ure 4, which shows the result of multiple shock inversion of P-waves recorded by the IRIS network.

Vertical displacements of Okushiri were measured by Shimamoto et al. (Shimamoto et al., personal communication, 1993). According to Shimamoto et al., the earthquake subsided and tilted the island. The amount of subsidence ranges from about 20 cm (±10 cm) at the northern end to about 90 cm (±10 cm) at the southern end of the island. This Okushiri subsidence seems to support the idea that the earthquake's main rupture occurred on the westerly dipping steep fault plane as suggested from the east-west cross-section of the aftershock distribution (Figure 2) and the inversion of the long-period seismic waves (Figure 3b).

No clear precursory events had been reported before the earthquake, except for a temperature increase of hot springs at Kamuiwaki on Okushiri and the occurrence of local earthquakes felt only on the island. The springs' usual temperature is about 60°C, according to the manager, but it increased to approximately 80–90°C about 10 days before the quake and the hot springs stopped flowing afterward.

Continuous measurements of crustal deformation have been made at several land stations on the Japan Sea side of Hokkaido. We made a preliminary analysis of strainmeter and tiltmeter records from the nearest station, KKJ, which is about 50 km from the source area, but no clear precursory event was found.

Figure 5 shows that the source area is now covered by many temporary instruments that have been set up jointly by several universities.—*Ichiro Nakanishi, Shuichi Kodaira, Reiji Kobayashi, Minoru Kasahara, Department of Geophysics, Faculty of Science, Hokkaido University, Japan; and Masayuki Kikuchi, Yokohama City University, Department of Earth Sciences, Japan*

References

Kobayashi, Y., On the initiation of subduction of plates (in Japanese), *Earth Monthly*, *5*, 510, 1983.

Nakamura, K., Possible nascent trench along the eastern Japan Seas the convergent boundary between Eurasian and North American plates (in Japanese with English abstract), *Bull. Earthq. Res. Inst., University of Tokyo*, *58*, 711, 1983.

Nakanishi, I., Y. Hanakago, T. Moriya, and M. Kasahara, Performance test on long-period moment tensor determination for near earthquakes by a sparse local network, *Geophys. Res. Lett.*, *18*, 223, 1991.

Tamaki, K., Geological structure of the Japan Sea and its tectonic implications, *Bull. Geol. Surv. Japan*, *39*, 269, 1988.

Unusual Rupture Process of the Japan Sea Earthquake

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On July 12, 1993, a large earthquake and associated tsunami caused terrible damage to the Japan Sea side of Japan, Korea, and Russia. The southwestern shore of Hokkaido and Okushiri Island were particularly hard hit. All aspects of this earthquake will undoubtedly be studied in great detail. This brief report focuses on the tectonic setting and some puzzles encountered in the preliminary seismological analysis.

At first glance, the July 12 event appears to have occurred on the "wrong side" of Japan (see Figure 1). The Pacific plate subducts to the west beneath northern Honshu and Hokkaido, and a Wadati-Benioff zone extends to 700-km depth beneath the Sea of Japan. Great underthrusting earthquakes are expected to occur on the east coast of Honshu and Hokkaido, such as the 1968 Tokachi-Oki (magnitude 8.2) and 1978 Miyagi-Oki (magnitude 7.6) earthquakes. Thus, the occurrence of large, shallow, underthrusting earthquakes on the west coast of Honshu and Hokkaido is somewhat odd. Nonetheless, there is now almost a continuous linkage of the rupture areas of such earthquakes off the western coasts of Honshu and Hokkaido, and this activity extends north to Sakalin.

The August 2, 1940, earthquake ruptured the northernmost segment along this margin; the June 16, 1964, Niigata earthquake ruptured the southernmost segment; and the May 26, 1983, Japan Sea earthquake then filled in a segment off northern Honshu [see *Fukao and Furumoto*, 1975; *Satake*, 1986]. It now appears that the July 12, 1993, event ruptured the segment between the 1940 and 1983 earthquakes (Figure 1).

The focal mechanisms of the 1940, 1964, and 1983 earthquakes are all consistent with the Sea of Japan thrusting beneath Honshu and Hokkaido. Since there is no deep Wadati-Benioff zone associated with the underthrusting of the Sea of Japan, one simple interpretation of the tectonics is that a new subduction zone is forming off the west coast of Honshu and Hokkaido [see *Nakamura*, 1983; *Seno*, 1985; *Cook et al.*, 1986; *DeMets*, 1992]. Thus, a closer look at this

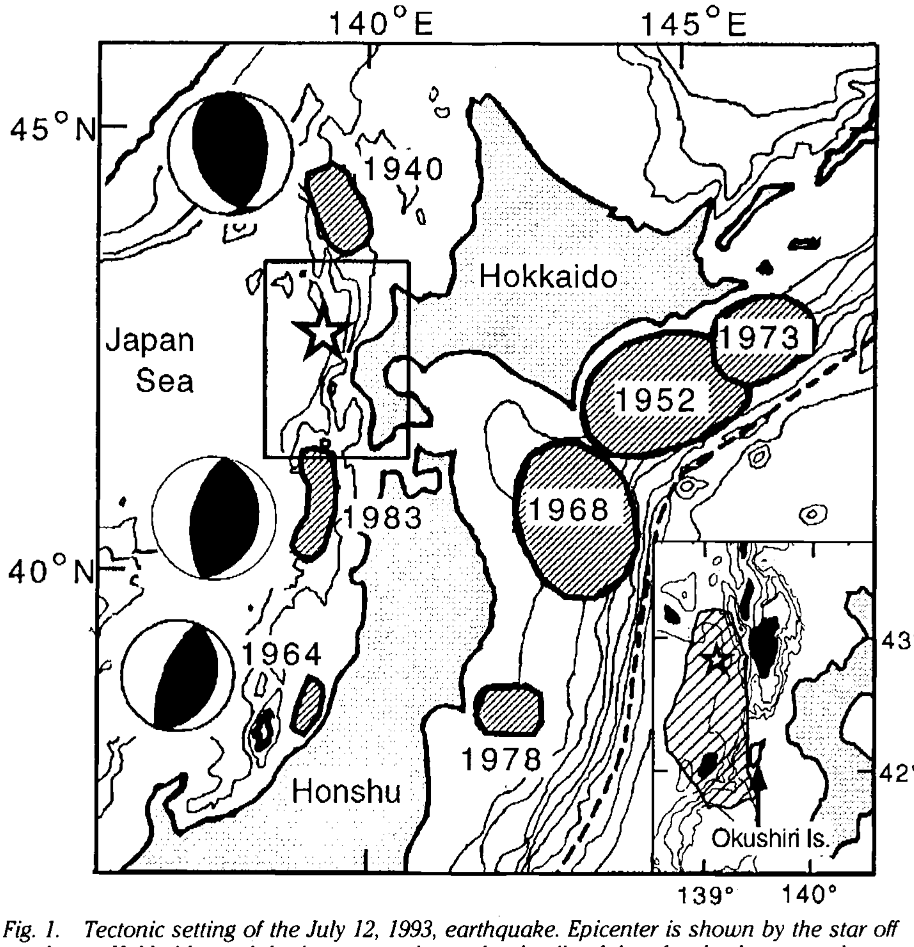

Fig. 1. Tectonic setting of the July 12, 1993, earthquake. Epicenter is shown by the star off southwest Hokkaido, and the inset map shows the details of the aftershock area and bathymetry of the outlined region. Pacific plate subducts along the Japan Trench (dashed) off the eastern coast of Japan. The aftershock areas of several recent large underthrusting earthquakes are shown, with the years of their occurrence. Aftershock areas of the recent large earthquakes on the Japan Sea side of Honshu and Hokkaido are also shown, with their focal mechanisms. The shaded quadrants are compressional, and all earthquakes have one nodal plane with a shallow dip toward the east.

region shows that the July 12, 1993, event is not on the "wrong side" of Japan—instead, Japan is unfairly burdened with active underthrusting on both sides!

The preliminary Harvard CMT focal mechanism for the July 12 earthquake is shown in Figure 2a (see *Dziewonski and Woodhouse* [1983] for details of method). From the viewpoint of subduction initiation, this is exactly what we would expect for the faulting geometry: a fault plane that dips at a shallow angle to the east, with the Sea of Japan thrust beneath Hokkaido. However, the U.S. Geological Survey focal mechanism determined from body wave inversion presents some dissenting information (Figure 2b, see *Sipkin* [1986] for details); it is also an underthrusting mechanism, but the nodal plane with the shallow dip (the candidate fault plane) is dipping toward the west rather than the east. To examine this discrepancy, we performed independent analyses of both the long-period CMT and body wave inversion to find the best focal mechanism. Our CMT focal mechanism (Figure 2c) agrees in the essential characteristic that the shallow dipping fault plane is clearly the eastward-dipping one, and the formal errors of the analysis do not allow the dip to be greater than 45°. Next, we employed a body wave inversion method that provides the best depth, moment tensor, and source time history of the earthquake [see *Ruff and Tichelaar*, 1990]. Using a total of fourteen P-waves with good azimuthal coverage of the focal sphere, we find that the best point source depth for the earthquake is between 10 and 15 km; the best focal mechanism has the shallow-dip nodal plane dipping to the west (in basic agreement with the USGS focal mechanism); and the source time history consists of an initial sharp pulse with duration of 10 s and moment release of 2 x 10^{20} Nm, followed by a complex, on-going rupture for at least another 40 s. These preliminary results seem to reinforce the discrepancy between the two methods. How can this paradox be resolved?

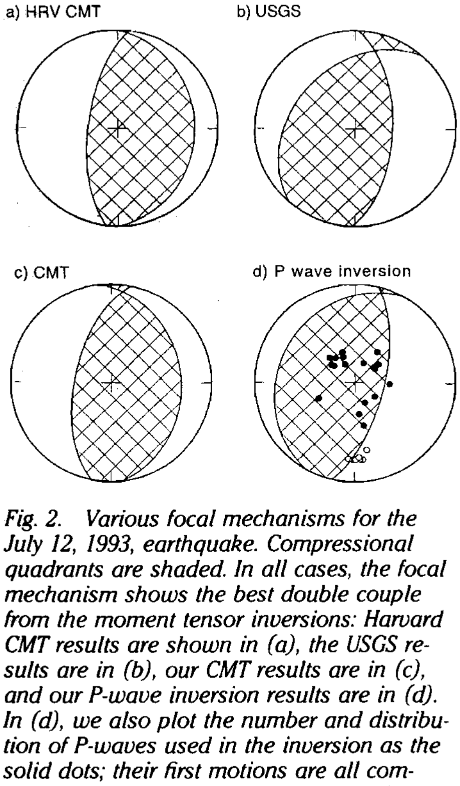

Fig. 2. Various focal mechanisms for the July 12, 1993, earthquake. Compressional quadrants are shaded. In all cases, the focal mechanism shows the best double couple from the moment tensor inversions: Harvard CMT results are shown in (a), the USGS results are in (b), our CMT results are in (c), and our P-wave inversion results are in (d). In (d), we also plot the number and distribution of P-waves used in the inversion as the solid dots; their first motions are all compressional. Additional first motion readings from the Japan stations are plotted as the open dots to the south; these first motions are all dilatational. They fall close to a nodal plane in (d), but these readings would be in the middle of the compressional quadrant of the CMT focal mechanisms.

The CMT method gives an integrated view of the overall faulting geometry. The body wave inversion uses higher frequency information and is potentially sensitive to changes in the fault geometry during the earthquake. For the July 12, 1993, earthquake, the initial sharp pulse is probably the dominant influence on the P-wave inversion results. The lower amplitude waves that follow may be generated by a different fault geometry; we can not say for sure one way or another with our preliminary analysis. Thus, our initial explanation of the discrepancy is that the focal mechanism with a shallow dip to the west is the correct geometry for the initial rupture of this earthquake, but most of the moment release occurred after the initial pulse with a different focal mechanism. The integral constraint is that the addition of these two focal geometries produces the CMT focal mechanism. This preliminary interpretation is certainly not unique, and it may eventually have to be discarded as more information becomes available. We have performed one test of this idea by acquiring some additional seismograms via the "gopher" system installed at the pre-POSEIDON data center in Japan. The P-wave first motions at these digital Japanese stations are all "down," and they are plotted on the focal mechanism in Figure 2d. These data are explained by the focal mechanism from the body wave inversion, but they are clearly inconsistent with the CMT focal mechanism. Thus, this first test appears to corroborate the notion that the rupture process of this earthquake started with one fault geometry and then switched to a different fault plane.

Even at this speculative stage, it is interesting to contemplate the tectonic significance of the seismological results. Figure 1 (inset) shows that the epicenter is at the northern end of the aftershock zone. Thus, perhaps convergence is accommodated by a westward-dipping fault in the northern part of the rupture area, and by a larger eastward-dipping fault along most of the aftershock zone to the south. Close scrutiny of the bathymetric charts seems to allow this possibility; there is a trough immediately to the east of a narrow ridge in the northern part of the source region (see filled region east of epicenter in Figure 1 inset). If we speculate that the fault plane dips to the west in this region, then the "polarity" must switch to an east-dipping fault in the vicinity of Okushiri Island. The Macquarie Ridge, south of New Zealand, offers another example of a newly forming subduction zone where the "polarity" of underthrusting switches back and forth [see *Ruff et al.*, 1989]. Perhaps new subduction zones undergo a "confused" stage in their growth before establishing a consistent polarity of subduction.—*Yuichiro Tanioka, Larry Ruff, and Kenji Satake, Department of Geological Sciences, University of Michigan, Ann Arbor*

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References

Cook, D. B., K. Fujita, and C. A. McMullen, Present-day interactions in northeast Asia: North America, Eurasian, and Okhotsk plates, *J. Geodynam.*, *6*, 33, 1986.

DeMets, C., A test of present-day plate geometries for northeast Asia and Japan, *J. Geophys. Res*, *97*, 17,627, 1992.

Dziewonski, A. M., and J. H. Woodhouse, An experiment in systematic study of global seismicity: Centroid moment tensor solutions for 201 moderate and large earthquakes of 1981, *J. Geophys. Res.*, *88*, 3247, 1983.

Fukao, Y., and M. Furumoto, Mechanism of large earthquakes along the eastern margin of the Japan Sea, *Tectonophysics*, *25*, 247, 1975.

Nakamura, K., Possible nascent trench along the eastern Japan Sea as the convergent boundary between Eurasian and North America plates, *Bull. Earthquake Res. Inst. Univ. Tokyo*, *58*, 711, 1983.

Ruff, L., and B. Tichelaar, Moment tensor rate functions for the 1989 Loma Prieta earthquake, *Geophys. Res. Lett.*, *17*, 1187, 1990.

Ruff, L., J. Given, C. Sanders, and C. Sperber, Large earthquakes in the Macquarie Ridge: Transitional tectonics and subduction initiation, *PAGEOPH*, *129*, 71, 1989.

Satake, K., Re-examination of the 1940 Shakotan-Oki earthquake and the fault parameters of the earthquakes along the eastern margin of the Japan Sea, *Phys. Earth Planet. Inter.*, *43*, 137, 1986.

Seno, T., Is northern Honshu a microplate?, *Tectonophysics*, *115*, 177, 1985.

Sipkin, S., Estimation of earthquake source parameters by the inversion of waveform data: Global seismicity 1981–1983, *Bull. Seismol. Soc. Am.*, *76*, 1515, 1986.