FUKUSHIMA LESSONS: THE DISCONNECT BETWEEN GEOLOGY AND NUCLEAR ENGINEERING

Triple Point raises issues of broad interest to the readers of *Elements* and explores different aspects of our science (teaching, publishing, historical aspects, etc.), our societies, funding, policy, and political issues. Contact Bruce Yardley (B.W.D. Yardley@leeds.ac.uk) if you have an idea for a future topic.

Allison Macfarlane

Recently, several seismic events at nuclear power plants exceeded the plants' "design bases" for ground motions. On 16 July 2007, a magnitude 6.8 earthquake damaged the Kashiwazaki-Kariwa nuclear plant in western Japan; the 11 March 2011 magnitude 9.0 quake and attendant tsunami caused multiple meltdowns at the Fukushima plant in northeastern Japan; and on 23 August 2011, a magnitude 5.8 earthquake caused minor damage at the North Anna nuclear plant in Virginia, USA. These accidents have exposed a disturbing disconnect between the knowledge needed by nuclear engineers to build safe nuclear power plants and the knowledge that geoscientists can provide to them.

Some nuclear engineers have claimed that reactors can be made "earthquake-proof," and, according to Scott Burnell of the U.S. Nuclear Regulatory Commission, "they [reactors] are designed to withstand just about everything short of a meteor strike" (Cyranoski 2007). Many in the nuclear industry claimed that the source of the Fukushima accident was the tsunami, not the earthquake (World Nuclear Association 2011), though the jury is still out on earthquake damage to the reactors and will be until they can be examined in detail. But the question is: can and do nuclear engineers integrate knowledge of Earth processes adequately so that reactors can be designed to withstand all that the Earth can throw at them?

The seismic design basis for a nuclear reactor is usually determined by the potential for ground motions at the site, which are estimated using historical data. This primary assumption is, in itself, problematic, because the historical period represents such a small slice of the possible geologic processes that could occur at a given location. To assure safety, nuclear engineers add an unspecified "safety margin" to their designs. Geologists are comfortable working with the concept of "deep time," and thus the use of historical data to guide predictions of future seismic events is inconsistent with geologic thinking. Nuclear engineers, on the other hand, design reactors that operate for 40 to 60 years, a timescale completely at odds with the geologic one.

Another source of disconnect between nuclear engineers and geologists is in their abilities to make accurate predictions. Nuclear engineers base many of their analyses on probabilistic performance assessments. Geology, on the other hand, is a retrodictive science, precise about the past but qualitative, at best, when predicting the future. Earth systems are complex and many of the processes and boundary conditions are not known or not well understood. They are thermodynamically open systems with processes that occur over very long timescales, making models of them difficult to validate or verify (Oreskes et al. 1994).

For instance, what matters during an earthquake at a reactor is the frequency of shaking and the acceleration of the ground. These ground motions depend on a variety of factors that go far beyond the simple energy released from the quake as indicated by magnitude measurements. Ground motions vary depending on the seismic source and the factors affecting wave propagation. Unique to the seismic source is the direction of wave propagation and the amount and type of slip on the fault. The factors affecting wave propagation include the rock and soil types along the wave path; the presence of mountains, basins, seas, and fault zones along the path; the age of the rock; and other aspects of the geologic environment. As a result, prediction of potential ground motions is a complex and difficult task.

Like Earth itself, geologic knowledge is dynamic and always in a state of flux. The nuclear industry sometimes treats this knowledge as static, not updating seismic hazard analyses for many years, for instance. Moreover, geology and its subdisciplines have experienced significant paradigm shifts over the past decades. The theory of plate tectonics only became fully integrated into geoscience in the 1970s, a period just prior to the time when many nuclear reactors were designed and constructed.

Paradigms continue to shift. Prior to the 2004 Sumatra earthquake, magnitude 9.3, seismologists generally thought that megaquakes occured only along certain subduction zones (Ruff and Kanamori 1980). After this quake, it became clear that megaquakes could happen along any subduction zone of sufficient length (McCaffrey 2007). Similarly, little evidence for large tsunamis was known from the area near Fukushima until a 2001 study of the 869 AD Jogan tsunami (Minouri et al. 2001)

Geologists are certainly not all-knowing, either. The occurrence of intraplate earthquakes, like the one at Mineral, Virginia, in August 2011, is a case in point. The geology of that section of the United States and the mechanisms that cause intraplate quakes are not well understood. Likewise, many faults, especially those that are not exposed at the surface, have not been identified. For instance, the fault that slipped and caused earthquake damage to the Kashiwazaki-Kariwa nuclear power plant in Japan in 2007 was not known to exist prior to the plant's construction.

Geologists make it hard for nuclear engineers because they often disagree about Earth processes. During a recent trip to Japan by the author, a number of Japanese nuclear industry colleagues pointed out that because the Jogan tsunami data were actively debated, they felt they could not act on them and increase the size of the protective seawalls.

The disconnect that exists between the geologic and nuclear engineering communities reflects their different approaches: geologists try to understand a dynamic, complex Earth with all its attendant processes, while engineers consider a given system over a specified period of time—but one that must work within that complex Earth system. Given the scale of the disconnect, is there a way to make nuclear reactors safer?

Clearly, a requirement to revisit seismic hazards on a regular basis (every few years) and include in the analysis societal impacts as they change over time would be valuable. Less reliance on probabilistic performance assessments when considering complex Earth system behavior would be a significant advance. Performance assessment allows some processes that otherwise might be important to be overlooked, as the Fukushima accident has shown. Complex Earth systems must be evaluated on a more qualitative basis, using a methodology termed a "safety case," which gathers all relevant quantitative and qualitative analysis together to predict future behavior (Ewing 2011).

Finally, we must recognize there are limitations to what we can do when interacting with Nature. Perhaps some places are simply not suitable for technologies such as nuclear power, the safety of which relies heavily on the stability of the Earth. Some parts of the Earth may be too dynamic for risky technologies.

Allison Macfarlane

Allison Macfarlane is an associate professor of environmental science and policy at George Mason University in Fairfax, Virginia. She received her PhD in geology from the Massachusetts Institute of Technology in 1992. She was recently a member of the White House's Blue Ribbon Commission on America's Nuclear Future. In 2006 MIT Press published her coedited book, *Uncertainty Underground: Yucca Mountain and the Nation's High-Level Nuclear Waste*. She was nominated by President Obama as the next chair of the Nuclear Regulatory Commission.

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MARC NORMAN INCOMING EXECUTIVE EDITOR OF *GCA*

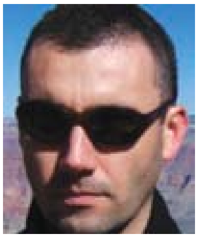
On 17 April 2012, Marc Norman was appointed as new executive editor of *Geochimica et Cosmochimica Acta* by the publisher, Elsevier. After a careful search, Marc was recommended by the Joint Publications Committee of the Meteoritical Society and the Geochemical Society and then nominated by the societies to Elsevier. In his e-mail greeting to the associate editors, Marc wrote, “My primary goal as executive editor will be to ensure that *GCA* maintains its standing as the premier journal for geochemistry.”

Since 2001, Marc has been at the Research School of Earth Sciences of the Australian National University, Canberra, where he holds the position of Senior Fellow. His research interests span both terrestrial and extraterrestrial topics. Six are currently listed on his home page (http://people.rses.anu.edu.au/norman_m/): magmatic systems and related ore deposits; NiS, PGE black shales, sedimentary geochemistry; laser ablation ICPMS; solution ICPMS; radiogenic isotopes (Sr, Pb, Nd, Os); and MC-ICPMS, TIMS. At the 43rd Lunar and Planetary Science Conference in Houston this year, he reported on the ages of lunar spherules, melt breccias, and zircons.

Marc has been a councillor, associate treasurer, and a member of the Publications Committee of the Meteoritical Society. In 2006 he cochaired the Cosmochemistry Task Group (with Herbert Palme) for the Goldschmidt Conference in Melbourne and is now chair of the Program Committee for the 2012 Meteoritical Society meeting in Cairns. In 2011 he organized a thematic issue of the *Australian Journal of Earth sciences*, which will be published in early 2012. From 2008 to 2011, he served on the Steering Committee for the first Australian Academy of Science Decadal Plan for Space Science, and he chaired the planetary science working group for the National Committee for Space Sciences within that effort.

His prior experience in the editorial area includes service on the editorial boards of the *Australian Journal of Earth Sciences* (2009–present), published by the Geological Society of Australia, and the *Open Mineralogy Journal* (2008–2010).

JAMES B. MACELWANE MEDAL TO NICOLAS DAUPHAS

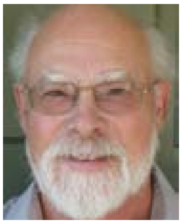


Nicolas Dauphas was awarded the 2011 James B. Macelwane Medal of the American Geophysical Union. The medal recognizes significant contributions to the geophysical sciences by an outstanding young scientist. His citationist writes that his “contributions to geochemistry and cosmochemistry are remarkable for their breadth and depth, covering geochemical processes at all scales and times, from the age of the galaxy to the evolution of ancient and modern igneous rocks.”

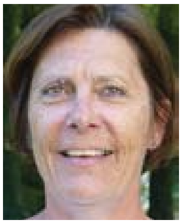
2011 AGU FELLOWS

Among the scientists elected as Fellows of the American Geophysical Union in 2011, we highlight those who have a primary affiliation with the Volcanology, Geochemistry, and Petrology Division or are members of one of *Elements*’s participating societies. Congratulations to all!

DON E. CANFIELD
For his outstanding contributions to understanding the biogeochemical cycling of sulfur and the oxygenation of Earth’s atmosphere

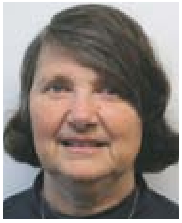


OLIVER CHADWICK
For his novel application of geographic and geochemical tools to advance understanding of how soils develop and interact with other parts of the Earth system

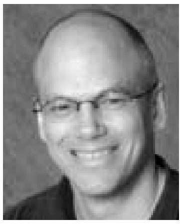


CATHERINE CHAUVEL
For key contributions to understanding mantle evolution through isotope studies of oceanic basalts and linking subducted sediments to arc magmas

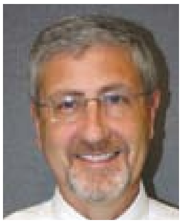
MARK M. HIRSCHMANN
For his exceptional work on igneous phase equilibria, illuminating the simplicity underlying experimental results on complicated natural solutions



SUZANNE MAHLBURG KAY
For her contributions to understanding the growth and evolution of continental crust in subduction zones

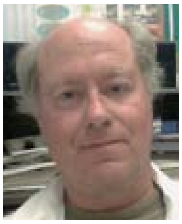


CRAIG E. MANNING
For his peerless experiments on the solubility of minerals in aqueous fluids at high temperature and pressure, a unique combination of rigor and realism, yielding timeless data and timely applications



WILLIAM F. McDONOUGH
For his major contributions to our understanding of the geochemistry of Earth’s interior

WILLIAM M. SEYFRIED JR.
For making major contributions to our knowledge of the chemistry of aqueous fluids and processes that take place near mid-ocean ridges



KEVIN J. ZAHNLE
For advancing understanding of how planetary-scale physical and chemical processes affect the evolution of planets and life on them

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