TRANSLATIONAL GEOSCIENCE: CONVERTING GEOSCIENCE DISCOVERY INTO SOCIETAL, ECONOMIC, AND ENVIRONMENTAL IMPACTS

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Translational geoscience—which involves the conversion of geoscience discovery into societal, economic, and environmental impacts—has significant potential to generate large benefits. But, it has received little systematic attention or resources. In contrast, *translational medicine*—which focuses on the conversion of scientific discovery into health improvement—has grown enormously over the past decade and provides useful models for advancing translational science into the geosciences and other fields.

The geosciences address many of society's greatest challenges, including (but not limited to) energy, water, and mineral resources; climate change; natural hazards mitigation; sustainable development; environmental protection; infrastructure and materials; and waste disposal. Past issues of *Elements* have addressed many of these topics, and this issue addresses the broader impacts of such topics as stable isotope biogeochemistry (Ehleringer et al. 2015), the application of stable metal isotopes to medicine (Albarède 2015), environmental mineralogy (Calas et al. 2015), and urban geochemistry (Ludden et al. 2015). Translational geoscience can accelerate the conversion of geoscience discoveries in these and other areas into greater societal, economic, and environmental impacts.

Before discussing translational science as potentially applicable to the geosciences, let's first look at how it has been developed and applied in the biosciences.

NEW VISION FOR TRANSLATIONAL SCIENCE

In his capacity as director of the US National Institutes of Health (NIH), Elias Zerhouni (2005) provided a new vision for translational science and took bold actions to "ensure that extraordinary scientific advances of the past decade will be rapidly captured, translated, and disseminated for the benefit of all Americans." Zerhouni (2005) launched a major program to support a nationwide consortium of hubs at 62 medical research institutions that could work together to improve the translational research process. Likewise, the European Commission established the European Advanced Translational Research InfraStructure in Medicine (EATRIS) program, which comprises over 70 leading academic institutions across Europe.

In 2011, Francis Collins, who succeeded Zerhouni as director of NIH, said the time was right to for "reengineering translational science." According to Collins (2011), "the triple frustrations of long timelines, steep costs, and high failure rates bedevil the translational pathway." He noted, "little focused effort has been devoted to the translational process itself as a scientific problem amenable to innovation." He further said, "translational science needs to shift from a series of one-off solutions toward a more comprehensive strategy." He launched NIH's National Center for Advancing Translational Sciences (NCATS), which addresses translation on a system-wide level as a scientific and operational problem.

The US White House has broadened the imperative for translation to include research supported by all federal agencies. A memorandum of 9 July 2015 from the Executive Office of the President of the United States (Donovan and Holdren 2015) says:

> The Nation depends on science, technology, and innovation to promote economic growth and job creation, maintain a safe and sufficient food supply, improve the health of Americans, move toward a clean energy future, address global climate change, manage competing demands on environmental resources, and ensure the Nation's security.
>
> Simply supporting research is not sufficient, however, Federal agencies should ensure that the results of that research are made available to other scientists, to the public, and to innovators who can translate them into the businesses and products that will improve all of our lives.

The imperative for translation also extends to the type of research and development (R&D) that strengthens the scientific basis for decision-making. According to Donovan and Holdren (2015), "Both mission-centered agencies and R&D agencies should focus on creating user driven information and tools that enable the translation of scientific observations to decision-making frameworks."

Despite its importance, investments in translational research should not come at the expense of basic research. Focusing on biomedical research in the United States, Zerhouni (2009) said, "Our country needs more and better translational research, both for the sake of our patients and because much of the research funding in the United States comes from the primary expectation of the American public that such scientific investigations will reduce the burden of disease. This is not to say, as many fear, that we should reduce our focus on basic research. On the contrary, I believe the opposite to be true..." Success in translational research may stimulate support for additional investments in basic research.

TRANSLATIONAL GEOSCIENCE

Geoscience is vastly different from biomedical science. Nevertheless, both can benefit from the principles of translational science. Adopting the approach of Collins (2011), translational geoscience would benefit from a focused effort devoted to the translational process itself as a scientific problem amenable to innovation. The geosciences would benefit from setting up institutions comparable to the NIH's National Center for Advancing Translational Sciences, which addresses translation on a system-wide level as a scientific and operational problem and convenes expert teams from diverse scientific disciplines and institutions to reduce, remove or bypass significant bottlenecks across the entire continuum of translation, as well as training future translational-science workers.

Natural hazards mitigation is one of many geoscience issues that would benefit from advances in translational science. This topic may also be amendable to collaboration between translational medicine and translational geoscience, at least to the extent that natural hazards mitigation is a field that addresses public health and safety.

A tsunami monitoring and warning system was installed in the Indian Ocean after the great Sumatra–Andaman earthquake and tsunami of 26 December 2004, which caused approximately 228,000 fatalities, 1.8 million people to become homeless, 5 million people to need immediate aid, and resulted in $14 billion in damages. Although UNESCO announced that the Indian Ocean Tsunami Warning System was "up and running" in June 2006, an editorial in the journal *Nature* (2006) stated that a tsunami in Indonesia had killed more than 500 people on 17 July 2006. In a tragic failure of translational science, a tsunami warning was received but the government did nothing with the information. The Indonesian science minister feared that raising a false alarm would cause unnecessary panic (Nature 2006).

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Regarding the Indian Ocean Tsunami Warning System, the same *Nature* (2006) editorial argued, "Too much emphasis has been put on the expansion of the high-tech early warning system, and not enough on improving local preparedness." Eight years later, and an opinion piece in *Nature* by Witze (2014) noted that this pattern still persisted despite concerted efforts to complete the communications chain: he states, "Ten years after the devastating Sumatra earthquake, warnings for the Indian Ocean go out, but often fail to reach the people most at risk … The geophysical components of the Indian Ocean tsunami-alert system generally work well … but warnings often fail to travel the last mile."

The effectiveness of the Indian Ocean Tsunami Warning System, which cost more than $450 million to set up, will be compromised greatly if further improvements in local preparedness are not achieved. Efforts in translational geoscience could benefit from advances in translational medicine, a field that has developed strategies for minimizing the multiple translational roadblocks that so often impede public health interventions, some of which involve communications, human behavior, organizational inertia, and allied topics (Woolf 2008).

Just as the Indian Ocean Tsunami Warning System was implemented after a devastating tsunami, most countries with earthquake early warning systems built them after a devastating earthquake (USGS 2014). Shortly after the 1995 Kobe (Japan) earthquake that resulted in 6,400 fatalities, Japan invested $600 million in an earthquake early warning system. The system operated successfully during the magnitude 9.0 Tohoku earthquake of 2011, and no trains were derailed as a result of this historic earthquake. Other countries that built earthquake early warning systems of varying quality and coverage after devastating earthquakes include China, after the 2008 Wenchuan earthquake that killed 87,587 people, and Mexico, after the 1985 Mexico City earthquake that killed 10,153 people (USGS 2014). The United States, and many other countries with major earthquake hazards, have not yet implemented early warning systems.

The US Geological Survey (USGS) and its partners are, however, implementing an earthquake early warning system for the west coast of the United States (Given et al. 2014). Earthquakes in this region cause an average annual loss of $4.1 billion. Research and development efforts for this system began in 2004 and a preprototype earthquake early warning system has been operating in California since January 2012. The USGS plans to implement a limited public warning system by 2018.

The technical implementation plan for an earthquake warning system for the west coast of the United States (Given et al. 2014) contains a short section on user education, which says, "Extensive outreach and education of both public and institutional users will be needed to ensure that earthquake early warning achieves the maximum beneficial effect. Users must be taught to take appropriate actions upon receiving a warning, and understand the limitations and reliability of warning information." Given et al. (2014) emphasize the importance of developing partnerships with appropriate agencies—including emergency management departments, communications specialists, and special user groups such as hospitals, transportation monitors, and utility providers—to ensure this education occurs. Although a full education plan has not yet been developed, local west-coast groups have been working for many years to improve preparedness, mitigation, and resilience through such organizations as the Earthquake Country Alliance, the Southern California Earthquake Center, and a wide range of partners. More than ten million Californians have participated in Great Shake Out earthquake drills. The combination of robust education and preparedness activities with a technologically advanced earthquake early warning system has the potential to become a model for translational geoscience.

The cost, complexity, and timeframe for developing and implementing earthquake and tsunami early warning systems are comparable to many examples in translational medicine. Translational geoscience can benefit from the advances made in translational medicine, which addressed such topics as improving emergency preparedness, communicating life-saving information to government officials and citizens, explaining false positives and false negatives, working with multiple stakeholders and organizations across all sectors of the economy and all levels of government, and collaborating with scientists and engineers across a broad range of disciplines.

Although he was speaking generally from a position within translational medicine, Collins (2011) makes a point that could equally well apply to translational geoscience, "Opportunities to advance the discipline of translational science have never been better. We must move forward now. Science and society cannot afford to do otherwise." Prompt actions will enable the geoscience research enterprise to be in the vanguard of the translational science revolution.

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