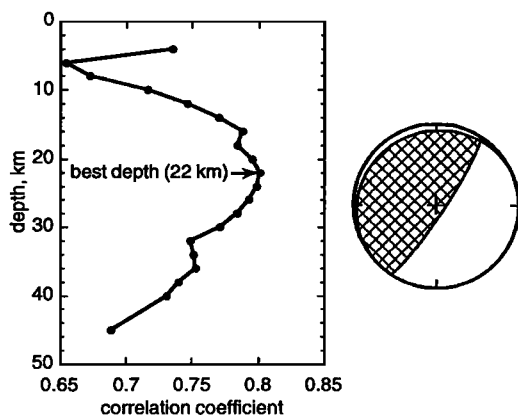
Figure 2. (Left) The correlation coefficient between the observed and synthetic body waves as a function of depth. (Right) The best double couple focal mechanism as a result of the MRTF inversion.
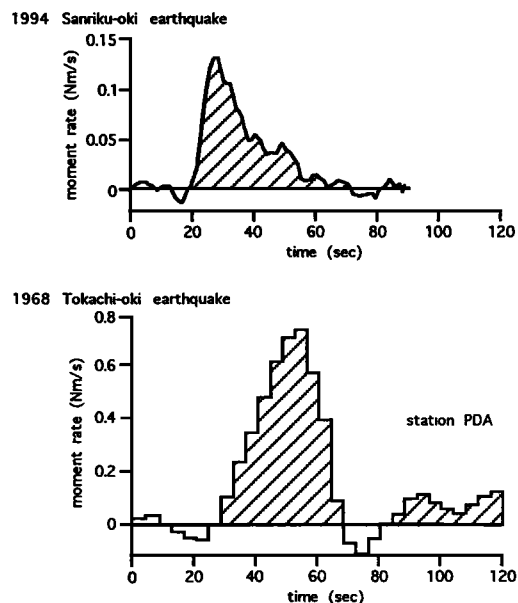
Figure 3. Comparison of the source time functions for the 1994 Sanriku-oki earthquake (from this study) and the 1968 Tokachi-oki earthquake (from *Schwartz and Ruff* [1985])

consistent with the best overall depth estimate of the 1994 Sanriku-oki event.

Source Time Function

The source time function of the 1994 earthquake estimated from body wave inversion is shown in Figure 3. The source time history consists of two stages: the initiation stage (duration 20 s) and the main pulse (duration 36 s and seismic moment of 2.3 x 10^{20} Nm). The long initiation stage is also observed in the source time history of the 1968 Tokachi-oki earthquake with a duration of about 30 s [*Kikuchi and Fukao*, 1985; *Schwartz and Ruff*, 1985] (Figure 3). The general shape of the 1994 source time function is similar to that of the 1968 Tokachi-oki event. However, in detail, the 1994 event took only 9 s from the onset of the main pulse to reach the maximum moment rate. The 1968 event reaches the maximum in about 30 s after the main pulse initiation. This difference should be related to the difference in the slip distribution of the two earthquakes. We then performed the joint inversion of tsunami and geodetic data [*Satake*, 1993] to estimate the slip distribution of the 1994 Sanriku-oki earthquake as shown below.

Tsunami and Geodetic Analysis

Data and Method

For the joint inversion, we used the tsunami waveforms recorded at 8 tide gauge stations, 4 in Hokkaido and 4 in Honshu. The tsunami waveform for each tide gauge station consists of 30-70 min of data with a sampling interval of 1 min. We also used the horizontal coseismic displacements observed at 10 GPS stations (Figure 4) operated by the Geographical Survey Institute of Japan [*Tsuji et al.*, 1995]. The tsunami Green's functions are numerically computed on actual bathymetry. Finite difference computations of the linear long wave equations are carried out with a grid size of 1 minute of the arc [*Satake*, 1995]. The initial condition of tsunami propagation is calculated from the vertical and horizontal displacements of the ocean bottom [*Tanioka and*
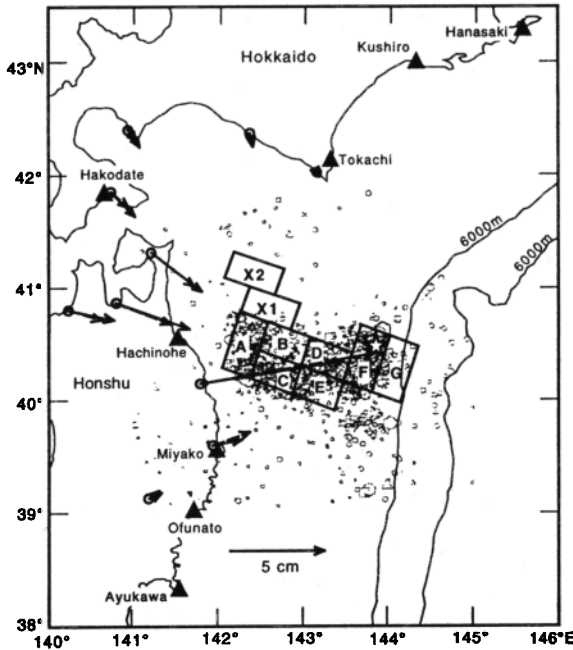
Figure 4. Fault model and fit to geodetic data. Frames show the location of nine subfaults. Results of the joint inversion for slip distribution are in Table 1. Solid and dashed arrows are the observed horizontal displacements [*Tsuji et al.*, 1995] and computed displacements, respectively. A star and gray symbols show the epicenter and aftershocks of the 1994 Sanriku-oki earthquake determined by *Matsuzawa et al.* [1995]. Triangles show the tide gauge stations used in this study.

Table 1 Slip distribution with nine subfaults

subfault	slip, m	subfault	slip,m
A	0.75±0.04	F	0.56±0.06
B	0.65±0.33	G	-0.01±0.12
C	0.93±0.43	X1	-0.04±0.13
D	0.73±0.08	X2	0.03±0.07
E	1.71±0.12		

Note: see Figure 4 for the subfault location.

width of subfaults A, F, and G are 60 km and 30 km, respectively. The length and width of subfaults B, C, D, and E are 30 km and 45 km, respectively. The centroid depth for each subfault is assumed to be 38 km for subfault A, 31 km for subfaults B and C, 23 km for subfaults D and E, 16 km for subfault F, and 10 km for subfault G. Furthermore, we add two more subfaults (X1 and X2) outside the 1994 aftershock area; those two cover the largest asperity of the 1968 Tokachi-oki event [Satake, 1989]. The length and width of the two additional subfaults are 30 km and 60 km, respectively. The result of the joint inversion is shown in Table 1. The observed and computed horizontal displacements (Figure 4) show a good agreement. The computed tsunami waveforms (Figure 5) also agree with the observations.

The largest slip, 1.7 m, found on subfault E, is almost twice as large as the second largest slip, 0.9 m, on subfault C. The best depth determined from the MTRF inversion, 22 km, lies on subfault E. There is essentially no slip on the two subfaults outside the aftershock area, X1 and X2. This indicates that the largest asperity ruptured by the 1968 Tokachi-oki earthquake did not rupture in the 1994 Sanriku earthquake. The slip on the shallowest subfault located near the trench, subfault G, is also practically zero, which indicates that the aseismic zone near the Japan trench was not ruptured by the 1994 Sanriku-oki earthquake.

The total seismic moment from all the subfaults is computed as 3.1×10^{20} Nm (Mw=7.6), assuming that the rigidity is 4×10^{10} N/m^2. This is slightly smaller than our CMT estimate of 4.5×10^{20} Nm (Mw=7.7), the Harvard estimate of 4.9×10^{20} Nm, and the USGS estimate of 4.0×10^{20} Nm. It is somewhat larger than the MTRF estimate of 2.3×10^{20} Nm and the ERI estimate of 2.2×10^{20} Nm. This scatter in the seismic moment estimates is "typical", and possibly due to the different frequency band of data or the different centroid depth.

The average error for the slip estimate is 15 cm. *Satake* [1989] determined the slip distribution of the 1968 Tokachi-oki

Satake, 1996]. The coseismic displacement is computed using *Okada's* [1985] equations. For error analysis, we applied the jackknifing technique [e.g. *Tichelaar and Ruff*, 1989].

Slip Distribution

We assumed a pure thrust-type fault (strike=200°, dip=10°, rake=90°) for the joint inversion of tsunami and geodetic data. We divided the aftershock area [*Matsuzawa et al.*, 1995] into seven (A-G) subfaults as shown in Figure 4. The length and
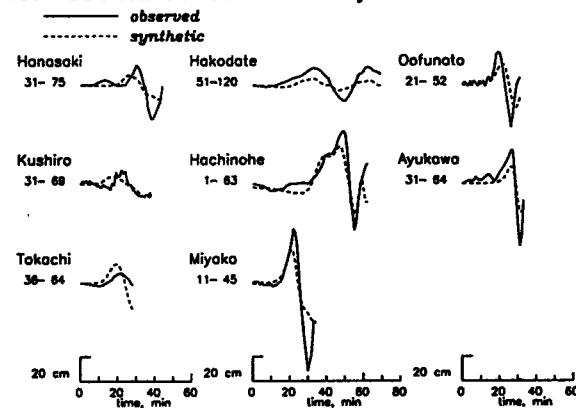
Figure 5. Comparison of the observed (solid) and computed (dashed) tsunami waveforms from the joint inversion for the nine subfaults in Figure 4. The numbers below the station name indicate the time range of the waveforms (in min after the origin time).
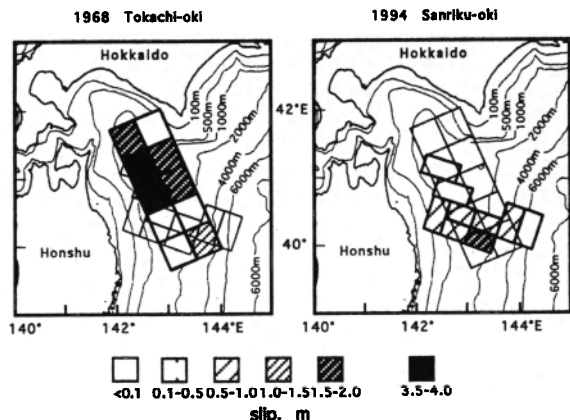
Figure 6. Comparison of the slip distributions for the 1994 Sanriku-oki and 1968 Tokachi-oki earthquakes.

earthquake from the inversion of tsunami waveforms with an average error of 47 cm. The spatial resolution also seems better for the 1994 Sanriku event, because we used the geodetic data as well as tsunami waveforms to estimate the slip distribution. Hence we could estimate the slip distribution for the 1994 Sanriku-oki earthquake using smaller subfaults.

Discussion and Conclusion

Sato et al. [1996] and Hartog and Schwartz [1995] suggest a westward rupture propagation for the 1994 Sanriku earthquake. If it propagated from the epicenter (subfault F) toward the west (subfault A) with a standard rupture velocity of 3 km/s, the source time function determined by the MTRF inversion and the slip distribution determined from the joint inversion are well-correlated. The peak moment release occurred in the region of subfaults D and E.

We compare in Figure 6 the slip distribution of the 1994 Sanriku-oki earthquake with that of the 1968 Tokachi-oki earthquake determined by Satake [1989]. The region of the largest slip for the 1994 Sanriku-oki earthquake corresponds to a region of relatively small slip for the 1968 Tokachi-oki earthquake. The region of the largest slip for the 1968 Tokachi-oki earthquake did not slip in the 1994 Sanriku-oki earthquake. These results indicate that the dominant asperities ruptured by the 1994 Sanriku and 1968 Tokachi-oki earthquakes are different, although the rupture areas overlap.

We found that the 1994 Sanriku-oki earthquake did not rupture the aseismic zone near the Japan trench. However, Tanioka et al., [1995a] suggest that the 1896 Sanriku tsunami earthquake might have ruptured the aseismic zone near the Japan trench. Future studies are necessary to understand the nature of the aseismic zone at the up-dip side of the seismic coupling zone.

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K. Satake, Seismotectonics Section, Geological Survey of Japan, Tsukuba, Ibaraki 305, Japan (e-mail: satake@gsj.go.jp)

L. Ruff, Y. Tanioka, Dept. of Geological Sciences, Univ. of Michigan, Ann Arbor, MI 48109-1063. (e-mail: ruff@umich.edu, tanioka@umich.edu)