Opinion

New Opportunities to Study Earthquake Precursors

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The topic of earthquake prediction has a long history, littered with failed attempts. Part of the challenge is that possible precursory signals are usually reported after the event, and the systematic relationships between potential precursors and main events, should they exist, are unclear. Several recent studies have shown the potential of new approaches to simultaneously detect earthquake foreshocks and slow-slip phenomena through ground deformation, seismic, and gravitational transients—weeks to months before large subduction zone earthquakes. The entire international community of earthquake researchers should be engaged in deploying instrumentation, sharing data in real time, and improving physical models to resolve the extent to which slow-slip events and earthquake swarms enhance the likelihood (or not) for later, larger earthquakes.

Experts discussed these apparent seismic and geodetic earthquake precursors and next steps in how to assess their impact on earthquake hazard assessment at a Committee on Seismology and Geodynamics meeting held in May 2019 in Berkeley, California (National Academies of Science, Engineering, and Medicine [NASEM], 2019). For example, slow slip occurred during a sequence of foreshocks on the Japan Trench megathrust that began 23 days before the 2011 M_w 9 Tohoku-Oki, Japan earthquake, culminating in an M_w 7.3 earthquake two days before the mainshock (Kato *et al.*, 2012; Ito *et al.*, 2013). Similarly, foreshocks and aseismic slip started at least two weeks before the 2014 M_w 8.1 Iquique, Chile, mainshock (Ruiz *et al.*, 2014; Socquet *et al.*, 2017). The foreshocks and motions prior to the Tohuku-Oki earthquake may also have been connected to a change in satellite-measured gravity gradients before the mainshock (Panet *et al.*, 2018), but the significance of these results continues to be debated (Wang and Bürgmann, 2019). Although many clusters of earthquakes and slow-slip events occur without foretelling a large earthquake (some lasting years, e.g., Ohta *et al.*, 2006; Tsang *et al.*, 2015; Uchida *et al.*, 2016; Rousset *et al.*, 2019), what is new in the past decade is that both seismic and geodetic precursors have been jointly observed before two major $M_w > 8$ earthquakes (e.g., Obara and Kato, 2016).

The societal implications of confirmed and repeatable precursory signals would be significant, but questions remain. How frequently do similar precursor candidates occur, and in which plate tectonic settings? How often do they result in larger earthquakes? Are there certain characteristics of the precursor(s) that make them more or less likely to result in a larger earthquake? What instrumentation do we need onshore and offshore, at or below the Earth's surface or in space, to best record precursory events? How do we improve operational earthquake forecasts to include new knowledge of both earthquake statistics from improved seismicity catalogs and geodetic transients? Are there settings in which precursory signals can lead to forecasts on timescales and at probability levels that are useful for saving lives and reducing the economic impact of earthquakes? How do we communicate information about the inferred hazard potential inferred from possible precursors in a clear and timely fashion?

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Cite this article as Pritchard, M. E., R. M. Allen, T. W. Becker, M. D. Behn, E. E. Brodsky, R. Bürgmann, C. Ebinger, J. T. Freymueller, M. Gerstenberger, B. Haines, *et al.* (2020). New Opportunities to Study Earthquake Precursors, *Seismol. Res. Lett.* **91**, 2444–2447, doi: 10.1785/0220200089.

To address these questions, there is an obvious need for more observations. Long-term seismometer and geodetic networks are needed both onshore and offshore at a range of sites, spanning a suite of fault-slip behaviors. For seafloor geodesy above the seismogenic zone of subduction megathrusts, continuous measurements and centimeter-level accuracy or better in the horizontal and vertical directions are needed. An increasing array of techniques are available including Global Positioning System-acoustic methods, seafloor absolute pressure gauges, acoustic ranging, borehole instrumentation (including tiltmeters and pore pressure for volumetric strain), and fiber optic strainmeters (e.g., Bürgmann and Chadwell, 2014 and presentations about seafloor instrumentation are posted from the 2019 Committee on Seismology and Geodynamics meeting; NASEM, 2019). For onshore observations, dense networks of continuously recording instruments are needed in many poorly instrumented subduction zones, and data sharing across political boundaries are essential to enable detection of long wavelength precursory signals (e.g., Bedford *et al.*, 2020). Over the decades, lab experiments have shown precursors (e.g., McLaskey, 2019), but understanding how these scale to natural systems has been a challenge. To bridge the gap between lab and natural earthquakes, field-scale experiments to better understand earthquake initiation, fault rupture, and earthquakes induced by human activities are underway in the Swiss Alps (see Data and Resources) and are proposed in North America (Savage *et al.*, 2017).

Along with new observations, there is a critical need for integrative physical models that can assimilate those observations, ideally for a real-time assessment of seismic hazard. A specific need that cannot currently be met is to rapidly incorporate the newly observed phenomena into physical models that modify previous estimates of earthquake hazard. For example, following the 2016 Kaikōura earthquake in New Zealand, slow slip on the subduction megathrust was observed near a highly stressed portion of the fault near Wellington (Wallace *et al.*, 2018). This led to an urgent request by the New Zealand government to incorporate the triggered aseismic slip episode into a timely and accurate forecast. Several methods were used to determine that the chance of an earthquake of magnitude 7.8 or larger in central New Zealand more than doubled (to about 5%) for a time period of ~12 months following the Kaikōura earthquake (Gerstenberger *et al.*, 2017). To better prepare for future precursor candidates, the scientific community should document "best practices" for dealing with slow-slip events and other possible precursors in earthquake forecasts, and the community should enhance efforts to complement statistical hazard assessments with physical model-based approaches (e.g., Kaneko *et al.*, 2018). To assess uncertainties in the forecasts, a systematic process of quantifying expert judgments about uncertain parameters (called expert elicitation) is an important (but not the only) component of these efforts and also provides a means to integrate and assess the results of a diverse suite of models and forecasts. Helping scientists gain exposure to expert elicitation practices in advance of such events will help streamline forecasting efforts, but when information is needed by civil protection authorities within short-time frames (e.g., 24–48 hr), expert elicitation can be challenging. However, there are rigorous methods that allow for rapid elicitation (e.g., Aspinall, 2010) and that can be implemented quickly if protocols have been established ahead of time.

An active area of research focuses on the question of whether there are certain characteristics of the precursor(s) that make them more or less likely to result in a large earthquake. There was debate at the meeting as to whether the precursors to the 2011 Japan earthquake were unusual enough (in terms of size and spatiotemporal evolution of the foreshocks) to warrant public statements of warning, an issue that garnered earlier prominence in the case of the 2009 L'Aquila, Italy, normal-faulting earthquake (Marzocchi *et al.*, 2014). Revisiting the timeline of events preceding the 2011 earthquake (and other candidate precursors) using current knowledge to evaluate what actions should have been taken by different stakeholders could be useful, perhaps as a tabletop exercise.

Given our growing understanding of earthquake precursors, it is clear that most swarms and/or slow-slip events do not produce large, damaging earthquakes, but some do. (The size threshold for a damaging earthquake depends on the location and vulnerability of the building stock.) Based on recent experiences like the 2016 Bombay Beach earthquake swarm, close to the overdue southernmost section of the San Andreas fault in California (McBride *et al.*, 2019), and the 2016 Kaikōura earthquake and slow-slip episode, it is clear that scientists will continue to be asked by civil protection or governmental authorities to calculate the increased probabilities of earthquakes associated with seismic and geodetic precursors. This is already being done for aftershocks in some places using just seismic data with operational earthquake forecasting (OEF).

Well in advance of any seismic unrest events, public communication about earthquakes requires planning, education, and training by those with governmental responsibility (e.g., Alexander, 2010; Lamontagne *et al.*, 2016; McBride *et al.*, 2019). Any new pre-event hazard alerts—potentially in the days, hours, and minutes prior to an event—should be part of a consistent continuum of information, extending from long-term hazard awareness education, through pre-event alert levels, earthquake early warnings, to guidance for immediate event response, and followed by further education while interest levels are high.

It seems clear that the prospects for short-term earthquake prediction (providing accurate time, location, and magnitude) remain poor. However, new opportunities exist to improve seismic and geodetic observations both onshore and offshore, to take advantage of various space-based observation systems, to improve data analysis with machine learning, and to make real-time updated estimates of earthquake probabilities using advanced physical models based on fault-loading models.

Many of these opportunities are highlighted by the U.S. initiatives to study subduction zones through both space and time (Gomberg *et al.*, 2017 and Subduction Zones in Four Dimensions [SZ4D], see Data and Resources; McGuire *et al.*, 2017). For example, fiber-optic cables for telecommunications offer tantalizing new directions for geophysical observations relevant to both onshore and offshore hazard assessment (e.g., Marra *et al.*, 2018; Lindsey *et al.*, 2019); recent observations of changes in seismicity rates and magnitude–frequency statistics prior to earthquakes provide a potential means to determine the likelihood of a swarm being followed by a larger earthquake (Gulia and Wiemer, 2019). Machine-learning tools have enabled detection of months-long plate boundary zone slip reversals prior to two megathrust events, offering not only a new signal, but also motivation to probe the physics of the long-wavelength changes (Bedford *et al.*, 2020). To some extent, public notice of foreshock precursors is already happening through OEF by some government agencies and through online services (e.g., Marzocchi *et al.*, 2014; Michael *et al.*, 2019; Nandan *et al.*, 2019; U.S. Geological Survey [USGS]; RichterX, see Data and Resources), but there is more work to be done, including rapid reporting and integration of geodetically observed transients.

Synthesizing the seismic and geodetic observations in subduction zones and developing physics-based models to link them into forecasts are international challenges. Instead of waiting centuries for large earthquakes to recur in a given location, we can use a global ergodic approach to understand earthquake precursors, statistically sampling earthquakes around the whole world instead of waiting for a statistically representative sample to accumulate over time in one area. Furthermore, lowering detection thresholds could also be helpful, as there are likely many more smaller events that may have precursors, thereby also potentially increasing the sample size for study—with the caveat that the scaling between small and large earthquakes must be considered. International coordination can alleviate the high cost of observations both on land at the desired density and offshore even at quite low density. In the United States, the SZ4D and USGS initiatives in subduction zones could be important parts of this international effort. Finally, most countries have their own agencies in charge of vetting and undertaking forecasts and deciding how and when changes to earthquake probabilities should be communicated to the public. Again, the international community of researchers should work together to share data in real time and exchange lessons learned toward improving forecasts based on potential precursor phenomena. The goal is to be prepared for the rapid response needed to forecast the outcome of the next coupled seismic swarm and slow-slip events.

Data and Resources

There are no new data or resources to report for this article. Information on field-scale experiments to better understand earthquake initiation, fault rupture, and earthquakes induced by human activities in the Swiss Alps at Bedretto Lab website available at http://www.bedrettolab.ethz.ch/activities/fear/. Data about Subduction Zones in Four Dimensions (SZ4D) are available at https://www.sz4d.org. Information on earthquake forecasting can be found at U.S. Geological Survey website available at https://earthquake.usgs.gov/data/oaf/overview.php. Data about RichterX platform are available at https://www.richterx.com/. All websites were last accessed in June 2020.

Acknowledgments

The authors thank Domenico Giardini, Andrew Michael, and Joan Gomberg for helpful reviews and all of the participants in the May 2019 workshop.

References

Alexander, D. E. (2010). The L'Aquila earthquake of 6 April 2009 and Italian Government policy on disaster response, *J. Nat. Resour. Pol. Res.* **2,** no. 4, 325–342.

Aspinall, W. (2010). A route to more tractable expert advice, *Nature* **463,** no. 7279, 294–295.

Bedford, J. R., M. Moreno, Z. Deng, O. Oncken, B. Schurr, T. John, J. C. Báez, and M. Bevis (2020). Months-long thousand-kilometre-scale wobbling before great subduction earthquakes, *Nature* **580,** no. 7805, 628–635.

Bürgmann, R., and D. Chadwell (2014). Seafloor geodesy, *Annu. Rev. Earth Planet. Sci.* **42,** 509–534.

Gerstenberger, M. C., Y. Kaneko, B. Fry, L. Wallace, D. Rhoades, A. Christophersen, and C. Williams (2017). Probabilities of Earthquakes in Central New Zealand, *GNS Science miscellaneous series*, Vol. 114, GNS Science, Lower Hutt, New Zealand, 23 p, doi: 10.3133/cir1428.

Gomberg, J. S., K. A. Ludwig, B. Bekins, T. M. Brocher, J. C. Brock, D. Brothers, J. D. Chaytor, A. Frankel, E. L. Geist, M. M. Haney, *et al.* (2017). Reducing risk where tectonic plates collide—U.S. Geological Survey subduction zone science plan, *U.S. Geol. Surv. Circular 1428*, 45 pp., doi: 10.3133/cir1428.

Gulia, L., and S. Wiemer (2019). Real-time discrimination of earthquake foreshocks and aftershocks, *Nature* **574,** no. 7777, 193–199.

Ito, Y., R. Hino, M. Kido, H. Fujimoto, Y. Osada, D. Inazu, Y. Ohta, T. Iinuma, M. Ohzono, S. Miura, and M. Mishina (2013). Episodic slow slip events in the Japan subduction zone before the 2011 Tohoku-Oki earthquake, *Tectonophysics* **600,** 14–26.

Kaneko, Y., L. M. Wallace, I. J. Hamling, and M. C. Gerstenberger (2018). Simple physical model for the probability of a subduction-zone earthquake following slow slip events and earthquakes: Application to the Hikurangi megathrust, New Zealand, *Geophys. Res. Lett.* **45,** 3932–3941, doi: 10.1029/2018GL077641.

Kato, A., K. Obara, T. Igarashi, H. Tsuruoka, S. Nakagawa, and N. Hirata. (2012). Propagation of slow slip leading up to the 2011 M_w 9.0 Tohoku-Oki earthquake, *Science* **335,** no. 6069, 705–708.

Lamontagne, M., B. Flynn, and C. Goulet (2016). Facing the communication challenges during an earthquake swarm period, *Seismol. Res. Lett.* **87,** no. 6, 1373–1377.

Lindsey, N. J., T. C. Dawe, and J. B. Ajo-Franklin (2019). Illuminating seafloor faults and ocean dynamics with dark fiber distributed acoustic sensing, *Science* **366,** no. 6469, 1103–1107.

Marra, G., C. Clivati, R. Luckett, A. Tampellini, J. Kronjäger, L. Wright, A. Mura, F. Levi, S. Robinson, A. Xuereb, and B. Baptie (2018). Ultrastable laser interferometry for earthquake detection with terrestrial and submarine cables, *Science* **361,** no. 6401, 486–490.

Marzocchi, W., A. M. Lombardi, and E. Casarotti (2014). The establishment of an operational earthquake forecasting system in Italy, *Seismol. Res. Lett.* **85,** no. 5, 961–969, doi: 10.1785/0220130219.

McBride, S. K., A. L. Llenos, M. T. Page, and N. van der Elst (2019). #EarthquakeAdvisory: Exploring discourse between government officials, news media, and social media during the 2016 Bombay Beach Swarm, *Seismol. Res. Lett.* **91,** 438–451, doi: 10.1785/0220190082.

McGuire, J. J., T. Plank, S. Barrientos, T. Becker, E. Brodsky, and E. Cottrell (2017). The SZ4D initiative: Understanding the processes that underlie subduction zone hazards in 4D, *Vision Document Submitted to the National Science Foundation. The IRIS Consortium*, 29 September–1 October 2016, 63 pp., available at https://www.iris.edu/hq/files/workshops/2016/09/szo_16/sz4d.pdf (last accessed June 2020).

McLaskey, G. C. (2019). Earthquake initiation from laboratory observations and implications for foreshocks, *J. Geophys. Res.* **124**, 12882–12904, doi: 10.1029/2019JB018363.

Michael, A. J., S. K. McBride, J. L. Hardebeck, M. Barall, E. Martinez, M. T. Page, N. van der Elst, E. H. L. Field, K. R. Milner, and A. M. Wein (2019). Statistical seismology and communication of the USGS operational aftershock forecasts for the 30 November 2018 M_w 7.1 Anchorage, Alaska, Earthquake, *Seismol. Res. Lett.* **91,** 153–173, doi: 10.1785/0220190196.

Nandan, S., G. Ouillon, D. Sornette, and S. Wiemer (2019). Forecasting the full distribution of earthquake numbers is fair, robust and better, *Seismol. Res. Lett.* **90,** no. 4, 1650–1659.

National Academies of Science, Engineering, and Medicine (NASEM) (2019). Committee on seismology and geodynamics 2019 Spring Meeting on New Opportunities to Study Tectonic Precursors, available at https://www.nationalacademies.org/event/05-09-2019/committee-on-seismology-and-geodynamics---spring-2019-meeting (last accessed June 2020).

Obara, K., and A. Kato (2016). Connecting slow earthquakes to huge earthquakes, *Science* **353,** no. 6296, 253–257.

Ohta, Y., J. T. Freymueller, S. Hreinsdóttir, and H. Suito (2006). A large slow slip event and the depth of the seismogenic zone in the south central Alaska subduction zone, *Earth Planet. Sci. Lett.* **247,** nos. 1/2, 108–116.

Panet, I., S. Bonvalot, C. Narteau, D. Remy, and J. M. Lemoine (2018). Migrating pattern of deformation prior to the Tohoku-Oki earthquake revealed by GRACE data, *Nature Geosci.* **11,** no. 5, 367.

Rousset, B., Y. Fu, N. Bartlow, and R. Bürgmann (2019). Weeks-long and years-long slow slip and tectonic tremor episodes on the south-central Alaska megathrust, *J. Geophys. Res.* **124,** 13,392–13,403, doi: 10.1029/2019JB018724.

Ruiz, S., M. Metois, A. Fuenzalida, J. Ruiz, F. Leyton, R. Grandin, C. Vigny, R. Madariaga, and J. Campos (2014). Intense foreshocks and a slow slip event preceded the 2014 Iquique M_w 8.1 earthquake, *Science* **345,** no. 6201, 1165–1169.

Savage, H. M., J. D. Kirkpatrick, J. J. Mori, E. E. Brodsky, W. L. Ellsworth, B. M. Carpenter, X. Chen, F. Cappa, and Y. Kano (2017). Scientific exploration of induced seismicity and stress (SEISMS), *Sci. Drill.* **23,** 57–63.

Socquet, A., J. P. Valdes, J. Jara, F. Cotton, A. Walpersdorf, N. Cotte, S. Specht, F. Ortega-Culaciati, D. Carrizo, and E. Norabuena (2017). An 8 month slow slip event triggers progressive nucleation of the 2014 Chile megathrust, *Geophys. Res. Lett.* **44,** 4046–4053, doi: 10.1002/2017GL073023.

Tsang, L. L., A. J. Meltzner, B. Philibosian, E. M. Hill, J. T. Freymueller, and K. Sieh (2015). A 15 year slow-slip event on the Sunda megathrust offshore Sumatra, *Geophys. Res. Lett.* **42,** no. 16, 6630–6638.

Uchida, N., T. Iinuma, R. M. Nadeau, R. Bürgmann, and R. Hino (2016). Periodic slow slip triggers megathrust zone earthquakes in northeastern Japan, *Science* **351,** no. 6272, 488–492, doi: 10.1126/science.aad3108.

Wallace, L. M., S. Hreinsdóttir, S. Ellis, I. Hamling, E. D'Anastasio, and P. Denys (2018). Triggered slow slip and afterslip on the southern Hikurangi subduction zone following the Kaikōura earthquake, *Geophys. Res. Lett.* **45,** 4710–4718, doi: 10.1002/2018GL077385.

Wang, L., and R. Bürgmann (2019). Statistical significance of precursory gravity changes before the 2011 M_w 9.0 Tohoku-Oki earthquake, *Geophys. Res. Lett.* **46,** 7323–7332, doi: 10.1029/2019GL082682.

Manuscript received 26 February 2020
Published online 8 July 2020