ers. Complex templates would be needed to direct self-assembly from solution. Such complexity does exist, for example, in DNA origami structures (*7*), but these molecules have not been harnessed as templates.

Optical techniques to study the plasmon resonances of individual objects also need further development if 3D plasmon rulers are to be fully exploited. Fluorescence microscopy has long been used because the excitation light does not interfere with the signal (it is at shorter wavelengths and is readily filtered out), but its use is limited to investigation of fluorescent molecules. More complicated methods will be needed to generate the contrast necessary to detect individual nanoscale plasmonic objects (that show no fluorescence) and to monitor their spectral response over a relatively large range. The efforts of Zsigmondy and Siedentopf in the early 20th century to study individual gold colloids have been reinvigorated with the advent of modern spectrometers capable of quantitative analysis (*8*), although more advanced optical techniques continue to be developed (*9–11*).

Plasmon rulers excel at the dynamic monitoring of molecular distance changes on a single-molecule level. Just as with FRET distance rulers, absolute distances are not as easily obtained with plasmon rulers, because the calibration of an individual ruler is a challenging task on the single-molecule level; however, absolute distances are routinely deduced (on static objects) by imaging techniques, mainly electron microscopy. Monitoring the structural dynamics of single molecules is central to the understanding of biological function and, more fundamentally, to the general understanding of nonequilibrium processes on a molecular level (*12*, *13*). The 3D ruler concept of Liu *et al*. provides a novel twist by introducing multiple coupled plasmon modes that interact in a way that provides rich structure in spectra that are otherwise often featureless. It should be feasible to extend this idea toward even more complicated plasmon structures that may respond to local changes in a very complex way.

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GEOPHYSICS

A Tale of Two Earthquakes

Networks of GPS detectors can provide a detailed picture of the dynamics of earthquakes before, during, and after the event.

Kosuke Heki

Thousands of lives were saved by the "Large Tsunami Warning" announcements of the Japan Meteorological Agency that followed the Tohoku-Oki earthquake of 11 March 2011. A similar alert followed the Central Chile (Maule) earthquake on 27 February 2010. Understanding better how such earthquakes develop might provide even more effective early-warning systems to help mitigate their devastating power. Four papers in this issue—by Sato *et al*. on page 1395 (*1*), Simons *et al*. on page 1421 (*2*), Ide *et al*. on page 1426 (*3*), and Vigny *et al*. on page 1417 (*4*)—report on both of these magnitude 9 (*M*9) earthquakes, illustrating the use of networks of Global Positioning System (GPS) detectors to reveal how the Earth's surface deformed during and after the events.

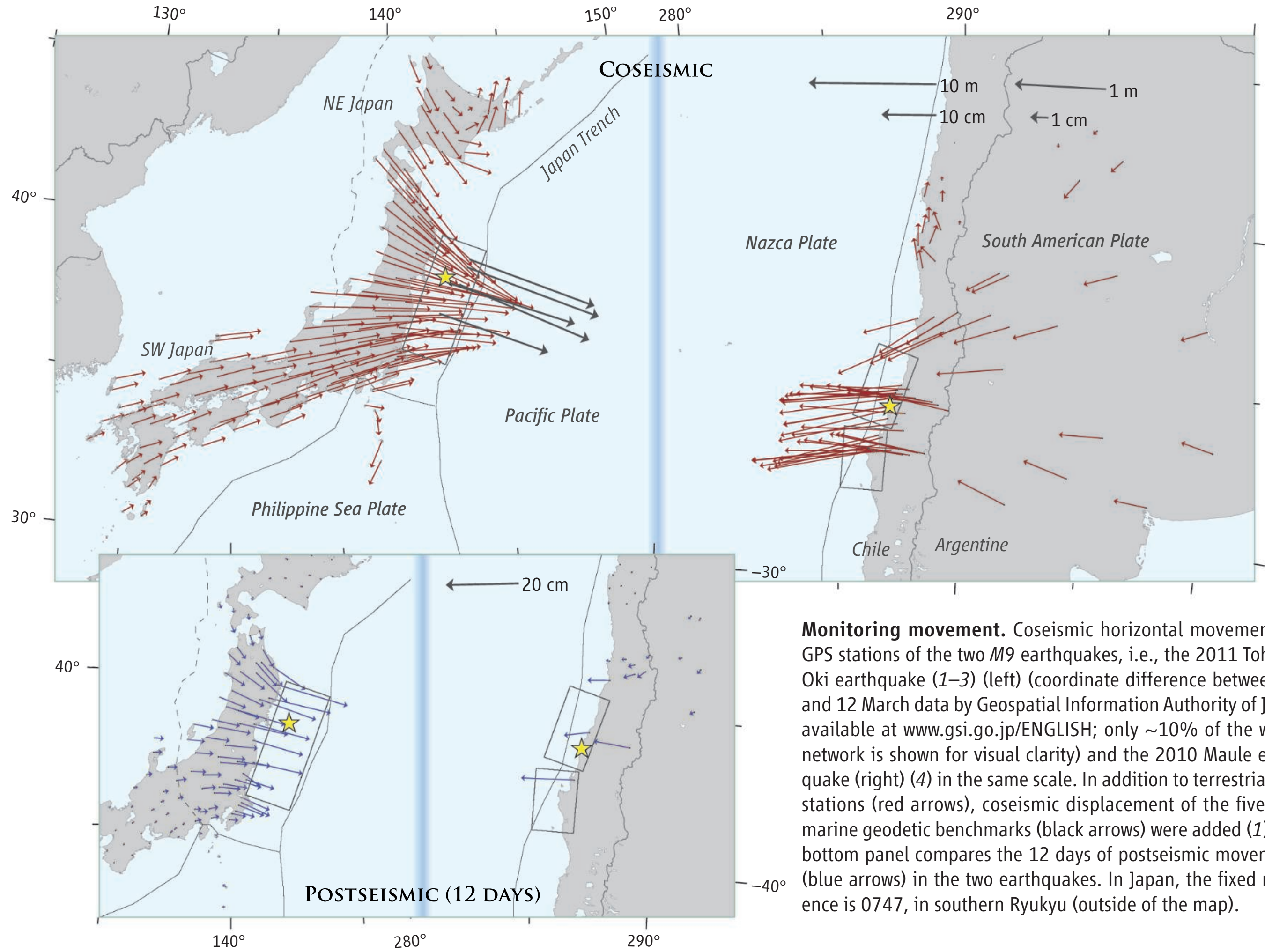
Four *M*9 earthquakes hit Kamchatka, Aleutian Islands, Chile, and Alaska in a relatively short period between 1952 and 1964. After remaining silent for more than 40 years, *M*9 earthquakes have resumed: the 2004 Sumatra-Andaman (*M*9.2) (*5*), 2010 Maule (*M*8.8), and 2011 Tohoku-Oki (*M*9.0) earthquakes. The last two are the first *M*9 events to be studied by dense networks of continuous GPS observing stations. The region of the Chilean subduction zone reported on by Vigny *et al*. is known as the Concepción-Constitución seismic gap (*6*), because it fits the "seismic gap" hypothesis—that the recurrence history of past earthquakes suggests imminent rupture. Thus, multiple international teams deployed GPS stations in the area, resulting in a dense network of seismic detectors.

Tsunamis are caused by coseismic vertical movements of the sea floor. Coseismic crustal movements in the 2010 Maule earthquake were observed at ~90 GPS stations and observed continuously at ~60 sites (*4*) (see the figure). The earthquake released east-west compressional strain accumulated in South America by the eastward subducting Nazca Plate. Meters of westward displacements occurred along the Chilean coast with smaller displacements extending across the continent to the Atlantic coast. In the 2011 Tohoku-Oki earthquake, eastward displacements extended as far as Kyushu in southwest 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 northeastern Japan shoreline was farther away from the trench, and coastal lowlands already suffer from inundation at high tide caused by the coseismic subsidence of this earthquake. This subsidence will not be compensated by future interseismic uplift (*7*).

The largest displacement of a GPS station on land was about 5 m in both earthquakes (southwest of Concepción in Chile, and in the Oshika Peninsula in northeast Japan). In Japan, measurements of sea-floor positioning revealed eastward coseismic movement of 24 m near the epicenter, ~100 km off the coast (*1*). This, together with the 31-m displacement east-southeast (not included in the figure), measured by the Tohoku University group at a submarine benchmark ~175 km offshore, would be the world record for measured coseismic displacement .

Large interplate earthquakes are often followed by silent fault slip (afterslip), and this causes postseismic crustal movement in the same direction as that of coseismic jumps (*8*). Postseismic movement of ~15 cm was recorded in Concepción in the first 12 days after the Maule earthquake (*4*). In

Department of Natural History Sciences, Hokkaido University, Sapporo 060-0810, Japan. E-mail: heki@mail.sci.hokudai.ac.jp



Monitoring movement. Coseismic horizontal movements of GPS stations of the two *M*9 earthquakes, i.e., the 2011 Tohoku-Oki earthquake (*1*–*3*) (left) (coordinate difference between 10 and 12 March data by Geospatial Information Authority of Japan available at www.gsi.go.jp/ENGLISH; only ~10% of the whole network is shown for visual clarity) and the 2010 Maule earthquake (right) (*4*) in the same scale. In addition to terrestrial GPS stations (red arrows), coseismic displacement of the five submarine geodetic benchmarks (black arrows) were added (*1*). The bottom panel compares the 12 days of postseismic movements (blue arrows) in the two earthquakes. In Japan, the fixed reference is 0747, in southern Ryukyu (outside of the map).

Japan, postseismic movement in the same period reached 20 cm at Yamada, Iwate. The difference in displacement between co- and postseismic movements suggests that coseismic slips concentrate on discrete asperities (the area where most seismic energy is radiated), whereas afterslip is distributed more uniformly within the ruptured plane. In Chile, such a difference is seen in the station to the north of the fault that moved southwestward during the earthquake but westward after the earthquake.

GPS receivers usually record phases of microwave signals from satellites every 30 s. In Chile, high-rate (reading the phase every second) sampling was taken at eight stations. This makes a GPS receiver a seismometer to directly record displacement, which has so far been obtained by integrating acceleration or velocity records of conventional seismometers. High-rate GPS receivers showed the complex history of the movement of the San Javier station, east of Constitución, during the ~2-min period of the earthquake. The station first moved southwestward, then turned right moving northward, and suddenly turned left ~1 min after the rupture start, ending up with cumulative movement of ~3 m toward west-northwest. Such displacement seismograms are useful to infer rupture propagation speed and rupture sequence of multiple asperities. The Japanese GPS network also records 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 the seismic gap hypothesis was not valid in the Japanese case. Seismologists had anticipated recurrence of the 1978 *M*7.4 Miyagi-Oki event instead of a *M*9 event (*9*). 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 geophysical phenomena. Vertical deformation of layer boundaries with density contrasts [e.g., sea floor and Moho (base of the Earth's crust)] and changes in rock density around the fault produce subtle changes in gravity. The 2004 Sumatra-Andaman earthquake was the first earthquake whose gravity change was detected by satellite gravimetry (*10*). The Maule earthquake was the second (*11*), and the Tohoku-Oki earthquake will be the third. The combination of dense detector networks and the suite of new techniques will provide a picture of earthquakes and their dynamics never before available.

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