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# A Tale of Two Earthquakes

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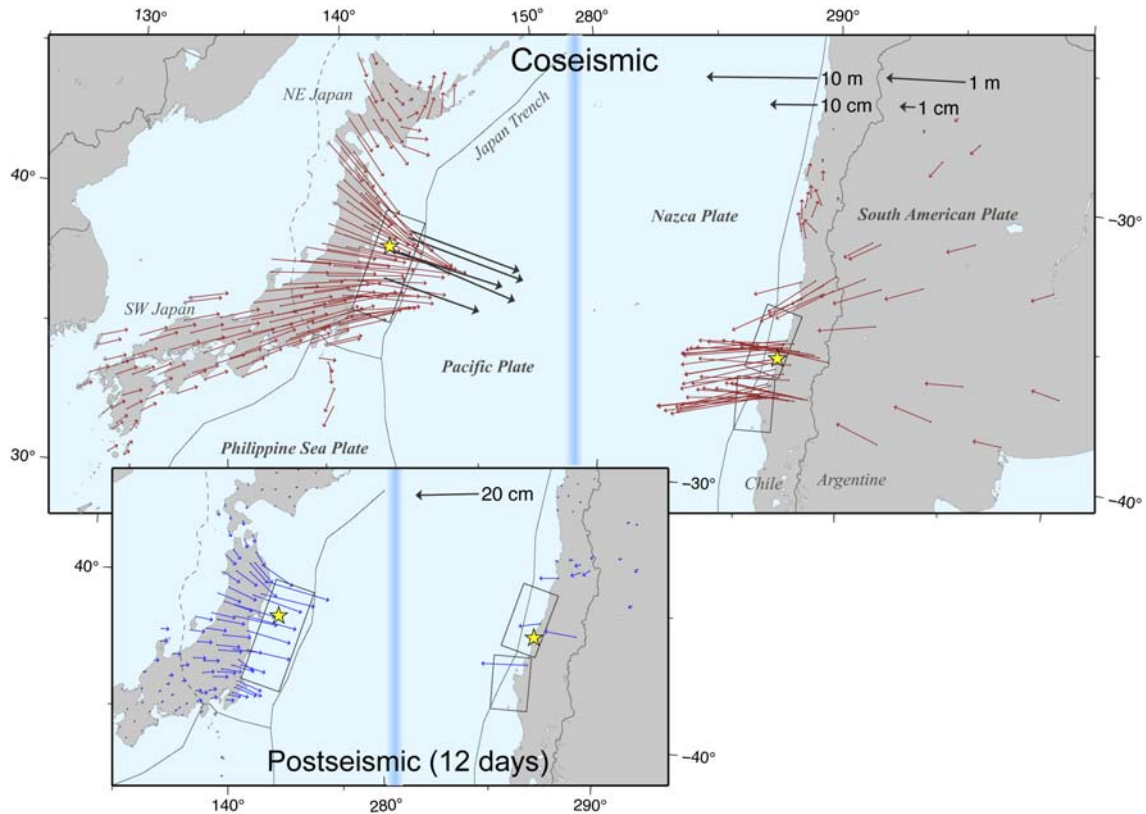
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Tsunami of the Tohoku (NE Japan) District Taiheiyo-Oki earthquake (or simply the Tohoku earthquake here) attacked the Pacific coast of NE Japan in the afternoon, March 11, 2011. The tsunami killed thousands of local people, but several times as many people survived by spontaneous evacuation following the immediate announcement of “Large Tsunami Warning”, the most serious kind of the three grades of official tsunami warnings by the Japan Meteorological Agency (JMA). The Pacific Tsunami Warning Center in Hawaii alerted Middle and South American countries to possible tsunami arrivals, and small tsunami did reach the Easter Island, Chile. JMA issued the same warning about a year earlier, in the morning, 2010 Feb. 28, to call attention to the tsunami traveling all the way from Chile, after the earthquake on the previous day, the Feb. 27 Central Chile (Maule) earthquake (~2 meter tsunami actually arrived at NE Japan). It seems as if the two subduction zones on the opposite corners of the Pacific Ocean were communicating with each other through tsunami. Tsunamis are caused by coseismic vertical movements of sea floor. Vigny et al. (1) report how the Earth’s surface deformed in and after the Maule earthquake using Global Positioning System (GPS).

Four magnitude nine (M9) class earthquakes hit Kamchatka, Aleutian, Chile and Alaska in a relatively short period 1952-1964. After silence over forty years, M9 class earthquakes resumed to hit the Earth, i.e. 2004 Sumatra-Andaman ( $M_w$  9.2) (2), 2010 Maule ( $M_w$  8.8), and 2011 Tohoku ( $M_w$  9.0) earthquakes. The last two are the first M9 class events whose behaviors were studied by dense networks of continuous GPS observing stations. This segment of the Chilean subduction zone was known as the Concepción-Constitución seismic gap (3), a segment in subduction zone where the recurrence history of past earthquakes suggests imminent rupture. Thus multiple international teams deployed GPS stations, resulting in a fairly dense network.

Coseismic crustal movements in the 2010 Maule earthquake observed at ~90 GPS stations (they observe continuously at ~60 sites) (1) are shown in Fig.1. The earthquake released east-west compressional strain accumulated in South America by the eastward subducting Nazca Plate. Meters of westward displacements occurred in the Chilean coast with smaller displacement extending across the continent to the Atlantic coast. They are compared with the 2011 Tohoku earthquake, where significant eastward displacements reached even Kyushu, SW Japan. In Chile, because the boundary between coseismic uplift and subsidence roughly coincides with the coastline, coastal towns experienced relatively small vertical movements. However, the NE Japan shoreline was farther away from the trench, and coastal lowlands now suffer from inundation at high tide caused by coseismic

subsidence down to a meter. Unfortunately, we cannot expect interseismic crustal movement to recover such coseismic subsidence there (4).



**Fig. 1.** Coseismic horizontal movements of GPS stations of the two M9 class earthquakes, i.e. the 2011 Tohoku earthquake (left) (coordinate difference between Mar.10 and 12, data by Geospatial Information Authority of Japan available at [terras.gsi.go.jp](http://terras.gsi.go.jp), only ~10 percent of the whole network is shown for visual clarity) and the 2010 Maule earthquake (right) (1) in the same scale. In addition to terrestrial GPS stations (red arrows), coseismic displacements of the five submarine geodetic benchmarks (black arrows) were added (5). To reduce contrast of coseismic displacement vector lengths, their lengths were set proportional to the logarithm (see legend). The bottom panel compares the 12 days postseismic movements (blue arrows) in the two earthquakes. In Japan, the fixed reference is 0747, in southern Ryukyu (outside of the map).

The largest displacement of a GPS station on land is ~5 m in both earthquakes (southwest of Concepción in Chile, and in the Oshika Peninsula in NE Japan). In Japan, sea floor positioning performed by Japan Coast Guard revealed the eastward coseismic movement of 24 m near the epicenter, ~100 km off the coast (5). This, together with the 31 m displacement toward ESE (April 18 release by Jiji-Tsushin, not included in Fig.1), measured by the Tohoku University group at a submarine benchmark ~175 km offshore, would be the world record of the coseismic displacement ever measured.

Large interplate earthquakes are often followed by silent fault slip (afterslip), and this causes postseismic crustal movement in the same direction as coseismic jumps (6). Postseismic movement

of ~15 cm was recorded in Concepción in the first 12 days after the earthquake (1). In Japan, postseismic movement in the same period reached 20 cm at Yamada, Iwate. Clear difference in displacement azimuths between co- and postseismic movements suggests that coseismic slips concentrate on discrete asperities while afterslip is distributed more uniformly within the ruptured plane. In Chile, such difference is seen in the station to the north of the fault that moved southwestward in the earthquake but westward after the earthquake.

Normally, GPS receivers record phases of microwave from satellites every 30 seconds. Receivers are capable of higher sampling rates, but this is more than enough for estimating daily site coordinates to draw Fig.1. In Chile they performed high-rate (reading phase every second) sampling at eight stations, to track station movements by the second. This makes a GPS receiver a seismometer to directly record displacement, which has been obtained by integrating acceleration or velocity records of conventional seismometers. High-rate GPS showed the complex history of the movement of the San Javier station, east of Constitución, during the ~2 minute period of the earthquake. The station first moved southwestward, then turned right moving northward, and suddenly turned left ~1 minute after the rupture start, ending up with cumulative movement of ~3 meters toward WNW. Such near-field displacement seismograms are useful to infer rupture propagation speed and rupture sequence of multiple asperities. The Japanese GPS network also does 1 Hz sampling routinely at most of the stations. This technique will become a popular tool to study earthquake source mechanics.

A difference between the two earthquakes is that seismic gap hypothesis was not valid in the Japanese case (i.e. seismologists anticipated recurrence of the 1978 M7.4 Miyagi-Oki event instead of a M9 event) (7) but did work in Chile (2). We should not have complete confidence in seismic gaps, but it would be fair to say that its basic concept is not wrong.

Crustal deformation causes several spin-off geophysical phenomena. Vertical deformation of layer boundaries with density contrasts (e.g. sea floor and Moho) and changes in rock density around the fault makes subtle changes in gravity. The 2004 Sumatra-Andaman earthquake was the first earthquake whose gravity change was detected by satellite gravimetry (8). The Maule earthquake was the second (9), and the Tohoku earthquake will become the third. These two earthquakes are expected to move the Earth's spin axis toward similar directions (after R. Gross, Jet Propulsion Lab.). Their sum would become 10-20 cm, and might be detected by space geodesy after careful analyses of polar motion.

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