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Advancing Subduction Zone Science After a Big Quake

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After a long quiet period for earthquake activity with magnitude greater than 8.5, several great subduction megathrust earthquakes occurred during the past decade: Sumatra in 2004 and 2005, Chile in 2010, and Japan in 2011. Each of these events caused loss of life and damage to critical infrastructure on an enormous scale. And, in April, a M_w 8.2 earthquake occurred off the Chilean coast.

International collaboration and immediate release of seismic data following a great subduction zone earthquake have served the seismological community well. For example, after the 2010 $M_w = 8.8$ earthquake in Maule, Chile, the Centro Sismologico Nacional (CSN) of the Universidad de Chile in Santiago led an international campaign to study and characterize the event; data collected from these efforts are freely available. The campaign not only aims to ensure that any who want to study the event can do so but also highlights the need for more international collaboration and planning for advancing subduction zone science.

Quickly Collecting Needed Data

At subduction zones, geophysical observatories with a range of instrumentation onshore and offshore—including broadband and strong ground motion seismometers, geodetic instruments, and magnetotellurics—allow researchers to study the spectrum of deformation from fractions of a second to decades. High-resolution imaging capabilities provide critical information about fault geometry and the region's physical properties.

The 2011 Tohoku-Oki earthquake, for instance, occurred in the most densely instrumented country in the world; the scientific payoff of this instrumentation was clear [*Tajima et al.*, 2013]. Data collected during and after the earthquake allowed scientists to learn more about how the earthquake ruptured and why the tsunami was so large.

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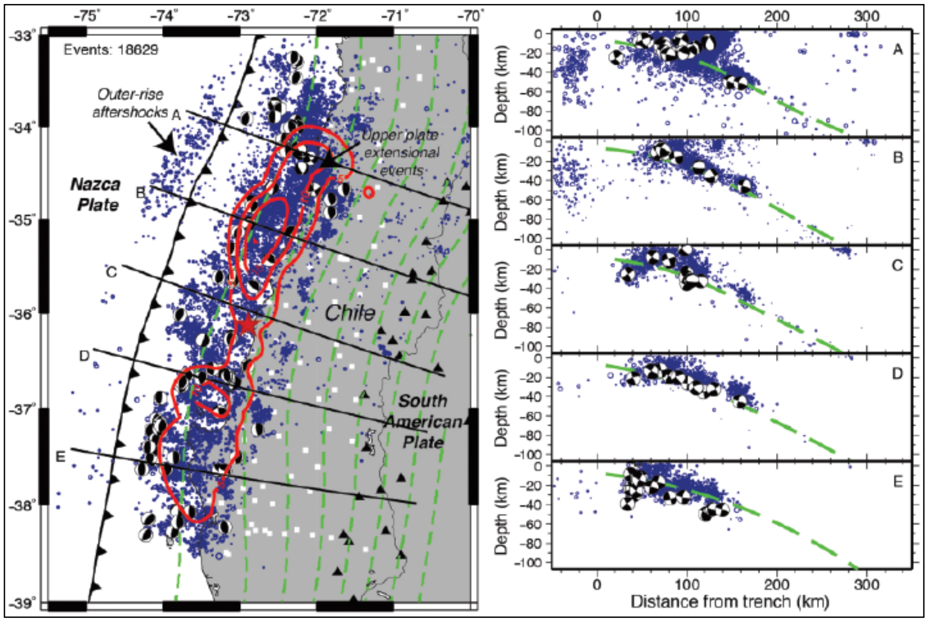

Fig. 1. *Aftershock locations (blue dots) in (left) map view and (right) cross sections A–E based on automatic processing of the International Maule Aftershock Deployment (IMAD) data set between 15 March and 24 May 2010. Regional moment tensor inversion results (beachballs) from* Rietbrock et al. *[2012] show the type of faulting. The tiny white squares are the IMAD seismic stations deployed after the mainshock. Red contours show the amount of slip (with a 5-meter contour interval) during the mainshock rupture from* Lorito et al. *[2011]. The slab contours starting at 40 kilometers depth (green dashed lines spaced every 20 kilometers) are from* Hayes et al. *[2012], and the red star is the mainshock epicenter from the National Earthquake Information Center. The black triangles are active volcanoes.*

With few exceptions, however, most of the roughly 55,000 kilometers of subduction margins on Earth are only sparsely instrumented. Many countries that have a subduction zone margin do not yet possess the infrastructure to support seismic and geodetic monitoring. Given this lack of infrastructure, scientists have started to scrutinize how to quickly mobilize after an earthquake to deploy instruments within close proximity to the earthquake's rupture zone.

International Coordination After the 2010 Maule Earthquake

The 2010 Maule earthquake started in the center and ruptured to the north and south along a 500-kilometer segment of the Nazca–South American plate boundary. Although the Chilean margin had been relatively well studied with temporary experiments prior to the event, only a few permanent seismic stations were operational along the rupture zone at the time of the earthquake.

Seismologists from Chile, France, Germany, the United Kingdom, and the United States immediately realized the importance of drastically increasing the density of seismic stations to observe the aftershock sequence and provide data for detailed structural imaging. After scouring their warehouses for available instrumentation and scrambling for funding, they set about organizing a deployment.

Coordinating an international deployment after a major earthquake is a challenging endeavor. Because seismic instrumentation is not often sitting on the shelf, time is critical, and the possibility of damaging infrastructure makes transportation and logistics difficult. Nonetheless, seismologists began carting seismometers, recorders, and solar panels across the planet to Chile within a few days.

CSN played a central role in bringing together the project's participants. Much of the coordination occurred in a makeshift "war room," a meeting room at the Universidad de Chile, in between forays into the field to deploy the first stations.

Despite its ad hoc beginnings, the international alliance deployed and operated more than 140 seismic stations along the length of the aftershock zone on short notice and achieved a balanced spatial distribution.

Chilean seismologists began deploying seismic stations a day after the mainshock, and the international teams started 1 week later. The network was fully deployed after 1 month; it operated at full scale for 6 months and then at progressively reduced scales for the next 6 months. More than 50 people contributed their time and energy to make this deployment, known as the International Maule Aftershock Deployment (IMAD), a success.

IMAD's Data Policy

Early on, a decision had to be made regarding IMAD's data policy.

As a global science, seismology pioneered many areas of international collaboration and open data. For example, the Federation of Digital Seismic Networks has allowed scientists from all over the world to use seismic data. The Incorporated Research Institutions for Seismology (IRIS) Data Management Center (DMC) in the United States and the European Integrated Data Archive (EIDA) have provided data access to seismologists worldwide.

Building on this, IMAD scientists quickly decided that the data would be open to the community without embargo, making IMAD the first internationally coordinated response to a major earthquake with an open data policy from day one. For the U.S.- and French-funded groups, opening up data was required as part of their funding, but for other groups, this was not mandatory.

Anyone can download IMAD's data via the Internet from the day it was archived at a data center. In the 3 years since the earthquake, more than 9 terabytes of data have been downloaded from more than 140 unique IP addresses, representing users in 16 countries.

Initial Results

The science emerging from the IMAD deployment and similar efforts by the geodesy community are illustrated by many published papers. In addition, participants in IMAD and others working on the earthquake held a workshop 4–8 March 2013 in Concepción, Chile (near the 2010 Maule earthquake epicenter), to talk about the new discoveries from this unique data set and lessons learned from studies of the event.

IMAD's efforts have helped locate more than 100,000 aftershocks, construct more than 400 aftershock focal mechanisms (Figure 1), and identify 1550 repeating earthquakes in the aftershock sequence [*Agurto et al.,* 2012; *Hayes et al.,* 2013; *Lange et al.,* 2012; *Rietbrock et al.,* 2012], demonstrating that many aftershocks occur on the deeper portions of the fault zone and between the high-slip patches on the plate interface.

Many other aftershocks occurred as intraplate events in the downgoing and overriding plates [*Ryder et al.,* 2012]. For example, several large-magnitude events ($M_w = 6.8$ and 7.0) near the Chilean coast showed oblique extensional faulting in the upper plate [*Ryder et al.,* 2012]. *Bedford et al.* [2013] used GPS data to quantify the afterslip pattern on the plate interface during the postseismic phase and compared this to the aftershocks to suggest that some aftershocks may be related to crustal fluid (presumably water from the ocean) lubricating faults.

Local traveltime tomography has highlighted a fast *P* velocity anomaly near the hypocenter [*Hicks et al.,* 2012], interpreted to be a subducted seamount, which might have promoted earthquake nucleation but suppressed the development of large coseismic slip in the hypocentral region. Embedding the IMAD data into a larger-scale tomography model has indicated a possible slab tear just south of the Maule rupture zone in the deeper mantle [*Pesicek et al.,* 2012], and changes in the fast direction of seismic velocities measured on the IMAD stations have helped to constrain mantle flow around the slab [*MacDougall et al.,* 2012].

Future Plans for Subduction Zone Science Research in Chile

In Chile, CSN is currently expanding its seismic network. As of January 2014, 40 new stations (including 10 stations jointly deployed by IRIS and CSN) have been deployed with broadband, strong ground motion, and, in some cases, continuous GPS instruments. When completed, the nearly 100-station network will significantly improve the monitoring capabilities of Chile.

Scientists envision an even broader coordination of data collection in Chile. For example, the Integrated Plate Boundary Observatory Chile (IPOC) project in northern Chile is a Chilean-French-German cooperation composed of a distributed network of multidisciplinary instrumentation to study earthquakes and deformation at the northern Chile margin. Other models of plate boundary observatories in Japan, New Zealand, Costa Rica, and Cascadia, along with IPOC, provide important starting points for thinking about future plate boundary observatories.

Lessons Learned

The IMAD experiment has shown that an open data policy, implemented from day one, had no detrimental impact on the research interests of the groups involved, especially for the young researchers. International collaboration fostered a welcoming research environment. Outside groups brought fresh perspectives and exploited the data in ways for which there would have been insufficient manpower otherwise.

IMAD and projects similar to it do not operate in a vacuum, however. Knowing this, the seismic community is working on ways to reward data acquisition activities and open data archiving so that providing fully open data becomes standard. Some data centers (e.g., IRIS DMC and EIDA) will soon issue persistent identifiers (such as digital object identifiers, or DOIs) for data sets, allowing them to be cited like scientific publications. In this way, the impact of data acquisition activity will be recognizable. For this to work, however, reviewers and journal editors would have to make sure that data sets are properly cited in published papers.

Work on IMAD also revealed that the scientific community may find it useful to standardize best practices for responding to a major earthquake, seeking out better mechanisms for funding, and heightening international communication for community-driven responses so that scientists can mobilize after future earthquakes even faster. IMAD also highlighted how more coordination between onshore and offshore seismic and geodetic efforts is important for deriving all the benefits of a rapid response.

Although aftershock deployments are important for understanding the postseismic processes, permanent plate boundary observatories are required to record details of the preseismic and coseismic parts of the earthquake cycle so that earthquake hazards and risk can be best characterized. IMAD showed how planning for future observatories should be integrated with the region's earthquake monitoring needs.

More internationally coordinated aftershock deployments, coupled with an increase in permanent international and multidisciplinary plate boundary observatories, will allow scientists to build on these lessons. Through such coordinated efforts and open data policies, scientists can dramatically advance subduction zone science.

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