Recognizing Foreshocks from the 1 April 2014 Chile Earthquake

Emily E. Brodsky and Thorne Lay

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breaks down rapidly as the pests or pathogens evolve to evade or overcome the resistance gene. Transgenic approaches allow the simultaneous introduction of multiple different resistance genes (stacking) into a single plant variety, which generates more durable resistance in a desired variety. This strategy is analogous to the use of drug combinations (cocktails) when treating diseases like tuberculosis and HIV infection, and has proven effective both in disease treatment and in preventing the emergence of multidrug-resistant bacteria and viruses.

Transgenic modification also permits the alteration of specific biochemical pathways and genetic networks. Examples can be found among efforts to enhance nutrition, including the genetic modification of "golden rice" to increase its beta-carotene content (*11*). The overexpression of a transcription factor from the flowering plant *Arabidopsis thaliana* in soybean dramatically boosts grain yield by extending the length of time of vegetative development. The result is a larger plant capable of supporting greater seed yield (*12*). Improved water-use and nitrogen-use efficiencies are attractive targets to increase yields while reducing unsustainable inputs such as irrigation water and nitrogen fertilizer (*6*). More audacious goals include the transgenic engineering of rice (and other C_3 crops) to introduce C_4 metabolism—a more efficient carbon fixation pathway—and thereby increase photosynthetic capacity (*13*).

Although the "intelligent breeding" approach that is guided by DNA markers has been much less controversial, there remains considerable public opposition to the deployment of genetically modified organisms (GMOs), especially in the food supply. One consequence has been the focus of regulatory agencies on the technology to develop the plant rather than on the properties of the engineered plant itself. This regulatory morass has delayed the availability of golden rice more than a decade at a probable cost of tens of millions of lives (*6*, *14*). Efforts to address concerns about the safety of GMOs have chiefly focused on evidence-based refutation of claims of real and potential adverse outcomes (*6*), but have not alleviated concerns. The scientific community is understandably reluctant to move beyond evidence-based logic, but must explore new approaches to advocate GMOs.

In seeking new crops to sustainably feed an expanding world population, there is compelling need for a multipronged approach that includes traditional breeding, molecular breeding, and genetic modification. We need to accelerate this new green revolution in the lab, in the field, and through better communication outside the scientific community if we are to address the nearly 3 billion chronically undernourished people worldwide.

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GEOPHYSICS

Recognizing Foreshocks from the 1 April 2014 Chile Earthquake

Seismic activity preceding recent large earthquakes, including the 1 April 2014 earthquake in Chile, hints that some large earthquakes may potentially be predictable.

Emily E. Brodsky and Thorne Lay

Are there measurable, distinctive precursors that can warn us in advance of the planet's largest earthquakes? Foreshocks have long been considered the most promising candidates for predicting earthquakes. At least half of large earthquakes have foreshocks, but these foreshocks are difficult or even impossible to distinguish from non-precursory seismic activity. The foreshocks for the 1 April 2014 Chile event and other recent large earthquakes suggest that observable precursors may exist before large earthquakes.

Statistical models of interacting earthquakes suggest that big earthquakes are most likely to happen when regional earthquake activity is already high (*1*–*4*). However, the same models also indicate that the probability of any given earthquake being a foreshock is low, because small earthquakes are often not followed by large ones.

Data for the 2011 M_w 9.0 Tohoku, Japan, earthquake suggest that detectable precursory processes may occur for some large plate boundary earthquakes. Twenty-three days before the earthquake, a series of smaller earthquakes began, migrating toward the future mainshock hypocentral region at a rate of several kilometers per day; then, 2 days before the mainshock, a M_w 7.3 earthquake struck within 10 km of the mainshock nucleation site (see the figure, panel A). Data from geodetic instruments recovered from the sea floor after the M_w 9.0 earthquake showed that the fault had slipped slowly during the foreshock sequence (*5*, *6*). No additional slow slip was detected on the fault immediately before the mainshock (*7*). Bouchon *et al*. have recently suggested that ~70% of interplate earthquakes are preceded by similar sequences extending to months prior to mainshocks (*8*). It seems that some large earthquakes might be predictable.

This newfound optimism is tempered by two major scientific and practical concerns. First, it remains difficult to distinguish elevated earthquake activity prior to a mainshock from earthquake swarms that do not culminate in a major event (*9*). The foreshocks of Tohoku may have been a random cluster that then triggered the mainshock (*10*). If so, the predictive value of the foreshocks is limited because such random clusters will often not trigger large mainshocks. However, the slow slip inferred from the sea-floor geodetic data is a more widespread, and hence potentially more predictable, precursory process. Unfortunately, the sea-floor data are too sparse to allow a unique interpretation of the apparent slip.

The scarcity of ocean floor measurements highlights the second, practical bar-

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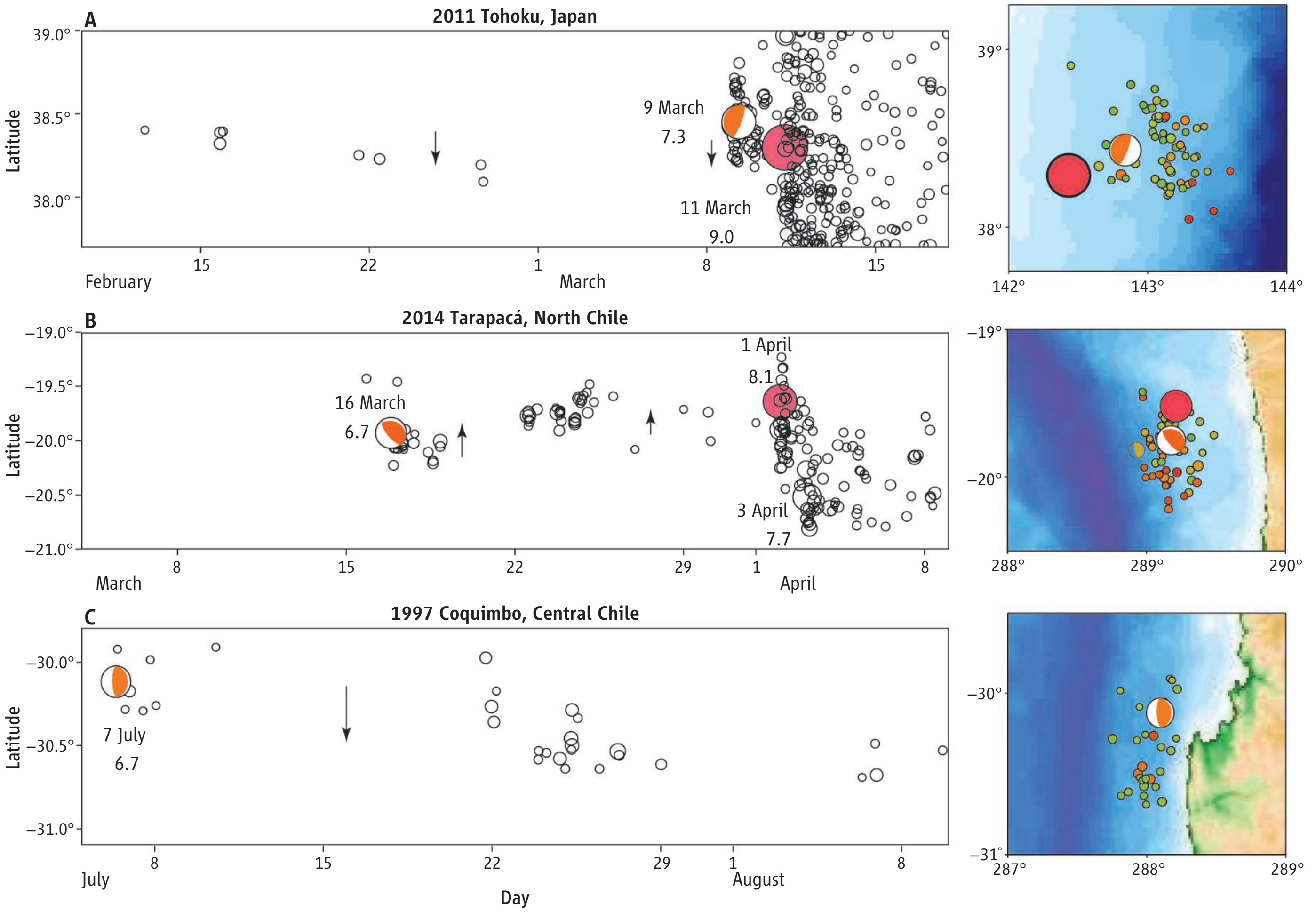

Precursors or not? Plate boundary thrust sequences for the 2011 M_w 9.0 earthquake in Tohoku, Japan (**A**), the 1 April 2014 M_w 8.1 earthquake in north Chile (**B**), and the 1997 central Chile sequence (**C**). Red dots indicate great earthquake epicenters. The fault geometries of large foreshocks are indicated by orange focal mechanisms (the 1997 sequence was not followed by a great event). Arrows indicate migration direction. In the maps on the right of each panel, color denotes depth of foreshocks (red, 5 to 15 km; brown, 15 to 25 km; green, 25 to 35 km).

rier to uncovering possibly subtle signals of precursory subduction zone fault activity. The tantalizing offshore geodetic data for the Tohoku event were not available until ships could retrieve the instrumentation after the earthquake. Real-time telemetry of offshore ocean floor deformation data for subduction zones is critical to any hope of using these signals in prospective forecasting. Building and maintaining such offshore networks is technically possible but would require substantial infrastructure development (*11–13*).

The difficulties in evaluating possible earthquake precursors came to the forefront in the 1 April 2014 M_w 8.1 earthquake in north Chile. The mainshock was preceded by nearly 2 weeks of moderate to large offshore earthquakes on the plate boundary fault (megathrust). Similar to the Tohoku activity, the sequence migrated over about 2 weeks at a rate of several kilometers per day to the location of the 1 April mainshock initiation (see the figure, panel B). The sequence was located in a recognized seismic gap (a region that has not had large earthquakes for a long time, but is known to be capable of them). The last large earthquake rupturing the plate boundary in this region occurred in 1877.

Both the local population and the scientific community reacted to the foreshock sequence with trepidation. Without a firm scientific footing for assessing the migrating sequence, the authorities could only communicate general concern about the unusual seismic activity and remind people that they should always be prepared for a major earthquake in this region (*14*). Relatively few casualties resulted from the earthquake. The potential remains for a much larger event to rupture the remaining ~80% of the seismic gap in this region.

The dilemma confronting the geophysical and local communities is exemplified by comparing the north Chile and Tohoku sequences (see the figure, panels A and B) with the Coquimbo earthquake sequence that struck central Chile in 1997 (panel C). The 1997 earthquakes were similar in size, number, and faulting geometry to those along north Chile in 2014 and occurred in a seismic gap that last ruptured in 1943. However, as yet, no large earthquake has followed.

Combining the seismic signals with the tectonic context may provide a guide as to whether such sequences are foreshocks preceding an imminent mainshock rupture. All three earthquake sequences lasted for a few weeks, migrated along the plate boundary at a rate of a few kilometers per day, had shallow depths of ~20 km on the megathrust with interplate slip, and released a total seismic energy equivalent to M_w 6.8 or larger. However, two features distinguish Tohoku and north Chile from central Chile. Geodetic data indicate that the Tohoku and north Chile sequences were on regions of the plate boundary that were frictionally locked. Both regions had not experienced a large earthquake for over a century, so large strains should have accumulated in these regions. Geodetic measurements near the central Chile sequence indicate that the megathrust is not as strongly locked as in the other regions (*15*). With a relatively short time (54 years) since the last large event, less strain should have built up. It is unclear whether slow slip of the plate boundary occurred for either of the Chile sequences, because no offshore geodetic instrumentation exists for detecting it.

Whether earthquakes are predictable or not is still an open question, but perhaps there is now some cause for optimism. Preparatory processes of slow slip and seismic migration before large plate boundary earthquakes can be monitored with a combination of seismic and geodetic observations, both on-shore and off-shore, if investments are made in instrumentation. More data will be needed to establish whether such observations can lead to confident assessment of imminent earthquake potential.

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APPLIED PHYSICS

Electronic Control of Circularly Polarized Light Emission

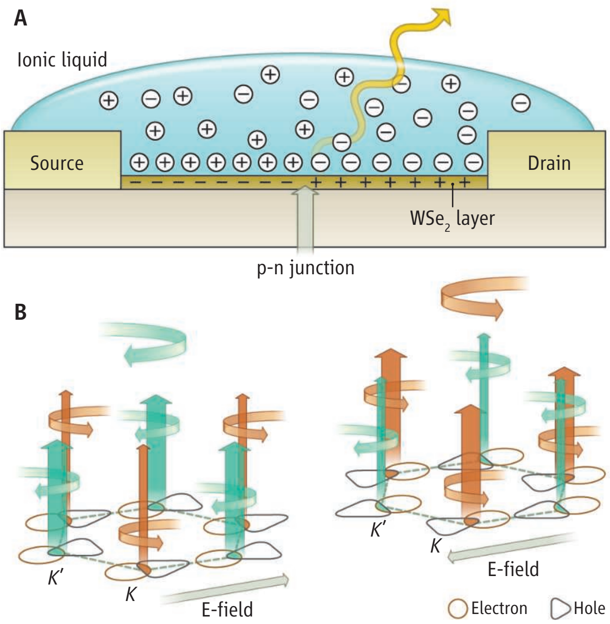
The handedness of circularly polarized light, which is normally controlled by rotating filters, was switched by the electric field direction in a light-emitting device.

Jana Zaumseil

Circularly polarized (CP) light has many applications, including circular dichroism spectroscopy (to determine the secondary structure of proteins), three-dimensional (3D) displays, spintronics, and even quantum computation. However, CP light is usually created with optical filters, and changing the handedness (left or right) of the polarization requires mechanical rotation of the filters. Alternatively, chiral organic light-emitting diodes with a fixed circular polarization or spin light-emitting diodes, which require an external magnetic field, could be used. On page 725 of this issue, Zhang *et al.* (*1*) demonstrate CP electroluminescence from monolayers and multilayers of tungsten diselenide (WSe_2) and other transition metal dichalcogenides (TMDs). The handedness of the CP light is directly controlled by the direction of the in-plane electric field. This effect is not only interesting for applications, but also reveals the "valley" properties of the electronic bands of 2D TMDs.

Unlike bulk TMDs, monolayers of TMDs lack inversion symmetry and exhibit a direct band gap. The electronic structure is usually described by how the energy changes with carrier momentum, and the direct gap occurs at two points with the same energy but different momenta, called *K* and *K*′—the so-called valleys. The lack of inversion symmetry and the strong spin-orbit coupling in monolayer TMDs also leads to distinctive optical selection rules. Specifically, electronic transitions near the *K* and *K*′ points couple only to right- or left-handed CP light, respectively. Single-layer MoS_2 shows CP photoluminescence when excited with CP light (*2*).

Current-driven or electroluminescent CP light emission would be the next step toward a practical device and requires creating a p-n junction where electron-hole recombination occurs. The TMD flakes cannot be easily doped, so the hole- and electron-rich regions must be induced electrostatically. One possibility is a field-effect transistor (FET) structure with two gate electrodes underneath the channel, one to induce holes and the other to induce electrons. The resulting p-n junction is rectifying, and electron-hole recombination and light emission take place, as has been shown for WSe_2 monolayers (*3*–*5*). However, with emission efficiencies of 0.01 to 1%, they are far from being competitive with thin-film organic light-emitting diodes, which regu-



A bias for circularly polarized light. (**A**) Zhang *et al.* created a p-n junction within a thin flake of WSe_2 that generates light through charge recombination. A frozen ionic liquid electrolyte acts as the gate electrode, causing both holes and electrons to accumulate within the transistor channel. (**B**) Because of the large in-plane electric field, the hole and electron distributions (triangular and circular contours) are shifted in opposite directions in momentum space. This shift creates a different electron-hole overlap for the *K* and *K*′ valleys and unequal generation of left- and right-handed circularly polarized light. The net handedness can be changed by reversing the applied bias.

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