Takashi Murakami and Rodney C. Ewing, guest editors

Fukushima Daiichi

More than One Year Later
The 2011 Tohoku Earthquake
Examining the Nuclear Accident
Land-Surface Contamination
Atmospheric Dispersion and Deposition of Radionuclides
Oceanic Dispersion Simulations of $^{137}$Cs
Interactions between Nuclear Fuel and Water
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Fukushima Daiichi

Free Issue

Guest Editors: Takashi Murakami and Rodney C. Ewing

Fukushima Daiichi:
More than One Year Later
Rodney C. Ewing and Takashi Murakami

The 2011 Tohoku Earthquake
Jeroen Ritsema, Thorne Lay, and Hiroo Kanamari

Examining the Nuclear Accident at Fukushima Daiichi
Edward D. Blandford and Joohong Ahn

Atmospheric Dispersion and Deposition of Radionuclides from the Fukushima Daiichi Nuclear Power Plant Accident
Anne Mathieu, Irène Korsakissok, Denis Quélo, and others

Land-Surface Contamination by Radionuclides from the Fukushima Daiichi Nuclear Power Plant Accident
Naohiro Yoshida and Yoshio Takahashi

Oceanic Dispersion Simulations of 137Cs Released from the Fukushima Daiichi Nuclear Power Plant
Yukio Masumoto, Yasumasa Miyazawa, Daisuke Tsumune, and others

Interactions between Nuclear Fuel and Water at the Fukushima Daiichi Reactors
Bernd Grambow and Christophe Poinssot

About the Cover: Aerial photo taken by a small unmanned drone on March 20, 2011, showing the crippled Fukushima Daiichi nuclear power plant in Fukushima Prefecture, northern Japan. From top to bottom: Unit 1, Unit 2, Unit 3, and Unit 4. Photo courtesy of Air Photo Service Co. Ltd., Japan

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Breaking the “boundary” between “applied” and “fundamental” science is also needed: on which side of the boundary are topics such as radiation-induced damage in minerals and materials, the thermodynamic properties of actinide systems, or the trapping of fission products and actinides at mineral–water interfaces? Perhaps there will be a proper answer in the time we have left to answer this question: the longer the time left to research, the more the fundamental aspects may be explored. But the Fukushima Daiichi crisis reminds us that expertise is sometimes needed on a very short timescale for decisions to be taken in a few days and for a technological solution to be immediately made available.

Facing the consequences of a major nuclear disaster is clearly a global issue, despite the fact that the management of a nuclear reactor is local. This is evident when considering the terrestrial fluid envelopes—the atmosphere and ocean—are stirred by global circulation and so have worldwide effects. International cooperation needs to be exemplary in urgent situations, and here too it is a matter of breaking boundaries to provide the most useful expertise from all nations. Many countries have been and still are currently involved with damage evaluation in Fukushima, decontamination procedures, and the management of nuclear waste, including its disposal in geological repositories, are the main domains of the nuclear cycle in which mineralogists and geochemists are usually involved. Many research activities are then shared between geological/environmental science and materials science, as both domains become more and more interlinked on topics of mutual interest. The successful “Scientific Basis for Nuclear Waste Management” symposia and proceedings of the Materials Research Society have, for the past 35 years, been a forum involving mineralogists and geochemists, together with materials scientists, and have resulted in original contributions to this area of research. But breaking boundaries between mineralogy and materials science and sharing time and effort between both fields is sometimes not easy, as is often the case in multidisciplinary science. In fact, the extraordinary effort required to do research across disciplinary boundaries may have the effect of making mineralogy seem less relevant, because little credit is given for this effort as soon as it leaves the Earth science sphere. Ironically, the broader application of mineralogy and geochemistry to societal problems may have planted the seeds for their demise in some traditional Earth science departments.

We must develop robust, scientifically based predictive models to properly react to unusual situations.
A little more than one year after the Fukushima tragedy, this issue of Elements provides a summary of the nuclear accident as it has been reconstructed and the lessons that other facilities can take from it, and it gives an overview of the resulting contamination in the air, soils, and ocean. The Perspectives section provides six different points of view on the future of nuclear power in the aftermath of Fukushima. And Travelogue offers an account of a scientist’s visit to the evacuation zone. These articles reveal that behind the human tragedy, a large number of scientists are working hard to provide the data necessary to understand the accident and find solutions.

Kudos to guest editors Takashi Murakami and Rod Ewing who accepted the challenge of assembling this issue of Elements under a much accelerated schedule: the first invitations to authors were sent out at the end of August 2011. Our gratitude also goes to the authors, who accepted the challenge of writing review articles while so much data are still being amassed—like trying to hit a moving target.

At Goldschmidt 2010, I was impressed by the argument Tennessee Senator Lamar Alexander made in favor of nuclear power as the energy of the future. In his keynote presentation, he reviewed all the energy sources in terms of the land used to produce the energy. For example, the land occupied by one nuclear plant producing enough power for 90,000 homes is one square mile. To produce the same amount of energy, solar power requires 15 square miles, petroleum 18. But the Fukushima Daiichi nuclear power plant accident reminds us that when something goes wrong in this industry, a huge territory can be impacted and the economic costs of bringing an accident under control are staggering. This does not include the suffering of people who have been displaced from their homes and face an uncertain future. About 90,000 persons who lived in the evacuation zone near the plant have not been able to return to their homes. We dedicate this issue to them, and also to the 20,000 persons who died in the aftermath of the earthquake and tsunami.

Earth scientists are providing the scientific basis for addressing critical questions, such as when it will be safe to return to the contaminated areas. This requires multidisciplinary teams that need to avoid being made irrelevant by answering, “We need to do more work.” Answers are needed now and have to be clearly communicated to decision makers.

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Georges Calas (georges.calas@upmc.fr)
University Pierre et Marie Curie, Paris

UPCOMING EDITOR

We are delighted that Patricia (Trish) Dove of Virginia Tech has accepted our invitation to join the editorial team. She will replace Tim Drever, whose term ends in December 2012. We will formally introduce Trish in the first issue of 2013.

ABOUT DUPLICATE COPIES – PART 2

From time to time, we receive inquiries regarding the management of subscriptions, such as these: “I joined society X and am also member of society Y but I am still receiving only one copy of Elements. I would like this second copy to be shipped to a colleague in Estonia!” “I would be happy to only have online access to Elements and save you the mailing costs.” “My husband and I both receive Elements. We only need one copy; please eliminate mine.”

As explained in the April issue (8: 84), Elements’ financial model requires that we eliminate duplicate mailings. This reduces printing and mailing costs, and these savings are passed on to the participating societies in the form of lower subscription rates. So even if you belong to more than one society, you should only receive one copy of Elements. We ask our readers to encourage colleagues who are interested in receiving Elements to join one of the participating societies.

Although granting requests like online access only might seem like a good idea, it could end up being expensive, as managing these requests would be very time consuming and might necessitate the hiring of a subscription manager, thus erasing any saving and probably increasing costs, which would then have to be passed on to the societies. Put your unneeded paper copy of Elements to good use: depending on the topic, send it to your dean, give it to a student, a colleague, or a neighbor.

Pierrette Tremblay, Managing Editor

Elements makes a splash in Natural History

With its timely and societally relevant topics, Elements has effectively permeated the mineralogy, geochemistry, and petrology community and has even reached other interested scientists and administrators. When geoscientists have the chance to reach out to the general public, it is important that they make the effort to do so. Such an opportunity occurred recently when the editor-in-chief of Natural History magazine, Vittorio Maestro, contacted Barb Dutrow and Darrell Henry, guest editors of the October 2011 Elements issue on tourmaline, about writing an article for his magazine. Associated with the American Museum of Natural History, Natural History’s mission is to promote public understanding and appreciation of nature and science. Maestro had read the Tourmaline Diaries: an eye-catching mineral and its many facets” appeared in the March 2012 issue of Natural History. Natural History has a circulation of about 50,000, with 1900 libraries and an audience of nearly 200,000.

Barb Dutrow, Louisiana State University
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 megauquakes occurred only along certain subduction zones (Ruff and Kanamori 1980). After this quake, it became clear that megauquakes 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.

REFERENCES


Allison Macfarlane
MARC NORMAN INCOMING EXECUTIVE EDITOR OF GCA

On 17 April 2012, Marc Norman was appointed as new executive editor of Geochemica 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 Meteorite 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.


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 citation writes that his “contributions to geochemistry and cosmochemistry are remarkable for their breadth and depth, covering geochronological 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

CATHARINE 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

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 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

Triple Point Cont’d from page 165


Phase ID and elemental analysis on a benchtop

The new 5th generation MiniFlex™ XRD diffractometer has twice the power of its nearest competitor as well as a wide range of options.

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NOTE FROM THE EDITORS: SIX PROMINENT SCHOLARS, POLITICIANS, AND POLICY MAKERS WERE ASKED THE QUESTION “WHAT HAS BEEN LEARNED FROM THE FUKUSHIMA DAIICHI EVENT AND HOW WILL THIS IMPACT THE FUTURE OF NUCLEAR POWER?”

THE IMPORTANCE OF CLEAR COMMUNICATION
Ian G. McKinley

The damage to the Fukushima reactors provided frightening images that shook confidence in nuclear power around the world. It is easy to forget that, as yet, there is no indication of radiological harm to the general public. Confusing and incorrect comparisons with the completely different situation in Chernobyl highlight a major lesson to be learned from this incident: the importance of clear communication.

Communication failed at every level. Known tsunami risks were not communicated to those charged with assessing natural hazards to nuclear facilities. The developing situation in the damaged units after the tsunami was poorly communicated to both the government and the general public, delaying decisions that could have limited the consequences and helped avoid unnecessary panic. Tools that could have been used to help plan the response to releases of radioactivity were introduced too late, and their output was presented in a way that only increased confusion and public concern. It should be emphasized that this was not simply a result of the chaos immediately after a major disaster nor was it limited to Japan—9 months after the Fukushima event, newspaper, TV, and Internet articles continued to sow confusion around the world.

At the Daiichi site, contamination levels are high and remediation will be a major challenge. Although hotspots and increased radiation levels exist off-site, health hazards from the radiocesium isotopes that now dominate activity levels are very small. Nevertheless, demonstration cleanup projects have been initiated and regional remediation will follow. A rich country like Japan can justify such actions, even if the health benefit is marginal compared to the effort invested. Such an objective perspective on the risks involved should, however, be clearly explained in order to reassure local residents and involve them in decisions about the actions that need to be taken.

Poor communication has also meant that, so far, potential options for optimizing the remediation work are being missed. Major efforts are being invested to manage lightly contaminated soil; however, this soil could be better utilized as ground cover on the more highly contaminated reactor site, providing radiation shielding and reducing doses to workers.

The communication problem extends to wider, international issues resulting from this incident. In several cases, knee-jerk reactions from poorly informed politicians have resulted in moves away from nuclear power, without any balanced consideration of the potentially larger environmental and public health hazards of the fossil fuel alternatives that would be introduced in its place. More seriously, the fact that two recent devastating tsunamis have resulted from megathrust earthquakes has focused risk assessment on this particular hazard combination—without considering that the historical record shows much larger tsunamis from other sources, such as volcanoes and landslides. Indeed, much of the infrastructure that supports our high population densities is located in areas where a natural catastrophe in coming decades is not just possible, it is inevitable. As was the case before Fukushima, the technology exists to assess such hazards and, to a certain degree, minimize consequences or prepare responses. Unless the existence and usefulness of such technology is effectively communicated to decision makers, however, these lessons will have to be relearned after the next natural catastrophe.

FURTHER BACKGROUND INFORMATION

The Fukushima Daiichi incident in context:

Tsunami risk overview:

IMPROVING INTERNATIONAL COOPERATION
Catherine Cesarsky

The Fukushima Daiichi accident undoubtedly has shaken the world of nuclear power in a very serious way and will leave indelible marks. Even after the release of the preliminary report by the Japanese investigation committee chaired by Yotaro Hatamura, not everything is known of the sequence of events and of their final consequence.

Main Lessons for Present Reactors
A first lesson from Fukushima is that very unlikely events may combine with each other in unanticipated ways, so the concept of “emergency preparedness” will have to be revisited. The main cause of the Fukushima accident was the tsunami, which resulted in the loss of the cooling capabilities and the internal electrical supply, including some of the emergency batteries. The design of the plant was highly resistant to earthquakes but had a limited protection against floods. Thus, in addition to a well-defined design basis, a nuclear plant must have some potential to resist external hazards that are “beyond design.” Most operating light water reactors already have dedicated systems to cope with severe-accident conditions. For example, in France, passive hydrogen recombiners to protect against hydrogen accumulation were installed years ago. France will also be putting in place a rapid intervention force with off-site power supplies and cooling capabilities. Also, it has been proposed to identify an ultimate set of systems (“hard core”) and to have them available in bunkers at the site in case of extreme conditions.

At Fukushima, for a few days after the tsunami and under very difficult conditions, the decay heat removal was maintained using on-site water reservoirs and pumping systems requiring no AC electrical supply. Thus a large early release of radioactive material was avoided.

1 Ian G. McKinley (ian.mckinley@mcm-international.ch) is a technical consultant at MCM, Baden, Switzerland, and, since December 2011, a visiting professor atOkayama University, Japan. He was initially involved in the synthesis of relevant international experience to help plan on-site and off-site remediation. Currently he is supporting assessment of the first demonstration remediation projects and planning subsequent regional cleanup actions.

2 Catherine Cesarsky is the High Commissioner for Atomic Energy in France and advisor to the French government on science and energy issues. She holds a physics degree from the University of Buenos Aires and a PhD in astronomy from Harvard University (1971). She is a member of the French Académie des Sciences and a foreign member of the National Academy of Sciences (USA), the Royal Society (UK), and the Swedish Academy of Sciences. She was visiting the Rokkasho nuclear reprocessing plant in Japan on March 11, when the earthquake and tsunami struck Japan.
and the Japanese government was able to evacuate people in time. The Hatamura committee argues that these systems could have been operated in a better way. The necessity for superior preparation and training of the plant staff is therefore another key lesson.

In terms of accident progression, a significant part of the radioactive inventory has been retained in the reactor containers, and it appears that the three coriums are trapped in the concrete basements of the reactors. For present reactors, in-depth studies of the physics and chemistry of severe accidents will have to be carried out. This knowledge is essential for defining management procedures and for developing severe-accident simulators devoted to operator training. Resistant instrumentation will also be required for ascertaining, as far as possible, the plant condition during an accident.

**Future of Nuclear Power**

For most countries involved, nuclear energy will likely remain an essential component of the low-carbon energy mix. The Fukushima accident has demonstrated the appropriateness of the safety objectives assigned to the new generation of reactors (generation III), which feature additional systems dedicated to severe-accident mitigation (e.g., corium retention, hydrogen explosions).

After more than thirty years of cooperation following the Three Mile Island (USA) accident, Fukushima also raises doubts about the efficiency of international cooperation. After Fukushima, improvements should be actively sought in:

- Speeding up current initiatives for harmonizing safety requirements, crucial to assessing the full compliance of commercial projects to internationally agreed-upon safety criteria for generation III reactors
- Progressing towards better harmonized safety regulations and sharing of best practices
- Developing international training
- Enhancing international cooperation in regulatory research, safety, and radiation protection
- Generalizing periodic nuclear power plant “stress tests” followed by peer reviews (as done in the European Union)
- Studying concrete measures to provide mutual assistance to operators in case of severe accidents, an issue especially important for small- and medium-sized electric utilities

After Fukushima, nuclear energy will have to regain public and political acceptance. A rational and consensual determination of all the consequences of the Fukushima accident and a “dynamic safety” approach with full use of lessons learned from the accident and stress tests will contribute to this challenging objective.

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**A JAPANESE PERSPECTIVE**

Atsuyuki Suzuki

The massive earthquake and immense tsunami on March 11, 2011, raise a fundamental question: Are human beings capable of managing unprecedented natural disasters? The question is also begged by the great 1755 Lisbon earthquake, which profoundly shocked Europeans. This event compelled a number of philosophers, including Immanuel Kant, to alter their thoughts drastically. As far as the Fukushima nuclear accident is concerned, my answer is “yes.” My optimism is based on the performance of the nuclear power plants located in the coastal areas of northeastern Japan, where no serious consequences were experienced, even though these areas were subjected to a nearly equal-magnitude tsunami.

As an example, consider reactors #5 and #6 at Fukushima Daiichi. One of the three emergency diesel generators installed at Unit 6 remained available, and operators were able to successfully connect it to both units and provide sufficient power for accident management at these units. This surviving generator was air-cooled, not water-cooled, and it was installed at an elevation high enough to avoid the tsunami. This is an example of a defense-in-depth safety concept, where a diversity of designs offers the greatest resilience to an extraordinarily unlikely event.

In addition to diversity in design, we have learned the usefulness of prudent conservatism when considering natural phenomena that are conceivably always associated with the unknown. One of the issues that Japan’s nuclear industry missed was to take into account the historical tsunami records in the analysis of reactor safety. The scientific knowledge obtained in recent years had indicated that a tsunami of a magnitude similar to that of the March 2011 event occurred in 869 AD in these areas; this fact was not known in the late 1960s and early 1970s, when the construction permits were granted. Unfortunately, no action was taken to reflect the new knowledge in order to enhance reactor safety. Thus, an overwhelmingly important point raised by the accident is that new scientific findings should be adopted promptly and properly in order to improve nuclear safety. This is particularly true if the new information is related to extreme natural events that are difficult to predict.

After the accident, nuclear policy in Japan was placed under review. Priority was given to the environmental remediation of contaminated off-site areas and to implementing the dismantlement of the damaged reactors. These tasks will require patience, as well as substantial expenditures. The future of the nuclear power industry in Japan rests heavily on the successful achievement of off-site environmental remediation and the removal of nuclear material from the damaged reactors.

In the aftermath of the accident, however, there are countries that have not changed their policy, but continue to pursue their plans for reactor construction, and the Japanese government has expressed its readiness to be actively committed to the international nuclear business. Worldwide, energy security is critical. The political situation in the Middle East, for instance, underscores the inherently fragile nature of the international oil market, which can potentially affect the world economy. Naturally, the future of global nuclear power depends on such international energy circumstances, and my perception is that the global impacts of the accident will gradually disappear, as more realistic assessments are made.

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3 Atsuyuki Suzuki is the president of the Japan Atomic Energy Agency (JAEA) and a professor emeritus of nuclear engineering at the University of Tokyo. Currently he leads the special task force at JAEA specifically dedicated to the partnership programs dealing with Fukushima matters, including environmental remediation of off-site areas as well as postaccident management of the nuclear power plants and environmental restoration of on-site areas.
ENVIRONMENTAL REMEDIATION, WASTE MANAGEMENT, AND THE BACK END OF THE NUCLEAR FUEL CYCLE

Joonhong Ahn

The Japanese government has promised to make every effort to limit the dose rate in air in areas contaminated by the Fukushima accident to below 1 millisievert (mSv) per year (typical background exposures in Japan are 1 mSv per year). It has been estimated that decontaminating the highly contaminated areas (i.e., >1 megabecquerel/m²) will generate an estimated 24 million m³ of contaminated material. The estimated cost of disposal of the wastes from highly contaminated areas is a few trillion yen (one trillion yen = 8 billion US dollars). If areas with lower contamination by radioactive activity are also included in the cleanup, the total volume of waste material and the associated cost will be much greater; however, the health risks in areas of low contamination have been judged to be insignificant. Thus, considering the potential scale of the cleanup effort, the question “how clean is clean enough?” has emerged as a much-debated issue involving the convergence of technical, political, and societal concerns.

Over the past decade, the Nuclear Waste Management Organization (NUMO) of Japan has been responsible for the process of public participation in the siting of a geological repository for high-level and long-lived radioactive wastes. However, no municipality has yet to volunteer to host such a site on its territory. Now, a siting process that was deadlocked before the accident has become even more difficult. The realization of the amount of material that will result from decontamination related to the Fukushima accident and the necessity of moving forward with a solution have delayed the siting process for a repository for high-level radioactive waste. On the other hand, this delay may be a valuable opportunity for developing trust and new approaches for decision making that could lead to a break in the deadlock over selecting a site for a geologic repository.

Public discussion has also extended to a reconsideration of Japan’s nuclear fuel cycle policy, particularly at the back end, that is, interim storage, reprocessing of spent nuclear fuel, and final geological disposal. Japan is the only non–nuclear weapons country with an industrial-scale capability for uranium enrichment and spent fuel reprocessing that has been approved by the international community. The motivation for developing a full-fledged, complete fuel cycle capability has been a national policy of energy security and independence. Plutonium generated in light water reactors and future fast breeder reactors has been considered to be a semi-indigenous resource. Because of the sodium leak in the Monju fast breeder reactor in 1995 and the technical difficulties with the vitrification process at the Rokkasho reprocessing plant, there was already growing public skepticism about the current nuclear fuel cycle strategy.

Due to the events at Fukushima, public agreement and perceptions concerning the development of nuclear power in Japan have changed significantly, and there is much discussion about whether the current nuclear fuel cycle policy should be revised. In any conceivable future scenario, including phasing-out nuclear power or abandoning the recycling of plutonium, the transition will require at least a generation. To successfully manage this transition period, interim storage of spent fuel will be essential. The protection of long-term storage facilities from natural disasters and terrorism will be a crucial technical and societal issue. The fate of accumulated plutonium should also be clearly accounted for, especially in the phase-out scenarios. New fuel cycle policies should be established from the viewpoint of making spent fuel more robust against accidents and disasters and reducing the risk of proliferating weapons-useable materials.

The Post-Fukushima Nuclear Industry in Mongolia

Undraa Agvaanluvsan

The history of nuclear activities in Mongolia offers a good example of the development of nuclear capabilities in a developing country. Mongolia, once Communist, was closely linked to the former Soviet Union. The training of nuclear scientists began in the early 1960s, and most Mongolian scientists received their postgraduate degrees and research experience in nuclear physics at the Joint Institute of Nuclear Research in Dubna, Russia.

Though nuclear power was held in high esteem, there was also a strong fear of nuclear activities. This was due to the dual nature of nuclear technology. The two blocs in the Cold War, one led by the United States and Europe and the other led by the Soviet Union, were in a nuclear arms race. As nuclear weapons were being tested, both sides claimed that the other was an “evil” force pursuing the development of an “evil” weapon. At the same time, both sides argued that they needed nuclear weapons for their defense. In order to sustain this policy, nuclear weapons were viewed as a necessary evil. The combined feeling of fear and allure was quite widespread among the Mongolian people, and this paradox was only enhanced by the fear engendered by the Chernobyl accident in 1986 and the hope created by the Democratic Revolution in 1990.

The Democratic Revolution brought Mongolia the freedom to adopt an independent nuclear policy. The anti–nuclear weapons sentiment is reflected by Mongolia’s declaration that it would be a nuclear weapons–free country. Nuclear policy making remained mostly dormant until 2009, when Parliament approved the historic Nuclear Energy Law and Nuclear Energy Policy. With some of the world’s largest and least explored uranium reserves, Mongolia knew that it needed a new policy in order to become a supplier of uranium for nuclear fuel. Thus, Mongolia joined the “nuclear renaissance,” as did more than 30 other countries that were considering building nuclear power plants. During this time, support for the nuclear industry among the Mongolian public and political leaders was strong.

The situation changed after Fukushima. Rumors that the Mongolian government was considering building a nuclear-waste-disposal site caused much anxiety and opposition among the people. Although the government refuted the accusations, opposition groups formed against the government. The public, taking advantage of the new social media technologies, was not convinced by the government. This was mainly because the Mongolian government could not articulate its position and strategy for nuclear development. The rumors and discussion only ceased with a presidential decree in 2011, which stipulated that there would be no contract negotiations or cooperation in the nuclear arena without the approval of the National Security Council of Mongolia.

Mongolia does not yet have a nuclear power plant, nor is there a national consensus on how its extensive uranium reserves should be developed. Mongolia is an example of how difficult it is to develop a national nuclear policy in the post-Fukushima environment.

4 Joonhong Ahn is a professor in the Department of Nuclear Engineering at the University of California, Berkeley. He has led numerous joint research projects involving institutions in Japan, South Korea, and the United States, and the IAEA. He is currently conducting a joint research project with the Japan Atomic Energy Agency, in which criticality safety is being analyzed for geological disposal of molten nuclear fuel in the Fukushima reactors.

5 Undraa Agvaanluvsan, a nuclear physicist by training, is a former ambassador at the Ministry of Foreign Affairs and Trade of Mongolia, where she was in charge of nuclear energy and security issues at the time of the Fukushima event. Her expertise in nuclear science at Lawrence Livermore National Laboratory and in policy research at the Center for International Security and Cooperation, Stanford University, combined with her experience in nuclear-policy practice in the Mongolian foreign service, provides her with a unique and useful perspective on current concerns. The views expressed here are the author’s personal opinions and in no way express an official policy of the Mongolian government.
MAKING NUCLEAR POWER SAFER AND LESS PROLIFERATIVE AFTER FUKUSHIMA

Frank N. von Hippel

The Fukushima disaster made obvious some of the safety weaknesses of the General Electric boiling water reactors, including their small-volume containments. This was understood in 1972 within the U.S. Atomic Energy Commission (AEC), before Fukushima Daiichi Units 2 and 3 were licensed for operation and before the construction of Fukushima Unit 4 had even begun. A deputy director of the AEC’s Directorate of Licensing warned, however, that questioning this design “could well be the end of nuclear power. It would throw into question the operation of licensed plants [and] would make un licensable the…plants now under review.” He was later appointed chairman of the U.S. Nuclear Regulatory Commission (NRC). Even today, the majority of the political leadership of the NRC is still reluctant to revisit past decisions.

A potentially more serious consequence of poor design is the way in which current nuclear fuel cycle arrangements, which legitimize national enrichment and reprocessing plants, spread the bomb while spreading nuclear power. As former International Atomic Energy Agency (IAEA) Secretary General Mohamed ElBaradei argued in 2003, we should move toward at least multinational control of such facilities.

If nuclear power is to have a future, it must be made safer and less proliferative. But even if this can be accomplished, the role of nuclear power will be limited during the next few crucial decades, as we try to cap and reduce carbon dioxide emissions, unless we get much more serious about energy efficiency. Global growth of electric-power demand is literally outrunning our ability to build non–fossil fuel capacity, even in China and India where the growth of both total electricity consumption and nuclear power are most dramatic.

In 2008, nuclear power accounted for 13.6 percent of global electric power, down from a peak of about 17 percent in 1999. The IAEA’s projections of nuclear power have historically far exceeded reality, but in its 2011 projection, the IAEA predicts that nuclear power will account for only 6.2 to 13.5 percent of global electric power in 2050. Because of the rapid growth of demand, even this contribution will require global nuclear generating capacity to increase by 50–225 percent. The contribution of renewable energy—still mostly traditional hydropower—also declined between 1999 and 2008, by one percent to 19 percent, despite the rapid growth of wind and biomass energy.

The IAEA projections are based on its survey of national projections for the future of nuclear power, which, in aggregate, have declined by only about 5 percent since the Fukushima Daiichi accident. Many governments still believe in a future for nuclear energy, but it is no longer the dominant future many expected in the 1960s and 1970s.

If nuclear and other nonfossil sources of electric power are to play a more important role in limiting climate change, we must work on the demand as well as the supply side of the energy problem. Our new refrigerators and compact fluorescent bulbs consume one quarter as much power as the devices they replace, but much more is both possible and necessary.

6 Frank von Hippel is a nuclear physicist and a professor of public and international affairs at Princeton University, where he cofounded, in 1975, Princeton’s Program on Science and Global Security; in 1989, the journal Science & Global Security; and, in 2006, the International Panel on Fissile Materials. In the decades before the Fukushima Daiichi accident, von Hippel and coauthors spotlighted and suggested remedies to the dangers of reactor containment overpressure during an accident and the practice of dense-packing spent fuel pools.
FIELD RESEARCH INSIDE THE FUKUSHIMA RESTRICTED AREA

Satoshi Utsunomiya

On March 16, 2012, Ohkuma town, where the Fukushima Daiichi nuclear power plant is located, stood quietly and peacefully, except for workers in tyvek uniforms conducting remediation work and abandoned cows migrating along unused roads. The town appeared the same as usual, except for the absence of residents, some earthquake damage, and high beeping sounds from our survey dosimeter indicating maximum radiation readings greater than 30 μSv/h, even inside our vehicle. I was there with colleagues for a collaborative field study with Japan Atomic Energy Agency and Fukushima University.

Ohkuma town and vicinity are located in the restricted area, that is, within a perimeter of 20 km from the nuclear power plant (Fig. 1). By law, no one is allowed to enter the area without governmental permission. Security checkpoints have been set up on all roads into the area. A total of 78,200 residents were evacuated from the restricted area. Outside the restricted area, a “deliberate evacuation area” was designated, covering mainly Iitate village and Namie town, based on the area of contaminant distribution elongated toward the northwest; 10,550 residents were evacuated. The deliberate evacuation area was established by the government for those areas where the accumulated dose rate was estimated to be >20 mSv/year (Figs. 1, 2). People are not allowed to live in this area or to enter the area except for a quick return home, vehicle transit, or a short-term visit for public services or for business purposes. Although the extent of these areas was revised in April 2012 (Fig. 1), most remain deserted.

Within the restricted area, especially within 3 km of the power plant, the radiation dose increases dramatically. After a few hours of field work in Ohkuma (Fig. 3), the dosimeters on our chests read >90 μSv, which is about one-tenth of the annual dose limit for public exposure, 1 mSv/y, recommended by the International Commission on Radiological Protection. During our field work, the dose rate about 3 km south of the plant was as high as 60 μSv/h at 1 m above the ground. The highest dose rate measured was 630 μSv/h beneath a rainwater pipe at point 1 in Figure 1. Such spotty occurrences of high radioactivity have been recognized at many contaminated sites, but they do not appear on the large-scale maps of contamination.

The scientific challenges at Fukushima include the very low concentrations of radionuclides that must be detected (e.g., even 160,000 Bq/kg of $^{137}$Cs is only equivalent to ~50 parts per trillion), the characterization of the phases associated with each radionuclide, the heterogeneous size distribution of these phases in soils, the large area of contaminated land, and the wide variety of vegetation.

It is sometimes difficult to see how scientific studies can contribute to the mitigation of disastrous and tragic events. Mounting problems sometimes overwhelm us and obscure the scientific goals, but basic science will definitely be important to the strategies developed for restoration at Fukushima. Our group is contributing to the effort by carrying out Cs and Pu analyses in the contaminated area.

Finally, I express my greatest appreciation to Professors Nanba and Kawazu of the University of Michigan and to Messrs. Saito and Suenaga of the Ohkuma municipal government for transporting us to the area near the Fukushima power plant, as they exposed themselves to the same radiation dose as we did (Fig. 4).

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1 Satoshi Utsunomiya has been an associate professor in the Department of Chemistry, Kyushu University, since 2007. He received a PhD from the University of Tokyo in 2000 and worked for the University of Michigan prior to his current position. As a mineralogist and geochemist, he has been studying the migration of radionuclides in the subsurface and other geochemical problems using various nanocharacterization techniques.
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The Earth is a very geologically active planet. Rocks are recycled through erosion, burial, and melting, which makes it difficult to learn about the origin of the Solar System by analyzing samples from Earth. In order to understand the earliest processes in the Solar System, we have to study meteorites—specifically, chondrites, which are over 4.5 billion years old and contain the first solids to have formed in the Solar System. The Solar System formed from a cloud of gas and dust called the solar nebula, and its bulk chemical composition is known because about 99.8% of the mass of the solar nebula ended up in the Sun and we know the Sun’s composition from spectroscopic analysis of its light. From this composition, the sequence of minerals that should form by gas-to-solid condensation at high temperatures from the cooling solar nebula can be predicted. These very minerals, Ca–Al-rich oxides and silicates, can be found in refractory inclusions within carbonaceous chondrites. However, this was scarcely appreciated until the fall of the Allende meteorite in Mexico on February 8, 1969, because until then very little material had been available for study.

Within a few months of the fall, two tons of specimens of the Allende meteorite were recovered from a 50 km long strewnfield, and many specimens were distributed for study. Preliminary reports were published within a year of the fall (e.g. King et al. 1969), and an extensive report on the fall, recovery, and classification was published within two years (Clarke et al. 1970). A view of a slab surface of Allende (Fig. 1) shows that, typical of Cv-type carbonaceous chondrites, the meteorite is a jumble of refractory Ca–Al-rich inclusions (CAIs) and round objects called chondrules set in a dark, carbonaceous matrix. The chondrules and inclusions are not related to each other. Before becoming enclosed in the matrix, they formed individually as discrete objects in space. They have been preserved since the formation of the Solar System because they were incorporated into a parent body that was too small to have a geologically active surface.

At a time when geochemical laboratories were being modernized and equipped in anticipation of the first return of lunar samples, scientists suddenly had several tons of unique, extraterrestrial material to study. Allende provided the material for several important advances, including a classification scheme for refractory inclusions in Type 3 carbonaceous chondrites (Grossman 1975), which is still in use today, and the discovery that the oxygen isotope compositions of refractory inclusions are 18O-rich and do not fall on the terrestrial fractionation line (Clayton et al. 1977). Allende’s inclusions (e.g. Fig. 2) were found to have an average enrichment factor among the refractory elements of 17.5 relative to bulk Solar System abundances (Grossman et al. 1977), strong evidence for their formation at high temperatures. The first refractory inclusions shown to have excess 26Mg due to the decay of 26Al (Gray and Compston 1974; Lee et al. 1976) were from Allende, and the first studies of the distinctive rim layer sequences on refractory inclusions (Wark and Lovering 1977), indicative of processing in the nebula after they formed and before they were enclosed in the meteorite matrix, were also based on Allende samples. In addition, the first report of trivalent Ti in a refractory inclusion was based on the analysis of Ti–Al-rich pyroxene from Allende by Dowty and Clark (1973), who termed the phase “fassaite”; the presence of Ti^3+ is strong evidence for formation under very oxygen-poor (reducing) conditions, as would be expected for a system of solar composition. Note that all of these major breakthroughs in the understanding of refractory inclusions occurred within ten years of the fall of the Allende meteorite. In following years it was shown that CAIs were not simply condensates but that some had been molten at least once (MacPherson and Grossman 1981; MacPherson et al. 1984) or even twice (Simon et al. 2005). The study of
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**Table 1** MINERALS DISCOVERED IN ALLENDE SINCE 2007

<table>
<thead>
<tr>
<th>Mineral Name</th>
<th>Formula</th>
</tr>
</thead>
<tbody>
<tr>
<td>Allendeite</td>
<td>Sc₂Zr₂O₁₂</td>
</tr>
<tr>
<td>Hexamolybdenum</td>
<td>Mo₆Ru₆Fe₂ alloy</td>
</tr>
<tr>
<td>Monipite</td>
<td>MoNiP</td>
</tr>
<tr>
<td>Tistarite</td>
<td>Ti₂O₅</td>
</tr>
<tr>
<td>Davisite</td>
<td>CaScAl₂SiO₆</td>
</tr>
<tr>
<td>Grossmanite</td>
<td>Ca₃Ti₂Si₆O₁₈</td>
</tr>
<tr>
<td>Hibonite-(Fe)</td>
<td>(Fe, Mg)Al₂O₃</td>
</tr>
<tr>
<td>Panguite</td>
<td>(Ti, Al, Sc, Mg, Zr, Ca)₁₄O₃</td>
</tr>
<tr>
<td>Kangite</td>
<td>(Sc, Ti, Al, Zr, Mg, Ca)₁₄O₆</td>
</tr>
</tbody>
</table>

The research that has been done on Allende is far too vast and varied to be adequately summarized in this brief article. Suffice it to say that this meteorite has been a valuable source of pieces to the puzzle of the formation of the Solar System, and it will continue to be one for the foreseeable future.

**REFERENCES**


Dowty E, Clark JR (1973) Crystal structure refinement and optical properties of a Ti⁺⁺ fassaite from the Allende meteorite. American Mineralogist 58: 230-242


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**THE NEW TISSINT METEORITE**

It’s a well-known secret that meteorites fall to Earth all the time, but rarely does such an event happen in a place where people see the fireball and then find space rocks on the ground. July 18, 2011, marks a remarkable event, rare even among meteorite falls—for only the fifth time, a piece of Mars was witnessed to fall to Earth. The fireball and associated sonic booms that marked the rock’s atmospheric entry occurred in Morocco, a fortuitous coincidence for two reasons: many people in Morocco are experienced meteorite hunters, and the arid environment makes it one of the best places on Earth for the preservation of meteorites. Beginning in October, nomads began to find fresh, fusion-crusted stones in a remote area about 48 km from Tissint village, and over 10 kg have been recovered thus far. The meteorite was classified as a shergottite by Tony Irving and Scott Kuehner (University of Washington, Seattle), and its name, Tissint, was approved by the Nomenclature Committee on January 17, 2012 (search “Tissint” at www.lpi.usra.edu/meteor/index.php).

As the freshest fall of a Martian meteorite since 1962, Tissint is currently the subject of intense scientific scrutiny: it is a typical Martian basalt, consisting of olivine phenocrysts in a pyroxene–plagioclase groundmass, with accessory oxides, sulfides, and phosphates. Many (if not all) specimens are crosscut by glassy veins and pockets that formed as a result of shock during an impact on Mars, likely the impact that lofted the meteoroid from the surface of Mars. The shock melt pockets are similar to those in another famous Martian meteorite, Elephant Moraine 79001, in which trapped Martian atmosphere was found, providing the crucial piece of evidence for a Martian origin. But beyond the insights that will be gained into Martian igneous and shock processes, Tissint represents a unique opportunity to test curation and handling methods for future sample return (from Mars or elsewhere). Analyses to determine what contaminants the meteorite picked up in the Moroccan desert are underway, in order to establish a baseline to test whether Tissint preserves any Martian organic matter. Regardless of the outcome, Tissint is sure to become one of the most studied Martian meteorites—at least until the next one falls!

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Joonhong Ahn received doctoral degrees from the University of California, Berkeley (PhD, 1988) and the University of Tokyo (D Eng, 1989). He joined the faculty of UC Berkeley in 1995. His research deals with the performance assessment of advanced nuclear fuel cycles and the geological disposal of radioactive wastes. He led numerous joint research projects with institutions in Japan, South Korea, and the United States, and with the IAEA. He is currently conducting a joint research project with the Japan Atomic Energy Agency involving the analysis of criticality safety for the geological disposal of molten nuclear fuel in the Fukushima reactors.

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Bernd Grambow is a Professor of Excellence at the École des Mines de Nantes, France, where he holds the chair on nuclear waste disposal. He is head of the Subatech laboratory on high-energy nuclear physics, reactor physics and radiochemistry, a joint research unit at the IN2P3/CNRS, the École des Mines of Nantes, and the University of Nantes. He is also director of the new French national CNRS-academic/industrial research network NEEDS (nuclear: environment, energy, waste, society). His scientific expertise is in radiochemistry, nuclear waste disposal science, geochemical modeling, radionuclide migration in the environment, chemical thermodynamics, and the dynamics of solid/liquid interfaces.

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Irène Korsakissok did her PhD thesis in the field of air-quality modeling. Her thesis dealt with multiscale modeling and uncertainties in atmospheric dispersion models. Two years ago, she joined the Institut de Radioprotection et de Sûreté Nucléaire (IRSN), where she is in charge of the local-scale atmospheric dispersion model used for operational purposes. She also works on local-scale meteorological preprocessors and model uncertainties.

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Anne Mathieu has been a research engineer at the IRSN for six years. After a PhD on the dynamics of the atmospheric boundary layer, she became an assistant professor at the Université Saint-Quentin en Yvelines. She joined the IRSN to work on local- and large-scale atmospheric dispersion during accidental releases. Her current work focuses on the development of methods for the reconstruction of accidental releases using environmental observations.

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Denis Quéro has been a research engineer at the IRSN for five years. After a PhD in data assimilation of atmospheric chemistry, he joined the IRSN to develop an operational, large-scale atmospheric-dispersion model. His current work centers on impact studies related to accidental releases from nuclear facilities.

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Yoshio Takahashi is a professor of environmental geochemistry at Hiroshima University, Japan. In 1997, he received his PhD in environmental radiochemistry from the University of Tokyo. He then became a research associate in the Department of Earth and Planetary Systems Science at Hiroshima University and became a full professor in that department in 2009. His research interest is primarily in speciation studies applied to environmental chemistry and geochemistry to understand the fates of contaminants, geochemical cycles, and the evolution of the Earth. He is currently participating in a project on the migration of radionuclides emitted during the accident at the Fukushima Daiichi nuclear power plant.

Daisuke Tsumune is a senior research scientist at the Central Research Institute of the Electric Power Industry, Japan. He received a master’s degree and a PhD from Tohoku University, the latter on oceanic transport processes of artificial radionuclides originating from global fallout due to atmospheric weapons testing. His current research interests include tracer distribution and the transport mechanism of tracers, such as carbon, in the ocean; iron as a micronutrient; and artificial radionuclides originating from global fallout and from the Fukushima Daiichi accident. His goal is a better understanding of the role of oceans on climate and an assessment of oceanic pollution at the global scale.

Naohiro Yoshida is a professor in the Department of Environmental Chemistry and Engineering, a vice-director of the Inter-Departmental Organization for Environment and Energy, and an assistant vice-president at the Tokyo Institute of Technology. He is also the president of the Geochemical Society of Japan. He introduced the use of isotopomers, isotopic substituted molecules, as powerful tracers in the study of the cycles of materials of biogeochemical interest from the early Earth to present and future global change, life and biomedical diagnosis. He is currently involved in an intensive survey of radionuclide dispersal from the Fukushima Daiichi nuclear power plant.
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Elemental distribution for the examples mentioned above is easily displayed in an intensity format, and normally this would provide the required answer to the common question, “What is it?” But if concentration resolution is required, the operator may run into some trouble. How do you calibrate for a stain? What reference materials are readily available for a metal inclusion in a wire? How do you quantify components on a circuit board without removing them? This is where the second step to total small-spot analysis comes into play—UniQuant.

Small Spot/Mapping Description

Small-spot analysis is a rather easy concept to describe. The first step is for the XRF unit to image the sample surface. From this image it is possible, using the mouse, to click on areas of interest for analysis. For mapping, the operator selects one of a number of “shapes” and enlarges or contracts it to a size that best contains the area of interest. The sample is excited through the use of a primary X-ray beam. The secondary X-rays emitted are collimated through a 0.5 mm aperture. Small-spot analysis is a selection of one or more unique and individual points on a sample surface, each one producing a singular analytical result, whereas mapping is the joining of these individual points into a unified pattern to produce a 2- or 3-dimensional presentation along with intensity/concentration results for the selected area.

UniQuant Description

UniQuant uses the original factory calibration to determine concentrations in completely unknown samples. UniQuant is unique in its method of intensity measurements. Unlike other semiquantitative software programs, UniQuant uses a method known as peak hopping, instead of a continuous scan technique, to acquire the intensities for all measurable elements. The procedure of peak hopping allows for faster analysis by not wasting measurement time on any location where an element peak will not be found. UniQuant will measure every theoretical 2-theta angle for each element, including alternative lines for some heavier elements and background positions. By focusing the elemental counting times on peak locations only, UniQuant is able to provide more accurate results and lower detection limits compared to other scan-based semiquantitative methods. An interesting feature is that the counting time for each analytical line can be defined separately depending on the main interest of the analyst.

Mapping Example: Mapped Elements in a Geological Sample

Mapping imaging is a helpful way of better understanding a problem. The 2-D images can be viewed as individual element distributions or overlaid to give a more comprehensive correlation of the elements as a group. The 3-D images are single-element displays and can be rotated for a full 360-degree visualization or even a birds-eye view. While most maps are collected as intensity-only images, empirical calibrations can also be used to fully quantify the result. Geological samples can offer the most interesting and informative mapping images. In this example, one can see that the material is mostly Mn due to its uniform base and strong intensity response, but other elements are also present, with a large concentration of Si off to one side and the possible presence of a vein containing Ca, S, and P running through the center of the sampled area.

Conclusion

The examples presented here are only a fraction of the applications that many analysts are using today. The investigative capabilities of WDXRF have been shown to save thousands of dollars in process monitoring. With UniQuant, small samples are no longer a hindrance due to their size and a lack of calibrated materials. It is now possible to review coating thickness across a surface without the need of specialized instrumentation. Quantification using empirical calibrations on undersized or irregularly shaped materials is possible through the use of a standard laboratory WDXRF, even in situ. Mapping/small-spot analysis brings many benefits especially when combined with a standardsless routine such as UniQuant.

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Mapping the world ... one micron at a time

ultrafast contextual quantitative
SEM-based Petrographic Analyzers

Uranium ore from the Schwarzwalder Mine, in Ralston Buttes district, Jefferson County, Colorado, USA, mapped by QEMSCAN®. The image shows an atoll-like texture with veins mineralized by uranium-thorium (red), and lead (green) bearing phases.
This thematic issue of *Elements* describes the events at the Fukushima Daiichi nuclear power plant on March 11, 2011, and the aftermath.

**Keywords:** Tohoku earthquake, tsunami, nuclear power plant, meltdown, radioactivity

In the wake of a rare 9.0-magnitude earthquake, a devastating tsunami, and the partial meltdown of the cores of the three nuclear reactors then operating, there were some 300,000 refugees displaced from their homes, fully one-third of whom were in the 20 km radius evacuation zone around the Fukushima Daiichi nuclear power plant. The three nuclear reactors have been stabilized and cooling reestablished, but huge volumes of water, contaminated by radioactivity, require treatment and disposal. In the absence of domestic sources of fossil fuels, Japan has relied on substantial imports of coal and natural gas to generate electricity. Prior to March 11, the 54 operating nuclear reactors provided approximately one-quarter of Japan’s electricity. Following the events at Fukushima Daiichi, more than half of Japan’s nuclear reactors were shut down due to safety or service concerns, and all were subjected to government-mandated stress tests. However, it has proven difficult, due to public and political objections, to bring the reactors back on line, and in May 2012, the last operating nuclear reactor, located at the Tomari plant in northern Japan, was shut down for a scheduled inspection.

For the first time since 1966, Japan is not producing electricity from nuclear power plants as it enters a period of peak demand for electricity. There has also been a major review of the wisdom and cost of the Japanese closed fuel cycle, which embraces reprocessing, and it now appears that direct disposal of spent fuel in a geologic repository may be considerably cheaper. The great Tohoku earthquake has certainly shifted the ground under the future of nuclear energy in Japan, and the seismic waves of change have spread across the globe.

This issue of *Elements* arrives on your desk some months past the first-year anniversary, March 11, a date of thoughtful remembrance for those who lost their lives. The anniversary was also the occasion for many magazine and journal “special” issues that looked back at the details of the accident at the nuclear power plant. We have moved this issue of *Elements* beyond the clatter and noise of the first anniversary, because in this issue we summarize the impact of the accident on the environment, and this impact will stretch far into the future, well beyond many anniversaries. This issue begins with two papers that set the stage. The first is on the natural disaster of the earthquake and tsunami, and the second is on the technological disaster of the meltowns at the three nuclear reactors operating at the time. The next four articles deal successively with the dispersion of radioactivity into the atmosphere, the contamination of the surrounding countryside, the release of radioactivity to the ocean, and finally, the interactions of the damaged and melted fuel with water and the long-term release of radioactivity. We have also added an expanded Perspectives section, in which a diverse group of scientists and engineers with some connection to the event and its aftermath discuss the impact of this accident on the future of nuclear power. Two “boxes” provide basic information on the properties of spent fuel (Box 1) and units of radioactivity (Box 2).

As we reviewed the papers for this issue, one word, “accident,” caused us to pause and wonder if “accident” was the term for this “Black Swan” event, a rare, unanticipated event of high consequence. In what sense was the natural disaster and catastrophic failure at the Fukushima Daiichi nuclear power station an “accident”? Certainly, it was the forces of nature, the one-two punch of an earthquake and tsunami, that damaged the nuclear power plant, leading to loss of cooling and the subsequent meltdown of the nuclear reactors. But was this an accident? An accident is an “unexpected” event or “unfortunate occurrence or mishap.” Certainly, the tsunami was “unexpected” and “unfortunate,” but was it just bad luck that the seawall was too low or that the risk analysis failed to anticipate the size of a potential tsunami? Who bears the responsibility for failing to anticipate the scale and impact of this natural disaster? We now know that a tsunami of such size is rare, but it should not have been unanticipated. In fact, Japanese geoscientists warned of such a possibility in a paper published in 2001 in the *Journal of Natural Disaster Science*, and they pointed to a similar tsunami event—the Jogan tsunami of 869—that inundated the low-lying coast of northeastern Japan. We do not think we should find any solace in calling the March 11 event an accident, because in doing so, we relieve scientists and engineers of their responsibility to raise the appropriate warnings and absolve regulatory agencies for not listening to those warnings. A better word for the event of March 11 one year ago is “tragedy,” as in a Greek drama—a drama in which our *hubris* leads to a loss of contact with reality and to overconfidence in our competence and capabilities. A less confident person would have built a higher seawall.

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The amount of released radioactivity during a nuclear accident depends on the type of nuclear fuel, the burnup or the extent to which the $^{235}$U has fissoned, the chemical properties of the radionuclide-forming compounds in the fuel, and the maximum temperatures reached during the accident. The melting of the fuel in an operating or recently shut down nuclear reactor is due to a failure in the ability to cool the reactor core. Immediately after removal from a reactor core, fuel still generates several megawatts of power per tonne of fuel. Even after the fission process in the core is stopped by the insertion of neutron-absorbing control rods, radioactive decay of fission product elements continues to generate substantial amounts of heat. The decay heat can drive the temperature to well above the melting points of the metallic zircaloy cladding and the UO$_2$ fuel pellets, creating a corium magma.

At the Fukushima Daiichi nuclear power plant, the fuel was dominantly UO$_2$ enriched to about 3 to 5% in the fissile nuclide $^{235}$U. There was a limited amount of mixed-oxide fuel (MOX), which is a mixture of UO$_2$ fuel and ~6% PuO$_2$. The 32 MOX fuel assemblies in Unit 3 represented only ~6% of its core loading. In the reactor, the fission of $^{235}$U and $^{239}$Pu leads to a bimodal distribution of hundreds of fission product elements, e.g. $^{90}$Sr and $^{137}$Cs, from the “split” uranium atoms. In contrast, the more stable $^{238}$U captures neutrons and, with subsequent decay, creates heavier, transuranium elements, such as $^{239}$Pu, $^{239}$Np, and minor amounts of Am and Cm isotopes. The concentration of plutonium in UO$_2$ fuel typically reaches a value of approximately 1% Pu for average burnups. Thus, most of the Pu present at the Fukushima Daiichi plant was in the normal UO$_2$ fuel in the reactors and spent fuel storage pools, as compared with the amount of Pu in MOX.

Although hundreds of radioactive isotopes are created by the fission process, most have extremely short half-lives. The isotopes of greatest interest are those that are most quickly released and have half-lives of days to years, as they will be responsible for the immediate doses to surrounding populations: $^{131}$I (half-life = 8 days), $^{134}$Cs (2 years), $^{137}$Cs (30 years), and $^{85}$Sr (29 years). Longer-term environmental effects will be determined by radionuclides with much longer half-lives, but with correspondingly lower specific activities (the specific activity is inversely proportional to the half-life): $^{129}$I (15.7 million years) and $^{135}$Cs (2.3 million years). Other isotopes and their ratios provide the forensic evidence of what is happening in the core of the reactor. The $^{134}$Cs/$^{137}$Cs ratio can be used to estimate the fuel burnup. Other radionuclides, such as selected isotopes of the noble gases Xe and Kr with very short half-lives of a few days or, in the case of $^{85}$Kr, 11 years, are monitored carefully because they provide information on the state of the reactor core, such as whether recriticality has occurred. The fission product gases, such as Xe and Kr, and more volatile elements, such as Cs and I, provide a measure of the extent of the early release of radioactivity.

The chemical form of the fission product elements in the fuel will determine the ease and extent of their release. The fission product elements may be grouped into four broad types of materials: volatile elements, metallic alloys, oxide precipitates, and radionuclides incorporated into the UO$_2$ structure. The distribution of the radionuclides is not uniform because of the steep thermal gradient (~1000 °C) between the center of the fuel pellet and its edge, a distance of some 5 mm. The volatile elements are driven down the thermal gradient to grain boundaries and the “gap” between the fuel cladding and the fuel pellet. Noble gases form bubbles that decorate the surfaces of the grain boundaries and occupy the cladding gap. When there is a breach of the fuel cladding at high temperature, there is an instantaneous release of the noble gases (Xe and Kr) and more volatile elements (I and Cs). The transuranium elements, mainly Pu, are released much more slowly, because they are incorporated into the fuel. However the distribution of Pu is not uniform within the fuel pellet, the Pu being more concentrated at the edge of the pellet due to enhanced neutron capture in this region.

Based on experiments and the examination of damaged core material from nuclear accidents, such as the Three Mile Island meltdown, the early release of the noble gases Xe and Kr is high (~90%), of I is high (50 to 100%), of Cs is moderate (10 to 50%), of Sr and Ba is much lower (<10%), and of the transuranium elements very low (<0.01%). Of course, a catastrophic explosion can lead to substantially higher releases due to atmospheric distribution of particulate fuel. In the case of Chernobyl, these “hot particles” spread across Europe. The hydrogen explosions at Fukushima Daiichi apparently did not release particles of the fuel. During a nuclear accident and immediately afterwards, the radionuclides of greatest interest are the short-lived isotopes of Xe, Kr, I, and Cs. However, the much longer-term environmental impact and cumulative human exposure will depend on the fate of longer-lived nuclides, such as $^{129}$I and $^{135}$Cs, long after the decay of shorter-lived $^{131}$I and $^{137}$Cs.

### Box 1

**RADIONUCLIDE RELEASE DURING A NUCLEAR ACCIDENT**

Rodney C. Ewing

The amount of released radioactivity during a nuclear accident depends on the type of nuclear fuel, the burnup or the extent to which the $^{235}$U has fissoned, the chemical properties of the radionuclide-forming compounds in the fuel, and the maximum temperatures reached during the accident. The melting of the fuel in an operating or recently shut down nuclear reactor is due to a failure in the ability to cool the reactor core. Immediately after removal from a reactor core, fuel still generates several megawatts of power per tonne of fuel. Even after the fission process in the core is stopped by the insertion of neutron-absorbing control rods, radioactive decay of fission product elements continues to generate substantial amounts of heat. The decay heat can drive the temperature to well above the melting points of the metallic zircaloy cladding and the UO$_2$ fuel pellets, creating a corium magma.

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### Box 2

**UNITS OF RADIOACTIVITY, DOSE AND REGULATORY LIMITS**

<table>
<thead>
<tr>
<th>Unit*</th>
<th>Symbol</th>
<th>Conversion factors</th>
</tr>
</thead>
<tbody>
<tr>
<td>Becquerel (SI)</td>
<td>Bq</td>
<td>1 disintegration/s = 2.7 × 10$^{-11}$ Ci</td>
</tr>
<tr>
<td>Curie</td>
<td>Ci</td>
<td>3.7 × 10$^{10}$ disintegrations/s</td>
</tr>
<tr>
<td>Gray (SI)</td>
<td>Gy</td>
<td>1 J/kg = 100 rads</td>
</tr>
<tr>
<td>Rem</td>
<td>rem</td>
<td>0.01 Sv</td>
</tr>
</tbody>
</table>

* International units are designated SI

**BIBLIOGRAPHY** (in order of increasing detail)


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**Elements**

June 2012
Rapid seismological analyses, carried out within minutes of the March 11, 2011, Tohoku earthquake, were crucial in providing an earthquake ground shaking and tsunami early warning and in hastening the evacuation of the population along Japan’s northeastern coast. By 20 to 30 minutes after fault rupture began, these analyses had established that the event had a moment magnitude of $M_w = 9$ and involved shallow thrust faulting on the plate boundary megathrust. Preparation for future large earthquakes on megathrusts in Japan and elsewhere should include onshore and offshore geodetic monitoring of strain accumulation, implementation of rapid earthquake and tsunami warning systems, and public training and education for shaking and tsunami response.

KEYWORDS: Japan earthquake, megathrust, tsunami, earthquake early warning, rupture process

INTRODUCTION

The March 11, 2011, earthquake offshore from the Tohoku region of Japan ruptured a 300 km long by 200 km wide portion of the subduction zone megathrust fault at the boundary of the Pacific plate (Fig. 1). It was the fourth-largest recorded earthquake. The seafloor movement caused by the faulting generated a huge tsunami that devastated communities along the entire northeastern coast of Japan. Unprecedented video footage documented the imposing power of the ocean waves as they overtopped tsunami walls and coastal barriers, sweeping away entire towns. Flooding of the Fukushima Daiichi nuclear power plant led to a nuclear crisis that is still unfolding. The Tohoku earthquake and tsunami claimed some 20,000 lives. Many more lost their homes and livelihood, and economic losses are expected to reach $300 billion.

While devastating, the Tohoku earthquake resulted in societal impacts and a scientific response that were much different from those of the 2004 Sumatra-Andaman earthquake. The Sumatra-Andaman earthquake had a moment magnitude, $M_w$, of 9.2 and was due to the rupture of the subduction zone megathrust in southeastern Asia. It generated a massive tsunami that struck Sumatra, Sri Lanka, India, and Thailand, taking over ten times more lives than the Tohoku tsunami. No country around the Indian Ocean was prepared for such a large tsunami, and few warnings were issued, even for regions where the tsunami did not arrive until several hours after the earthquake. In contrast, seismological analysis of the 2011 Tohoku event commenced only seconds after the first ground vibrations were recorded at stations in Japan and around the world. While the rupture was still expanding (it took about 150 seconds for fault motions to complete), preliminary seismic wave analyses in an early warning system had established that a great earthquake of magnitude ~8 had occurred offshore from Honshu. Much of the well-prepared population began to evacuate after the initial tsunami warnings were issued. Predictions of potential tsunami run-up height (the maximum onshore water height) along the coast ranged up to 6 m, much lower than the actual values of up to 40 m, but the early tsunami warning broadcasts likely saved many lives.

By the time the tsunami hit the shores of northern Honshu about 15–30 minutes after the faulting began, the earthquake size had been estimated at $M_w = 8.8$ by the National Oceanographic and Atmospheric Administration (NOAA) Pacific Tsunami Warning Center (PTWC) and $M_w = 9.0$ by the U.S. Geological Survey (USGS) National Earthquake Information Center (NEIC) from analysis of seismic recordings in the western Pacific region. The fault geometry solutions clearly indicated that the Tohoku earthquake had occurred on the plate boundary megathrust and that a potentially devastating tsunami had likely formed. On the basis of rapid earthquake quantification, the PTWC issued accurate warnings for Pacific nations to be alert for significant tsunami waves over the next 24 hours.

The rapid earthquake analyses in Japan were enabled by the substantial investments in infrastructure for earthquake monitoring that followed the destructive 1995 Kobe earthquake. An extensive network of recently deployed geophysical instruments recorded the Tohoku earthquake both onshore and offshore. This network includes 1200 continuously recording GPS sensors in Japan (Sagiya et al. 2000; Ozawa et al. 2011), several dozen tide gauges and seafloor pressure sensors around Japan (Sato et al. 2011), NOAA’s DART buoy network in the Pacific (expanded after the 2004 tsunami), and thousands of seismometers in regional and global seismic networks. Near real-time telemetry of the seismic and ocean-wave data was essential for the rapid determination of the location and magnitude of the Tohoku earthquake and for direct measurements of the

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1811-5209/12/0008-0183$2.50 DOI: 10.2113/gselements.8.3.183
tsunami amplitudes near Japan and across the Pacific. Indeed, the Tohoku earthquake is by far the best scientifically recorded great earthquake to date, and it will be the best studied. A number of expert reports and over 100 reviewed scientific publications on the Tohoku earthquake have already appeared in major journals, including special issues of *Earth, Planets and Space* and *Geophysical Research Letters*.

Several agencies conduct seismological analysis to report earthquake epicenters, depths, and magnitudes in near real-time. In Japan, earthquake early warning (EEW) is one of the main responsibilities of the Japan Meteorological Agency (JMA). The aim of EEW is to rapidly locate earthquakes and estimate magnitudes using 1100 stations in the JMA seismic network and stations from the Hi-net network of the Japan National Research Institute for Earth Science and Disaster Prevention. On the basis of the analysis, the JMA is mandated to warn the public of the potential for strong ground shaking and tsunami.

The USGS NEIC is mandated to rapidly evaluate all significant global earthquakes (Hayes et al. 2011). The PTWC is responsible for issuing tsunami warnings after major earthquakes have occurred in the Pacific Ocean. Coordination among the JMA, PTWC, and NEIC is intended to ensure that consistent information is released to emergency responders. A timeline of the response to the Tohoku earthquake by these agencies is summarized in Table 1.

Hoshiba et al. (2011) and Ozaki (2011) describe the EEW sequence following the Tohoku earthquake. The EEW system was triggered at 14:46:40.2 Japan Standard Time when the primary (P) wave was recorded by the closest seismograph. Fifteen “forecasts” followed with updated information. After 5.4 seconds, the magnitude was estimated to be only 4.3, which is consistent with later determinations that the Tohoku earthquake began as a small, magnitude 4.9 earthquake (Chu et al. 2011). About 8 seconds after the trigger, the magnitude was updated to 7.2, and seismic intensity was predicted to be “5-lower” for the central Miyagi prefecture. In the fifteenth update, 116.8 seconds after the trigger, the EEW magnitude was estimated to be 8.1. This magnitude is at the upper limit of the JMA EEW magnitude scale because the short-period seismic instrumentation that the JMA relies on had gone off-scale. Nevertheless, within two minutes after the main trigger, it was clear that a major earthquake had occurred off the Pacific coast of Tohoku. Intensities of “6-upper” and “6-lower,” which are equivalent to ground accelerations of

### Table 1: The First Hour

<table>
<thead>
<tr>
<th>Time after detection</th>
<th>Source</th>
<th>Magnitude</th>
<th>Remarks</th>
</tr>
</thead>
<tbody>
<tr>
<td>5.4 sec</td>
<td>JMA/EEW</td>
<td>4.3</td>
<td>The first estimate</td>
</tr>
<tr>
<td>8.6 sec</td>
<td>JMA/EEW</td>
<td>7.2</td>
<td></td>
</tr>
<tr>
<td>116.8 sec</td>
<td>JMA/EEW</td>
<td>8.1</td>
<td>Final update and tsunami bulletin</td>
</tr>
<tr>
<td>2½ min</td>
<td>JMA (M)</td>
<td>7.9</td>
<td>The rapid JMA magnitude</td>
</tr>
<tr>
<td>9 min</td>
<td>PTWC</td>
<td>8.1</td>
<td>First tsunami bulletin</td>
</tr>
<tr>
<td>19 min</td>
<td>NEIC</td>
<td>7.9</td>
<td>Coordinated with JMA and PTWC</td>
</tr>
<tr>
<td>20 min</td>
<td>NEIC W-phase</td>
<td>9.0</td>
<td>Internal release only, limited data</td>
</tr>
<tr>
<td>22 min</td>
<td>PTWC W-phase</td>
<td>8.8</td>
<td>First internal release; assumed event depth of 84 km</td>
</tr>
<tr>
<td>33 min</td>
<td>rCMT (Polet and Thio 2011)</td>
<td>9.0</td>
<td>Internal release only</td>
</tr>
<tr>
<td>38 min</td>
<td>NEIC/PTWC</td>
<td>8.8</td>
<td>Coordinated update, public release</td>
</tr>
<tr>
<td>62 min</td>
<td>NEIC W-phase</td>
<td>8.9</td>
<td>Final automatic solution</td>
</tr>
</tbody>
</table>

JMA = Japan Meteorological Agency, EEW = earthquake early warning, PTWC = Pacific Tsunami Warning Centre, NEIC = National Earthquake Information Center, rCMT = rapid centroid-moment tensor

### Geophysical Investigations of the Tohoku Earthquake

Analyses of the Tohoku earthquake had two key stages: (1) near-real-time analysis of seismograms for first-order earthquake parameters and (2) integrated investigations of all geophysical recordings of the Tohoku earthquake and tsunami, foreshock and aftershock sequences, and field reconnaissance of ground shaking and tsunami impacts.

### Real-Time Analysis and Earthquake Warning

Rapid seismic analysis is primarily based on automated procedures that estimate the location of rupture initiation, the earthquake magnitude, and the faulting mechanism. The near real-time processing of information evolves as the rupture grows, and frequent revisions are made as recordings lengthen and new seismic data become available. Very rapid analysis of the earliest seismic arrivals is crucial for immediate response to strong ground shaking and tsunami danger.

![Map of the 2011 Tohoku earthquake region. The map shows aftershocks from the NEIC catalog, with depth less than 50 km, that occurred between March 11, 2011, and March 31, 2011. The three green contours indicate the 2011 rupture zone, with fault slip exceeding 1 m, 10 m, and 20 m, respectively (Yue and Lay 2011). The yellow and red patches indicate rupture zones related to previous large earthquakes. There is uncertain earthquake potential in the region outlined by purple dots (the possible “slip deficit zone”). The arrow indicates the direction of movement of the Pacific plate. Prefecture names are shown along the right side of the map, opposite their actual locations. M = magnitude](image-url)

![Figure 1](image-url)
The most rapidly produced long-period solution for the Tohoku earthquake is indicative of the spatial extent and the amount of slip on the earthquake. The Tohoku earthquake indicates the orientation of the fault and the strength and characterizations of the centroid-moment tensor (CMT) method developed in the early 1980s (Dziewonski et al. 1981) and differ primarily in the types of waveform data that are analyzed.

The CMT method relies on an initial estimate of the earthquake origin time, location, and depth obtained from, for example, the NEIC, PTWC, or JMA. The CMT analysis yields a point-source moment tensor. Moment tensor solutions for most earthquakes (including the solution for the Tohoku earthquake) are consistent with “double-couple faulting” in which the earthquake represents shear sliding along a planar fault. The moment tensor indicates the orientation of the fault and the strength and direction of shearing motion on the fault. The Tohoku moment tensor solution (Fig. 2) is consistent with slip on the interface between the subducting Pacific plate and the Okhotsk plate. The size of the earthquake is quantified by the seismic moment, $M_0$, and the moment magnitude, $M_w$ ($M_w = 2/3 \log_{10} M_0 - 9.1$). The seismic moment, $M_0$, of the Tohoku earthquake is estimated to be $4.3 \times 10^{22}$ N⋅m (newton meter), which gives $M_w = 9.0$. The seismic moment is indicative of the spatial extent and the amount of slip on the fault plane (and hence the deformation of the seafloor).

The most rapidly produced long-period solution for the 2011 Japan event was based on analysis of the W phase (Fig. 3), the earliest very long-period signal in a seismogram (Kanamori 1993). Typically, the W phase has lower amplitude than the later surface-wave signals, but it is well recorded for moderate and large ($M_0 > 6.5$) earthquakes. W phase analysis is particularly suited for rapid determination of the earthquake moment tensor because only a few minutes of recording are needed. Moreover, the analysis can be conducted automatically because the propagation of the W phase is accurately modeled using standard seismic models (Kanamori and Rivera 2008).

Automated W phase analysis was running at three institutions: (1) the USGS NEIC, (2) the NOAA PTWC, and (3) the Institut de Physique du Globe de Strasbourg. A robust W phase moment tensor for the Tohoku earthquake was computed 22 minutes after the earthquake origin time using the initial PTWC earthquake depth estimate and waveform data for 29 channels (Duputel et al. 2011) (Table 1). This solution provided an estimate of the moment magnitude, $M_w = 8.8$. This was upgraded to $M_w = 9.0$ after the source depth estimate was revised from 84 km to 24 km and additional waveform channels became available.

Other rapidly available long-period solutions include the rCMT solution (Polet and Thio 2011), which was determined 33 minutes after the Tohoku earthquake and was based on the analysis of slightly longer segments of long-period seismograms. The Global CMT (gCMT) solution (www.globalcmt.org) was published after analysis of 9-hour-long recordings of multiple-orbit surface waves.

The long-period seismic wave solutions indicated that the Tohoku earthquake was a thrust earthquake at shallow depth, with $M_w = 8.8$ to 9.1. Differences in estimated moment magnitude are due to differences in the types of seismic signals analyzed, the assumed earthquake depth, and estimates of the fault dip angle (Kanamori and Given 1981). Nevertheless, all solutions are consistent with the very first W phase solution, which had clearly established the potential for a large tsunami.

### Spatial Extent and Complexity of the Tohoku Earthquake Rupture

In the days and weeks following the earthquake, geophysicists further used a variety of available data to develop models of space–time slip on the fault plane that could be compared to previous large earthquakes in the region. This type of detailed earthquake rupture analysis advances our understanding of earthquake processes and the influence of prior ruptures. This contributes to the long-term assessment of the earthquake hazard in northeastern Japan and to preparations for future large events.

Finite-fault analysis resolves the spatial extent of the earthquake rupture and the variable slip distribution on the fault plane. Rapid analysis of finite faulting using seismic and geodetic data is now common and was applied by several groups to the Tohoku event (e.g. Hayes 2011; Lay et al. 2011; Shao et al. 2011; Simons et al. 2011). Quickly determined solutions are usually rather variable from...
The 1896 Meiji-Sanriku earthquake (magnitude 7.4) slipped over a 300 × 200 km² region of the fault offshore from Fukushima, Ibaraki, and Sanriku. The slip-distribution maps in short-period radiation came from the regions of largest slip in a down-dip region from the epicenter. Little-coherent records showed that high-frequency seismic waves were generated by differences in seismic radiation. Koper et al. (2011) estimated that the slip on the fault plane was variable and accompanied ever larger earthquakes. The main characteristics of the Tohoku rupture are now in models. The main characteristics of the Tohoku rupture are now in models. However, as they depend on data coverage and modeling assumptions, and it often takes some time for a consensus to develop on the best representation of the rupture process of a great earthquake.

The main characteristics of the Tohoku rupture are now similar in most published finite-source models (Fig. 4). The rupture duration was about 150 s, which is relatively short for an Mw 9 earthquake. The earthquake nucleated offshore from the Miyagi-oki area and involved large slip in the up-dip region near the trench and smaller slip in the regions offshore from Fukushima, Ibaraki, and Sanriku. Slip exceeded 1 m over a 300 × 200 km² region of the fault plane, with average values of 15–20 m. The largest slip is estimated to be 40–60 m, by far the largest earthquake slip ever reported.

The slip on the fault plane was variable and accompanied by differences in seismic radiation. Koper et al. (2011) showed that high-frequency seismic waves were generated in a region down-dip from the epicenter. Little-coherent, short-period radiation came from the regions of largest slip near the trench. The slip-distribution maps in Figure 4 provide a good match to the seismic, geodetic, and tsunami data. In particular, large shallow slip near the trench is required by the arrival time and narrow pulse of the tsunami at nearby deep-ocean pressure sensors (Fujii et al. 2011; Yamazaki et al. 2011) and by the timing of the onset of ground deformation in Japan as recorded by high-resolution GPS recordings (Yue and Lay 2011). The models also can account for large seafloor offsets measured by several independent procedures. Koketsu et al. (2011) demonstrate how many seismic and geodetic data can now be reconciled with similar models.

**PERSPECTIVES**

Although Japan has a long and well-documented history of large earthquakes and tsunamis, the 2011 Tohoku earthquake was much larger than any known earthquake during the past 1100 years. Given the lack of historical earthquakes of this size, the Mw 9 Tohoku earthquake caught most seismologists by surprise.

Earthquakes offshore from Honshu during the past century had estimated seismic magnitudes lower than 8.5 (Fig. 1). Among the largest earthquakes in the northern part of Japan were the 1968 Tokachi-oki (off the Tokachi coast) and 1994 Sanriku-Haruka-oki earthquakes. Off the Sanriku coast, the largest earthquakes occurred in 1896 and 1933 (Fig. 1). The 1896 Meiji-Sanriku earthquake (magnitude 8.2–8.5) was a thrust-faulting event at the northern end of the Tohoku earthquake zone that ruptured the shallow portion of the plate interface (Tanioka and Satake 1996). This was a “tsunami” earthquake according to the definition of Kanamori (1972), with strong tsunami generation as compared with the surface-wave seismic magnitude. The 1933 earthquake (magnitude ~8.3) involved extensional faulting in the bending oceanic lithosphere (Kanamori 1971). An earlier, large, tsunami-generating event, the 1611 Keicho earthquake, has poorly constrained magnitude and location, but appears to have been near the 1933 event.

Before the Tohoku earthquake, the seismic risk in Japan had been perceived as highest in the off-coast region of Miyagi, south of Sanriku. Here, a number of earthquakes with a magnitude of 7 or greater occurred in 1933, 1936, 1978, and 2005. The March 9, 2011, foreshock of the Tohoku earthquake occurred seaward of this zone. The roughly 30–40-year intervals separating these earthquakes formed the basis for the proposed relatively high seismic risk in the region, although it is not clear that these earthquakes are repeating events (Kanamori et al. 2006). The 869 Jogan earthquake is the oldest and largest earthquake in the region. It left a record of tsunami deposits on the Sendai Plain (Abe et al. 1990; Minoura et al. 2001; Sawai et al. 2008). Numerical simulations of tsunami run-up and inundation suggest that the 869 event had a magnitude of ~8.5 and that it was located up-dip from the Miyagi-oki events, but possibly not extending all the way to the trench (Satake et al. 2008). Known earthquakes with magnitudes between 7.1 and 7.8 that occurred in 1938 offshore from Fukushima and Ibaraki prefectures were studied by Abe (1977). There is no tsunami or seismic record of earthquakes in the region prior to the 1938 sequence.

The Tohoku earthquake ruptured across almost the entire width of the plate boundary megathrust, and the rupture extended from north of the Miyagi-oki ruptures to south of the Fukushima-oki region that ruptured in 1938 (Fig. 1). The rupture encompassed the likely area of the 869 event, but extended to the trench with large slip, similar to the 1896 rupture to the north. Thus it appears that the 2011 Tohoku event broke several adjacent portions of the megathrust that had previously failed in more localized ruptures (Lay and Kanamori 2011).

The study of older earthquakes off Honshu is primarily based on analyses of tsunami records and deposits. Such analyses are uncertain and have tended to play a secondary...
role in assessing the seismic risk in the region. Nevertheless, tsunami heights related to previous large earthquakes provided valuable guidance on the potential inundation and tsunami height of the Tohoku earthquake (Mori et al. 2011; EERI 2011), although the high run-up of the Tohoku tsunami had a much wider spread (Fig. 5). The maximum run-up height of the Tohoku tsunami was 39.7 m at Miyako. The historical records of maximum run-up height are 38.2 m for the 1896 Meiji Sanriku tsunami and 28.7 m for the 1933 Showa Sanriku tsunami. Deposits of the Keicho tsunami of 1611 have mostly been erased by human activity, but Hatori (1975) suggested that 6 to 8 m high tsunamis devastated the Sendai Plain and northern Fukushima areas. Tsunami deposits in the Sendai Plain associated with the 869 Jogan earthquake extend 1–3 km inland (1 km from the present coast) (Abe et al. 1990; Minoura et al. 2001).

There is no evidence that large earthquakes had occurred prior to 1938 along the Japan Trench east of Fukushima and Ibaraki prefectures. This region slipped in 2011, but probably less than 10 m or so. Allowing for 8 cm/year of convergence, there could be a significant "slip deficit" in this region if no other earthquakes occurred in the past 1000 years (Fig. 1). There is thus some concern for another large event in the future. The potential for this depends on the nature of strain accumulation in the region. While Japan has an extensive network of GPS ground-motion instruments, and these revealed that strain was accumulating in the mainland in Fukushima, but less so near Boso to the south (e.g. Suwa et al. 2006; Hashimoto et al. 2009), it is unclear whether there is still earthquake potential in this region. Japan has led the world in developing technology to monitor offshore deformation, and this will be particularly valuable for assessing the nature of strain accumulation along the megathrust south of the region of large slip in 2011. This is a costly and technically challenging endeavor. However, the important observations of seafloor deformation after the Tohoku earthquake in the Miyagi region (Sato et al. 2011) motivate long-term data acquisition, as these would have helped to recognize the potential for an earthquake as large as the Tohoku event.

Earthquake risk assessment is notoriously complicated because only a very short earthquake record is available. The Tohoku earthquake experience shows how difficult it is to anticipate infrequent, catastrophic events based on a short recorded history. However, the event also
demonstrated the value of efforts to mitigate the effects of earthquake shaking and tsunami; the high construction standards in Japan appear to have limited loss from shaking, and while the tsunami overtopped many tsunami walls, rapid warning and public preparation for response reduced the loss of lives, as compared with the 2004 Sumatra earthquake. The most promising technological approach is to extend rapid warning and monitoring capabilities, and to societal awareness and preparation. Japan has learned this lesson; the rest of the world should do so as well.

REFERENCES

Abe K (1977) Tectonic implications of the large Shioya-oki earthquakes of 1938. Tectonophysics 41: 269-289


Hayes GP (2011) Rapid source characterization of the 2011 Ms. 9.0 off the Pacific coast of Tohoku Earthquake. Earth, Planets and Space 63: 529-534


Hoshiba M, Iwakiri K, Hayashimoto N, Shimoyama T, Hirano K, Yamada Y, Ishigaki Y, Yukita H (2011) Outline of the 2011 off the Pacific coast of Tohoku Earthquake (Ms. 9.0)—Earthquake Early Warning and observed seismic intensity. Earth, Planets and Space 63: 547-551


Lay T, Ammon CJ, Kanamori H, Xue L, Kim MJ (2011) Possible large near-trench slip during the 2011 Ms. 9.0 off the Pacific coast of Tohoku Earthquake. Earth, Planets and Space 63: 687-692


Ozaki T (2011) Outline of the 2011 off the Pacific coast of Tohoku Earthquake (Ms. 9.0)—Tsunami warnings/advisories and observations. Earth, Planets and Space 63: 827-830


Polet, Thio HK (2011) Rapid calculation of a Centroid Moment Tensor and wave-height predictions around the north Pacific for the 2011 off the Pacific coast of Tohoku Earthquake. Earth, Planets and Space 63: 541-545


Shao G, Li X, Ji C, Maeda T (2011) Focal mechanism and slip history of the 2011 Ms. 9.1 off the Pacific coast of Tohoku Earthquake, constrained with teleseismic body and surface waves. Earth, Planets and Space 63: 559-564


Examining the Nuclear Accident at Fukushima Daiichi

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1811-5209/12/0008-0189$2.50 DOI: 10.2113/gselements.8.3.189

The major nuclear accident at the Fukushima Daiichi nuclear power plant more than one year ago was the result of a combination of four interrelated factors: site selection, external hazard assessment and site preparation, the utility’s approach to risk management, and fundamental reactor design. The reactor accident was initiated by a magnitude 9 earthquake, followed by an even more damaging tsunami. An insufficient tsunami defense-in-depth strategy led to significant core damage in three units and radioactive release to the environment. This paper provides a summary of the sequence of events that led to the accident and current efforts to contain and manage the released radioactivity.

Keywords: Fukushima Daiichi, nuclear power, accident, radioactive release

INTRODUCTION

In the early afternoon of March 11, 2011, Units 1, 2, and 3 at the Fukushima Daiichi nuclear power plant (Fig. 1) were operating at full power, while Unit 4 was undergoing fuel unloading and Units 5 and 6 were undergoing routine scheduled maintenance. A magnitude 9.0 earthquake occurred off the eastern coast of Honshu at 2:46 pm. The earthquake was the most powerful in the history of Japan. The three operating units immediately shut down automatically, as designed. Breakers and off-site power distribution towers failed due to the effects of the earthquake, causing a complete loss of power from the outside. Following the automatic shutdown of Units 1, 2, and 3, backup emergency diesel generators immediately started, providing backup electric power to critical emergency safety systems. Forty-one minutes after the earthquake and thirty-eight minutes after a tsunami alert was issued, the first of a series of seven tsunami waves arrived at the site. The maximum wave height was 14–15 meters, well above the 5.7-meter seawall designed to protect the site (IAEA 2011).

All electric power was lost to Units 1 through 4 within fifteen minutes after the first tsunami wave hit the station, and this led to a station blackout condition, that is, the complete loss of all sources of power. This paper is based on a detailed timeline of events that was developed by the Institute of Nuclear Power Operations (INPO 2011), which derived much of its information from direct and indirect interactions with the Tokyo Electric Power Company (TEPCO), the owner and operator of the station.

THE NUCLEAR REACTORS

The six Fukushima Daiichi nuclear reactors were able to produce a total of 5480 megawatts of electricity (MWe) at full capacity, making it one of the largest nuclear power stations in the world. All units were General Electric (GE) boiling water reactors (BWR). Unit 1, the first one built, was a GE design, BWR/3, with Mark I containment (Fig. 2). Units 2 through 5 were a later GE design, BWR/4, which still utilized Mark I containment.

Unit 6, the youngest and largest reactor, was a GE design, BWR/5, with Mark II containment. The plant was designed such that all the units have some common facilities and structures, such as a conventional island housing the turbines (Fig. 3). Facilities for handling the used fuel after irradiation, such as spent fuel pools and dry-cask storage facilities, were designed for use by all the units. Additionally, Units 1 and 2 shared a control room, as did Units 3 and 4.

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Figure 1 Aerial view of the Fukushima Daiichi nuclear power station before March 11, 2011. Unit 1 was the first one built and started operation in 1971; it is the smallest, at 460 mega-watt electrical (MWe). Units 2–5 each provided 784 MWe, and they started operation during the 1970s. Unit 6 is the largest of the units at 1100 MWe, and started operating in 1979. Source: TEPCO website
THE MAJORITY of nuclear power plants operating around the world are light water reactors (LWRs), which are either pressurized water reactors (PWRs) or boiling water reactors (BWRs). A LWR produces heat through controlled fission occurring in the fuel of the reactor core, and steam is ultimately used to drive power-generating turbines. In a BWR, steam is generated in the core and used to directly drive turbines, while in a PWR, a secondary loop is used to transfer the heat and ultimately drive the turbines. Both reactor types have been built over a range of electrical power outputs, typically ranging from several hundred megawatt electrical (MWe) to well over a gigawatt electrical (GWe). LWR fuel uses U-235 that has been enriched to roughly 3–5% (naturally occurring uranium contains 0.71% U-235) and fabricated into fuel rods that are approximately 1 cm in diameter and 3 m long. These fuel rods are bundled into square fuel assemblies that can be loaded into the reactor core. The reactor cores at Fukushima Daiichi contained 400 fuel assemblies in Unit 1, 548 fuel assemblies in each of Units 2–5, and 764 fuel assemblies in Unit 6. One of the safety challenges with LWRs is that they produce decay heat from the decay of fission products remaining in the fuel after the reactor has been shut down. Due to the decay heat, the reactor core requires continuous cooling following shutdown. Spent fuel is stored in spent fuel pools until it is cool enough for potential interim storage in dry-cask storage. According to TEPCo, the Fukushima Daiichi plant had a total of 1,760 metric tons of fresh and spent nuclear fuel (Marshall and Reardon 2011).

THE ACCIDENT
All on-site power was lost 55 minutes after the earthquake because many of the emergency diesel generators and switchgear rooms were flooded by the tsunami. Of equal importance, the seawater intake structure was destroyed by the tsunami, compromising the ability to remove heat from the shut-down reactors. Key plant equipment began to fail as plant operators started to lose all lighting and instrumentation due to damage and shorting in the DC backup batteries. Only one of the five emergency diesel generators in Units 5 and 6 continued to operate after the tsunami. The air-cooled emergency diesel generator in Unit 6 continued to function and supply electrical power so backup cooling systems could maintain functionality. Nuclear power safety is rooted in a defense-in-depth philosophy that involves the use of multiple, independent, redundant, and diverse barriers to prevent problems and accidents, together with corresponding emergency planning to address residual risks. However, it is shown in this paper that the defense-in-depth approach for dealing with the tsunami at the Fukushima Daiichi plant was insufficient.

STATION BLACKOUT
After losing all on-site AC power, plant personnel contacted the Japanese government and requested backup electric generators to restore critical safety equipment. Due to severe damage from the tsunami, the transportation of critical backup equipment to the site was delayed until later that evening. Helicopter transport of backup diesel generators was considered, but the weight of the generators exceeded the helicopter’s lift capacity. Finally, in the evening of March 11, backup, portable generators were put in service. Restoring the backup on-site power was made significantly more complicated by the fact that the tsunami had damaged the plant’s electrical distribution system. The initial inspection of the station switchyard confirmed that standby pumps for Unit 2 were functional, and therefore backup power efforts were directed towards Unit 2. Massive, temporary power cables were laid by station workers, and a connection was made to the associated power panel at 3:30 pm on March 12. It took approximately forty employees to lay the cable through the rubble and flooded areas.

At 3:36 pm an explosion occurred in the Unit 1 reactor building due to a buildup of hydrogen near the top of the building. The hydrogen came from steam reactions with overheated zirconium alloy fuel cladding, and was a result of the inability to cool the reactor core. This explosion distributed debris and damaged recently laid backup equipment, such as cables and portable generators. As a result of the explosion, five workers were injured, and the safety protocol for plant personnel was changed. Workers were required to wear protective equipment. The initial hydrogen explosion at Unit 1 certainly changed the nature of the emergency response and added much to the confusion. The site superintendent ordered personnel to proceed with preparations for venting Unit 3 just after 8 am and Unit 2 just before 2 pm on March 13.

REACTOR CORE COOLING
All nuclear power plants have some form of emergency makeup system to ensure there is water available in the event of a major pipe break. Heat in a BWR is removed during normal operation by generating steam in the reactor vessel, which then drives a turbine to generate electrical energy. When a reactor shuts down, the decay heat generated in the core is removed by bypassing the turbine and sending the steam directly to the condensers. When the
pressure in the reactor system drops to an acceptable point, the residual-heat-removal system is used to finish cooling down the reactor system (Fig. 4). In the event that the normal supply of water to the reactor vessel is lost, an isolation cooling system provides makeup water to the reactor vessel. Unit 1 was the oldest unit and utilized an isolation condenser (IC) to passively cool the core. The IC works on the principle that the heated, two-phase mixture of water and steam is buoyant, thus establishing a natural circulation loop with large heat exchangers located above the reactor for residual-heat removal. Units 2 and 3 utilized a reactor core isolation cooling system (RCIC) instead of an IC to cool the core in the case of an accident. The RCIC performs a function similar to that of the IC. It consists of a turbine-driven pump, associated piping, and required valves, and is used to deliver water to the reactor vessel at operating conditions. All of the units have an emergency core-cooling system (ECCS) that is capable of providing core cooling in the event of a loss-of-coolant accident. The ECCS consists of two high-pressure and two low-pressure systems. The high-pressure systems include the high-pressure coolant-injection (HPCI) system and the automatic-depressurization system (ADS), which is capable of depressurizing the reactor in the event of HPCI system unavailability. The low-pressure system in Unit 1 consists of a core-spray (CS) system, while Units 2 and 3 also utilize a low-pressure coolant-injection (LPCI) mode of the residual-heat-removal system in addition to the CS system. All of the units also have a borating system, which is used to shut down the reactor in the event that reactivity cannot be controlled. This system contains borated water, which is an effective neutron absorber and is used to stop the fission chain reaction in the core.

Immediately following the tsunami, all cooling and high-pressure makeup water to the reactors was lost. Steam-driven injection pumps were used to activate the RCIC system in Units 2 and 3; however, Unit 1 was unable to reestablish cooling through the IC. In all three units, the HPCI system was unavailable due to the absence of DC power. The steam-driven pumps ultimately failed, and the RCIC system stopped cooling Units 2 and 3. According to TEPCO estimates (TEPCO 2011a), Unit 1 was left without...
any water injection for 14 hours and 9 minutes following the station blackout. Units 2 and 3 were able to maintain adequate cooling for nearly 70 hours after the reactor shutdown and they eventually lost cooling capabilities for approximately 6 and a half hours. Because of this long period with no core cooling, substantial core damage occurred in Units 1, 2, and 3. “Core damage” refers to a core condition during a severe accident where the fuel can no longer maintain a geometry capable of allowing cooling and where temperatures exceed the melting point (~2800 °C) of the fuel. Boiling water reactors have a number of connections that penetrate the bottom of the reactor pressure vessel for core instrumentation and control rods. These penetrations provide potential pathways for leakage from the reactor pressure vessel. Interested readers should consult a recently released report from the United States Nuclear Regulatory Commission (NRC 2012), which discusses a research effort, initiated long before the Fukushima accident, to realistically estimate the outcomes of postulated severe-accident scenarios.

Core cooling was finally reestablished once the pressure in the primary system dropped enough to allow fire engines to inject seawater, and later freshwater; but by then it was too late, as substantial core damage had occurred. According to INPO (2011), core damage in Unit 1 most likely started within an hour and a half of the tsunami. Conservative estimates indicate that the cores in both Units 2 and 3 most likely melted and might have spun up approximately a meter to the bottom of the reactor pressure vessel. The full state of the damaged cores is not well known, and it will likely take many years before we fully understand the extent of fuel damage. It took nearly 4 years to assess the extent of damage to the fuel at Three Mile Island (NRC 1994) after the accident in 1979.

CONTAINMENT VENTING

The reactor containment structure is designed to prevent the release of radioactive material to the immediate environment. During severe accidents, the pressure inside the containment structure can be controlled through monitored venting in order to release stored energy. However, when venting occurs after damage to the core, the possibility of releasing radioactive material is much increased. At Fukushima Daiichi, safety procedures required venting when the operating pressure reached nearly double the maximum operating pressure. According to TEPCO severe-accident procedures, the chief of the Emergency Response Center, the site superintendent, is solely charged with determining whether to vent, but he can solicit input from other management personnel at the station. According to Japanese law, TEPCO did not need government permission to vent; however, government concurrence is preferable (INPO 2011).

For Unit 1, the site superintendent informed the government that he intended to vent the containment structure in order to reduce pressure. The government concurred; a press statement was issued just after midnight on the first day of the accident, and immediate evacuation measures were initiated in the nearby communities for those who remained. Shortly after the evacuations were completed, the procedure for venting the containment structure began just after 9 am on the morning of March 12. Five and a half hours passed before the containment structure was vented successfully due to the complexity of the operation. The radiation-exposure dose to workers had to be limited to no more than 300 mSv/h, with an additional limit of no more than 100 mSv in 17 minutes (for reference, the global average background dose for a human is approximately 3 mSv/y). Additionally, a lack of contingency procedures for venting containment under severe-accident conditions hindered progress (INPO 2011). These delays were the major factors involved in holding up the injection of water into the core of Unit 1, and they ultimately contributed to the severity of the accident.

As with Unit 1, a series of hydrogen explosions occurred in Units 3 and 4 several hours following the venting of units 2 and 3. The source of the released hydrogen was, again, exothermic reactions occurring at the exposed zirconium fuel cladding. While the pressure in the containment structure was increasing, the most likely source of hydrogen outside of containment was by leakage through the drywell head, which is used to access the drywell during maintenance (see Fig. 2). The hydrogen explosion in Unit 3 occurred just after 11 am on March 14 and significantly damaged secondary containment equipment and injured eleven workers. Finally, a hydrogen explosion occurred in the shut-down Unit 4 on March 15, the day after the explosion in Unit 3. The explosion at Unit 4 was peculiar since the plant was shut down; thus the hydrogen must have come from another unit. Currently, the most accepted explanation is that containment vent exhaust from Unit 3 circulated into Unit 4 through the shared standby gas-treatment system (SGTS).

SPENT FUEL POOL STATUS

The status of the spent fuel pools was of considerable concern as the events of the accident unfolded. The location of the spent fuel pools in the older-generation BWR designs with Mark I containment is particularly vulnerable during a severe accident because the pools are located at the top of the reactor building and in close proximity to the reactor pressure vessel (see Fig. 2). This design was originally to make fuel offloading easier by minimizing the distance the fuel had to move during refueling. With the exact source of the hydrogen and key spent fuel pool diagnostics unknown, there was early speculation that the pools had been compromised and that water might have been lost from at least one of the pools.

Spent fuel at Fukushima Daiichi is stored in each unit’s own spent fuel pool, as well as in a common pool and in on-site dry-cask storage. Once the station was under blackout conditions, all cooling capabilities for the unit spent fuel pools were lost, but this situation was not of immediate concern once emergency diesel generators were started. Water in the spent fuel pools experienced some “sloshing,” similar to the estimated minimal release of a few cubic meters of water from the pool at the Kashiwazaki-Kariwa plant after a magnitude 6.6 earthquake in 2007 (NISA 2009). Visual inspections using robots and analyses of the isotopic composition of the water in the spent fuel pools a month after the accident indicated that there was no serious damage to spent fuel in any of the pools or to the pools themselves. Any potential damage to the spent fuel was caused by flying debris from the hydrogen explosions. TEPCO inspections of the dry-cask storage building showed negligible damage.

REACTOR STABILIZATION AND DECONTAMINATION EFFORTS

As soon as the core coolant capability was restored by using the fire engine pumps, first with seawater and later with freshwater, another serious problem developed. Injected water that came in contact with the damaged fuel became highly contaminated with radioactivity. Because coolant circulation was not possible, the discharged water had to be stored separately. Soon, the floors of the turbine and reactor buildings were covered by highly radioactive water,
indicating that injected water was leaking from the reactor containment vessels. According to a TEPCO report (2011b) written two months after the accident, the concentrations of Cs isotopes (Cs-137 and 134) as of March 27, 2011, were about 3 million Bq/cm³ for each of them. The contaminated water soon started to overflow from the trench that connects buildings underground. This presented a very difficult situation. Water had to be injected into the cores to cool them, but this created the possibility of release of radioactivity to the seacoast environment by overflow of contaminated water. Due to the limited storage capacity, TEPCO had to release into the sea, with government approval, ~9000 m³ of contaminated water (6.3 Bq/cm³) kept in the storage facility in the centralized waste-treatment building. With the approach of the rainy season in June and July, it was urgently necessary to secure space for this contaminated water and to establish coolant circulation systems with a decontamination capability. As of the end of May 2011, the total volume of contaminated water was estimated to be 105,000 m³, containing about $7 \times 10^{17}$ Bq of radioactivity; the volume would have been expected to reach 200,000 m³ by the end of 2011 if no treatment and circulation had been established.

The contaminated water contained high concentrations of Na, K, Mg, Ca, Sr (nonradiogenic), and Cl, which originated from the seawater, as well as radioactive Sr, Cs, and I, which came from the damaged fuel. The major element composition of the seawater was the main difference between the wastewater at Fukushima and the wastewater generated in the Three Mile Island accident in 1979, where there was no injection of seawater. The treatment system for the contaminated water had specific requirements. First, the system had to be simple, so that it could be operated without remote handling. Second, the system had to be immediately available, which excluded options that required additional research. Third, the processing material had to be durable in a radiation field, and this excluded organic solvents and synthesized resins. Fourth, the system had to achieve sufficiently high decontamination factors, particularly for Cs, under high-salinity conditions, in order to eliminate the need for a secondary separation process.

TEPCO started operating the treatment system (Fig. 5) on June 17, 2011. This was important, because contaminated water in the trench was expected to overflow into the sea on June 20. At that time, there was 99,900 m³ of contaminated water in the reactor and turbine buildings of Units 1 through 4. Additionally, 21,700 m³ of contaminated water were stored in the centralized waste-treatment building, whose capacity was only 30,000 m³. Approximately 400 m³ per day of freshwater were required for cooling the three crippled reactors.

The treatment system consists of four parts: (1) An oil separator. (2) A Cs-adsorption system, developed by the US company Kurion, which consists of three subparts: (i) a pretreatment column packed with the sorbent SMZ, a surfactant modified zeolite, for removal of remaining oil and technetium; (ii) four parallel columns of the sorbent herschelite, for removal of Cs; and (iii) a column packed with the sorbent Ag-impregnated herschelite (AGH), for removal of iodine. The Kurion Cs-adsorption system was used in the water-treatment process at Three Mile Island. (3) A system for removing the remaining Cs, provided by the French company Areva, in which precipitation and coagulation are used. The decontamination factors for these processes have been relatively constant and high. The Kurion system has achieved decontamination factors for Cs ranging between 100 and 1000. The Areva system has achieved decontamination factors of 1000 to 10,000. Thus, an overall decontamination factor of 10,000 to 1,000,000 has been achieved for Cs. (4) On August 19, a second line, called Sarry, was added in parallel to the Kurion-Areva line. Developed by Toshiba-Shaw, this line uses Cs adsorption by titanates, and it has achieved about the same level of decontamination as the Kurion-Areva line.

Desalination by reverse osmosis and by evaporation was added on June 24 and August 7, respectively. The total throughput of the system from the oil separation stage through desalination was designed to be 1200 metric tons per day, and to generate 480 tons of freshwater a day. Thus, circulation of coolant water was begun on June 24.

Since implementation, the system has operated relatively free of difficulty. As of November 30, 2011, more than 175,000 m³ of contaminated water had been processed by this system. The volume of contaminated water stored in the reactor and turbine buildings has been reduced to 77,000 m³ from the initial 100,000 m³ in June. The volume of contaminated water stored in the centralized waste-treatment building has decreased from 22,000 m³ to 12,000 m³. In turn, 581 m³ of sludge containing Cs and

![Figure 5](https://example.com/image.jpg)
Defense-in-depth is a strong tool to utilize when dealing with unusually large events; however, it is not failure proof. All barriers ultimately have “holes,” such as the states of systems, equipment failure, human error, and equipment being in maintenance or out-of-service (Reason 1997).

The events at Fukushima following flooding by the tsunami were a direct consequence of insufficient tsunami defense-in-depth. Please note the barriers depicted are notional. Graphical concept adapted from Managing the Risk of Organisational Accidents, by James Reason (1997)

Figure 6 Diagram illustrating the concept of defense-in-depth. The events at Fukushima following flooding by the tsunami were a direct consequence of insufficient tsunami defense-in-depth. Please note the barriers depicted are notional. GRAPHICAL CONCEPT ADAPTED FROM MANAGING THE RISK OF ORGANISATIONAL ACCIDENTS, BY JAMES REASON (1997)

REFERENCES


298 vessels of wastes have been generated by the wastewater treatment system. After desalination, a total of 85,000 m$^3$ of salt water, which still requires treatment, has been generated and accumulated. Since the addition of the evaporation process in August 2011, condensation and volume reduction have been ongoing. With the successful and stable operation of the contaminated-water treatment system, cooling of the reactor cores has also been attained. On December 16, 2011, the Japanese government announced that the three crippled reactors were in a cold shutdown state.

However, final disposal of used adsorbent containing high concentrations of Cs will be an important issue as site cleanup, remediation, and decommissioning move forward. One important issue involving this spent adsorbent is hydrogen generation by radiolysis, as this process is enhanced by the presence of seawater, because hydrogen reoxidation reactions are hindered (Kumagai et al. 2011).

SUMMARY

The fuel in Unit 1 began to fail only a few hours after the station blackout caused by the tsunami. The fuel structurally failed and slumped to the bottom of the reactor pressure vessel as a melt. Reports from TEPCO have indicated that 0.7 m of the concrete below the reactor pressure vessel in Unit 1 was eroded by the molten corium interacting with the concrete (corium refers to the molten mixture of melted reactor-core constituents that exists during a severe accident). There are just over 10 m of additional reinforced concrete and steel protecting the environment below the damaged concrete. The cores melted in Units 2 and 3 as well; however, there is no evidence to date that there has been any basemat erosion in their respective drywells.

The sequence of events in Japan led to one of the most unsafe plant states for a light water reactor—a complete loss of on-site and off-site power, known as a station blackout. Insufficient defensive actions and an inadequate accident-mitigation response led directly to the overheating of three cores and resulted ultimately in controlled radioactive release to the nearby environment. The true failure at Fukushima Daiichi was the result of a completely inadequate defense-in-depth approach against a tsunami event. Defense-in-depth is a strong tool to utilize when dealing...
**Atmospheric Dispersion and Deposition of Radionuclides from the Fukushima Daiichi Nuclear Power Plant Accident**

Anne Mathieu, Irène Korsakissok, Denis Quéo, Jérôme Groëll, Marilyne Tombette, Damien Didier, Emmanuel Quentrec, Olivier Saunier, Jean-Pierre Benoit, and Olivier Isnard*

On March 11, 2011, an earthquake and tsunami hit the northeast coast of Japan and damaged the Fukushima Daiichi nuclear power plant, leading to the release of radioactive material into the atmosphere. We trace the evolution of radioactivity release to the atmosphere and subsequent dispersion as simulated by models, and we compare these to actual measurements. Four main release periods are highlighted. The first event had limited consequences to the north of the power plant along the coast; the second had no impact on Japanese territory because the plumes travelled toward the Pacific Ocean; the third was responsible for significant and long-term impact, especially northwest of the plant; and the last had consequences of lesser impact on the Tokyo area.

**KEYWORDS:** Fukushima Daiichi nuclear power plant, nuclear accident, contamination, atmospheric dispersion models, radioactive release

**INTRODUCTION**

The recent disaster at the Fukushima nuclear power plant was the most serious nuclear accident since Chernobyl in 1986. To accurately assess its impact on human health, an evaluation of the exposure due to radioactive materials dispersed in plumes and deposited on the ground is necessary. This objective was partly achieved by direct measurements. First, ground deposition was measured during and after the accident. In the early phase of the crisis, airborne measurements were made by the U.S. Department of Energy (DOE 2011). Moreover, since April 2011, a comprehensive and systematic survey of the environment based on soil samples has been completed by the Ministry of Education, Culture, Sports, Science and Technology of Japan (MEXT) and a group of Japanese researchers (e.g. Yoshida and Takahashi 2012 this issue). Using both sources of data, maps of ground contamination due to medium- and long-lived radionuclides (especially 134Cs and 137Cs) have been created. However, many uncertainties remain regarding the ground contamination due to short-lived radionuclides, such as 131I and 132I, which are major contributors to the gamma dose rate [gamma energy absorbed by the material per unit of mass and time (Gy/h)].

Second, from the beginning of the crisis, Japanese networks of measurement devices provided gamma dose rates and concentration measurements. About 80 stations showed significant gamma dose rates. Half the stations are located in Ibaraki Prefecture and the other half mainly in Fukushima, Kanagawa and Tokyo prefectures. However, many devices were not functioning because of earthquake and tsunami damage. Thus, the spatial coverage provided by the network was too limited to document in time and space the evolution of the plumes and their changing composition. Because the observational data are not sufficient, models of release, dispersion and deposition are required in order to assess the environmental and health impact of the Fukushima accident. This study offers a reconstruction of the atmospheric transport and deposition of the releases and provides the data required for the assessment of doses taken by the population.

**ATMOSPHERIC DISPERSION MODELS AND INPUT DATA**

**Atmospheric Dispersion Models**

The long-range Eulerian operational model ldX was used to model the dispersion of radioactivity at the scale of Japan, typically up to a few hundred kilometres from the source. The ldX model is based on the chemistry transport model Polair3D (Boutahar et al. 2004) and has been validated on the European Tracer Experiment (ETEX-I) and the Algeciras and Chernobyl accidents (Quéo et al. 2007). The statistical indicators for model-to-data comparisons have indicated the advantages of ldX as compared to other models. For instance, the analysis using the ETEX/I data indicated that 73% of the simulated concentrations were within a factor of 2 of the observations, and 80% of the values were within a factor of 5. Since Eulerian models are known to have difficulty in resolving steep gradients near point sources, the operational Gaussian puff model pX (Soulhac and Didier 2008) was used within 80 km of the Fukushima source.

Both models include consideration of radioactive decay. They also account for particle and gas removal from the plume and deposition on the ground through dry deposition and scavenging due to rain. Dry deposition was modelled using a simple scheme with a constant deposition velocity: \( v_{dep} = 2 \times 10^{-3} \text{ m/s} \). For wet scavenging, the parameterization used was of the form \( \Lambda = \Lambda_0 p_0 \), where \( \Lambda_0 = 5 \times 10^{-6} \text{ h/(mm.s)} \) and \( p_0 \) the rainfall intensity in millimetres per hour (Baklanov and Sørensen 2001). Depending on the atmospheric stability, the vertical diffusivity in the ldX model followed either Louis (Louis 1979) or Troen-Mahrt schemes (Troen and Mahrt 1986). Pasquill stability

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classes (Pasquill 1961) were used for pX. The spatial resolution for ldX simulations was the same as for the meteorological data input, and ten vertical levels were used.

**Meteorological Data**

The Fukushima plant is located in complex terrain, close to the sea and within 10 km of a mountainous area, where meteorological conditions are sometimes difficult to forecast. Therefore, several sources of meteorological data were considered. Operational forecasts from the European Centre for Medium-Range Weather Forecasts (ECMWF) and Météo-France (based on the ARPEGE model) were used, with a time resolution of 3 hours. ECMWF data have a spatial resolution of 0.125° × 0.125° (about 11 km × 11 km), and ARPEGE data have a resolution of about 0.5° × 0.5° over Japan. However, these models do not resolve the complex topography of Japan. Measurements of wind velocity and rainfall rate, collected at various sites in Japan, were used to evaluate the quality of the meteorological forecasts. The comparisons showed rather good model-to-data agreement, except for three events: forecast wind fields appear to be inaccurate on March 15 in the Fukushima area and on March 16 and 21 in the Ibaraki area. Despite these weaknesses, no other data have proven to be better for the characterization of the meteorological conditions at the Japan and hemispheric scales. Therefore, ldX simulations were driven by ECMWF data at the Japan scale, and ARPEGE data were used for hemispheric simulations.

For local-scale simulations, wind observations were used to compensate for the shortcomings in the forecasts. Following the analysis of forecasts and comparisons with observations, three-dimensional ECMWF data were used for pX simulations, except for March 15, when we preferred to use the uniform wind fields built from wind observations at the Fukushima Daiichi site. This solution had its own limitations, since we assumed that wind observed at Fukushima was homogeneous within the domain of simulation (80 km), but this did not take into account the natural spatial heterogeneity of flow.

Several rain events occurred in Japan during the Fukushima accident. The timing, spatial resolution and intensity of rain fields are of prime importance for the proper simulation of scavenging and deposition caused by rain. The resolution of meteorological models is too crude for an accurate representation of the spatial and temporal variability of rain episodes. Thus, radar observations of rain available at 10-minute intervals are best suited. Unfortunately, such data are only available for the pX spatial domain. Therefore, radar observations of rain were used for pX simulations, whereas the ldX model used ECMWF rain fields.

**Source Term**

The radioactive species released into the atmosphere during the Fukushima accident depended on the respective nuclide inventories per reactor unit. The released activities per reactor unit are shown in Figure 1. Seventy-three different radioisotopes were considered. The approach led to an overall estimate of 7.2 × 10^18 becquerels (Bq) discharged into the atmosphere, including 5.9 × 10^18 Bq of 133Xe, 1.9 × 10^17 Bq of 131I and 2.0 × 10^16 Bq of 137Cs. The proposed assessment is consistent with the released amount provided by NISA (2011) and NSC (2011), except for the noble gases, where xenon is underestimated by a factor of two.

The time evolution of the release was more difficult to determine. The quantity of each radioactive species released during venting or an explosion as well as the release duration were uncertain. Some information could be inferred from environmental measurements, but only to a point. Indeed, dose rates measured in the environment included all the gamma emitters present in the ground and in the atmosphere in the vicinity of the receptor. These measurements did not allow us to determine the isotopic composition or to distinguish the plume contribution from wet deposition. Activity concentration measurements or gamma-ray spectra analysis may help to infer the plume composition, but such measurements at Fukushima were far too few to remove the larger uncertainty. Besides, no near-field deposition or ambient air measurements could be used to improve the release estimates whenever the plume from Fukushima Daiichi was carried towards the ocean.

One year after the accident, the radioactive release still remains the key source of uncertainty in the simulations. Some preliminary and partial assessments of the release kinetics have become available (Chino et al. 2011; Stohl et al. 2011; Winiarek et al. 2012). All are based on environmental measurements. In the present study, the release kinetics were defined, first, by the chronology of events as provided by Tokyo Electric Power Company (TEPCO) (i.e. time of containment venting, flushing, onset of smoke, etc.) and by plant measurement parameters (i.e. water level and pressure in the reactor vessel, pressure in the containment), and second, by considering dose-rate peaks measured by on-site monitoring devices. In order to improve estimates of release rates and duration, dose-rate measurements distributed over Japan were used. The resulting source terms induced by damage to reactors 1, 2 and 3 are plotted in Figure 1. Four main periods of emission have been

![Figure 1](image-url)

**Figure 1**: Estimated rate of released activities per reactor in becquerels per second (Bq/s), including the contribution of 73 radioisotopes. Event 1 corresponds to March 12, event 2 to March 13–14, event 3 to March 15–16 and event 4 to March 17–26.
identified. Until March 16, the timing of the releases is based on specific events, such as venting and explosions, and thus is fairly reliable. The release rate and its distribution among radioisotopes were highly uncertain until March 14. From March 15 to 17, many measurements helped in estimating the release rate, but the composition of the release, in particular, the proportions of the noble gases, remains uncertain. From March 17 to 26, many uncertainties remain concerning both the sequence of events and the composition (rate and isotopic distribution) of the source term.

**DISPERSSION ANALYSIS FOR EACH EVENT**

**Event 1: Venting and Hydrogen Explosion at Unit 1**

The first release followed the explosion of Unit 1 on March 12 at 15:36 JST (Japanese Standard Time). Simulations suggest that the radioactive plume travelled first to the north along the Japanese coast and then turned towards the Pacific Ocean (Fig. 2a). Contamination of Japanese land resulting from the first event was due only to plume exposure and dry deposition northward along the coast. Only one gamma dose-rate station, located in Minamisoma, about 25 km north of the nuclear plant, detected the plume. The observed signal is in good agreement with pX simulations (Fig. 2a). However, the use of only one dose-rate station is not sufficient to validate the modelled release scenario.

**Event 2: Venting and Hydrogen Explosion at Unit 3**

The second event occurred between March 13 and 14 and was triggered by venting and an explosion at Unit 3. Fortunately, the wind was blowing towards the ocean, and no contamination of Honshu Island was detected. Again, the lack of observational stations prevents us from validating the release scenario. The consequences of the first two events for the Pacific Ocean have been described by Bailly du Bois et al. (2012).

**Event 3: Venting and Breach of the Wetwell at Unit 2**

The third event occurred between March 15 at 00:00 and March 16 at 12:00. First, between 0:00 and 5:00 JST, the venting of Unit 2 led to a released plume that moved to the south and then west. Second, at 6:00 JST on March 15, the sound of an explosion was heard, which may have come from Unit 3. This may have contributed in a minor part to that day’s releases. Around the same time, the pressurizing of reactor vessel 2 created a breach in the wet well (suppression chamber). Pressure-vessel measurements showed that during one day, the reactor vessel totally depressurized, leading to significant atmospheric releases. The resulting plume first went west, then northwest, and finally turned south toward the Pacific Ocean on March 16.

Forecasts by most of the meteorological services predicted the flow of the contamination toward the south and west of the nuclear plant, but they did not reproduce correctly the wind field carrying the plume to the northwest. Moreover, significant precipitation over Japan occurred when the flow travelled to the northwest. The most contaminated areas were those that experienced plume wash-out by precipitation. Thus, correct estimates of wind directions, precipitation timing and intensity, and release time and duration are crucial for accurately simulating the effective contamination. During the crisis, the significance of the contamination was first hinted at by an increase of dose rate in Iitate, located 40 km northwest of the power plant. Car-borne surveys and airborne observations by DOE and MEXT provided the data for mapping the high-dose-rate zone and deposition northwest of the Fukushima plant (Fig. 3a, b). Simulations by the System for Prediction of Environmental Emergency Dose Information (SPEEDI; Terada and Chino 2008) were the first to model the March 15 contamination in the northwestern area (NSC and MEXT 2011).

The ldX model driven by ECMWF data failed to accurately simulate the contamination to the northwest. The high-dose-rate area predicted by ldX is too far west, whereas pX simulations driven by wind observations at the Fukushima Daiichi site and radar observations of rainfall are in better agreement with observations (Fig. 3). Simulations show that contamination in the northwest was caused by wet deposition between March 15 at 21:00 JST and March 16 at 3:00. The pX deposition area is slightly too far north. This may be due to the use, during this episode, of a homogeneous wind field on a domain that was larger than the representative scale of the observations. Figure 4 gives examples of comparisons between model and observations for various dose-rate stations. The main contamination was observed in Iitate. Model-to-data comparisons are generally in good agreement; nevertheless, the peak values are often overestimated by pX, and the plume arrival is simulated with a delay of a few hours. The reconstruction proposed by Chino et al. (2011) shows the same deficiency in the modelled values. The discrepancies between model and observations may be due to several factors: inaccurate wind speed and direction, delays in the precipitation timing.
(especially in Iitate where rain was observed before it was detected by radar), underestimates of the amount of noble gas released and deposition models that do not account for complex processes (e.g. land-use spatial variability and particle-size variations).

**Event 4: Damage to Reactors 1, 2 and 3, Sprayings and Smokes**

Between March 17 and 26, new releases occurred due to the very poor condition of the reactors and perhaps the re-scattering of materials. White and grey smokes from Units 2 and 3 were also reported by TEPCO, especially on March 21 and 22 (TEPCO 2011). These releases were probably less significant than earlier ones, but they cannot be ignored because they explain some of the contamination caused mainly by wet deposition in the Tokyo and Ibaraki areas. Since there were no specific events, such as a venting or an explosion, the evaluation of the smoke releases can only be based on the on-site, observed gamma dose-rate signal. Various plumes travelled first east and then west.

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**Figure 3** (A) Map of ambient dose rate in microgray per hour (µGy/h) due to the plume on March 30, observed (painted areas) and simulated with pX (iso-contours). (B) Map of observed (dots) and pX-simulated (iso-contours) 134Cs deposits on March 30, in becquerels per square metre (Bq/m²). The circles correspond to distances of 20 km, 50 km and 80 km from the Fukushima Daiichi nuclear power plant.

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**Figure 4** Comparisons of ambient dose rate (cloud and ground shine), in microgray per hour (µGy/h), between ground measurements (in black) and pX simulations (in red) in (A) Kawauchi (20 km west) and (B) Iitate (40 km northwest of the Fukushima nuclear plant). Radar observations of rainfall rate, in millimetres per hour, are plotted in green.

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**Figure 5** Comparisons of ambient dose rate (cloud shine only) in microgray per hour, between ground observations (dots) and pX simulations (painted areas) on March 21 at (A) 6:00 and (B) 11:00. The circles correspond to 50 km, 100 km and 160 km from the Fukushima plant.
On March 21, a plume was measured in the morning in Ibaraki Prefecture, where ldX simulations have a delay of a few hours, probably due to inaccurate meteorological data (Figs. 5a, 6a). Later in the morning, the plume arrived in the Tokyo area (Figs. 5b, 6b). However, measurements in the Tokyo region showed that the main contamination occurred around March 15–16 (Fig. 6b), following event 3.

**DISPERSION AND DEPOSITION ON HONSHU ISLAND AND IN THE NORTHERN HEMISPHERE**

Model-to-data comparisons have been completed using available gamma dose-rate observations (SPEEDI and prefectural measurements). The comparison between observed and modelled gamma dose rates due to ground shine (after the plume is supposed to have left the area) shows an agreement within a factor of 5 to 10, and most of the time a factor of two. Model-to-data comparisons show an agreement within a factor of 5 for the gamma dose rate during the plume passage. Most of the time, the dose rate due to radionuclides in the air (“cloud shine”) is underestimated, and the dose rate due to radionuclides deposited on the ground only (“ground shine”) is overestimated. The airborne map of $^{137}$Cs deposition (see Fig. 1 in Yoshida and Takahashi 2012 this issue) (MEXT 2011) shows that the long-term impact of the accident is mainly located northwest of the plant where wet deposition occurred. Figure 7a, b illustrates the total deposition of $^{137}$Cs simulated at large and local scales. The locations of the contaminated areas are correctly identified by both models. Nevertheless, deposition fields modelled with ldX are smoothed because of the size of the mesh of the model. The northwestern contamination is too far to the west as modelled by ldX, but better reproduced by pX because of the use of wind observations. The pX simulations slightly underestimate the maximum values of radioactivity deposition close to the power plant, and the northwestern contamination is slightly too far north. Otherwise, the values of the pX deposition are correct as compared to observations.

The proposed scenario for the Fukushima accident can be indirectly evaluated by comparing simulations with observations recorded on other continents. Indeed, radioactive materials were detected on the western coast of the United States as early as March 16 (Bowyer et al. 2011; Diaz Leon et al. 2011) and arrived in most European countries on March 23–24 (Masson et al. 2011). The ldX model has been used to model the transport and evolution of the plume in the northern hemisphere. Preliminary comparisons in Masson et al. (2011) show that the predicted plume arrival times and the global patterns are consistent with observations over Europe.

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**Figure 6** Gamma dose rates (cloud and ground shine), in micrograys per hour, observed (black) and simulated with ldX (red) in (A) Ebisawa in the Ibaraki region and (B) in Tokyo. The rainfall rate, in millimetres per hour, from ECMWF data is plotted in blue.

**Figure 7** Simulation of total $^{137}$Cs deposited using (A) ldX and (B) pX. Values are given in becquerels per square metre (Bq/m$^2$). Compare it with the airborne survey results published in Yoshida and Takahashi (2012 this issue). The circles correspond to the distances from the Fukushima Daiichi plant.
CONCLUSIONS AND PERSPECTIVES

Models have been used to describe four different periods of radioactivity release as a result of the accident at the Fukushima Daiichi nuclear power plant. Three of the releases resulted in exposures to the population because of the movement of the plumes. The main ground contamination in Japan was caused by wet deposition northwest and south of the plant. When comparisons between model and observations are possible, results show that the modelled results are realistic. For some events, the lack of actual observations prevents validation.

Despite the good agreement between model and observations, many uncertainties remain in the source term and the meteorological conditions. An inverse modelling approach, as proposed by Winiarek et al. (2012), which was extended to gamma dose-rate measurements, may improve the source term assessment. For uncertainties, an ensemble approach may also be used (Mallet and Sportisse 2008). This method is based on an ensemble of simulations and is carried out using several dispersion models and/or a set of perturbed input data to describe their uncertainties. This approach allows one to quantify the uncertainties in the model output. Inverse modelling and ensemble methods appear to be powerful tools that should be used for operational purposes during emergency management.

The Fukushima accident has also highlighted other needs, such as the importance of having a monitoring strategy. As an example, gamma dose-rate observations were very useful, and airborne observations played a key role during the crisis. Nevertheless, even with these methods, the uncertainties are large. More activity-concentration and gamma-ray spectroscopy measurements, combined with rainfall measurements, would have significantly reduced the uncertainty in the modelled values.

ACKNOWLEDGMENTS

The source term assessment was done in collaboration with D. Corbin and J. Denis. They are gratefully acknowledged. The authors thank Météo-France for providing meteorological forecasts and especially J. P. Tonnelier for his decisive help in interpreting meteorological data and for sharing his expertise. The authors gratefully acknowledge the stakeholders of the IRSN technical crisis centre for their work during the Fukushima crisis.

REFERENCES


MEXT (2011) Xenon-133 and caesium-137 releases into the atmosphere from Fukushima Daiichi nuclear power plant: determination of the source term, atmospheric dispersion, and deposition. Atmospheric Chemistry and Physics Discussions 11: 28319-28394

NISA (2011) Regarding the evaluation of cesium-137 and iodine-131 source terms of an atmospheric dispersion model for accidental discharge of radionuclides with the function of simultaneous prediction for multiple domains and its evaluation by application to the Chernobyl nuclear accident. Journal of Nuclear Science and Technology 45: 920-931


Radionuclides, such as $^{134}\text{Cs}$, $^{137}\text{Cs}$, and $^{131}\text{I}$, were released during the Fukushima Daiichi nuclear power plant accident in March 2011. Their distribution was monitored by airborne surveys and soil sampling. The most highly contaminated areas are to the northwest of the plant and in the Naka-dori region of Fukushima Prefecture; this contamination was mainly the result of wet deposition on March 15. Radionuclides were also released on March 21, and they were dispersed up to 200 km south of the plant. The Cs/I ratios are different for these two events, probably because of differences on March 21, and they were dispersed up to 200 km south of the plant. The Cs/I ratios are different for these two events, probably because of differences in the initial ratios in the airborne plumes and the amount of wet deposition. Numerical simulations of the dispersion process and vertical profiles of radionuclides in soils are used to describe the contamination of soils.

**Keywords**: airborne monitoring, soil analysis, wet deposition, vertical profile, Fukushima Daiichi nuclear accident, radionuclides

**INTRODUCTION**

The Fukushima Daiichi nuclear power plant accident resulted in the release of huge amounts of radionuclides into the environment. The total amounts of the two main volatile radionuclides, $^{131}\text{I}$ and $^{137}\text{Cs}$, released into the atmosphere between March 12 and April 6, 2011, were estimated to be approximately $1.5 \times 10^{17}$ and $1.3 \times 10^{16}$ becquerels (Bq), respectively (Chino et al. 2011). Due to a strong wind from the west, most of the radionuclides were transported out over the Pacific Ocean (Yasunari et al. 2011). However, it is estimated that about 10–20% of the total radioesium and radioiodine emitted from the power plant were deposited over land in northeastern Japan (Morino et al. 2011). As a consequence of the land contamination shown by the airborne monitoring until April 2011, the area within 20 km of the Fukushima plant is now restricted, while other areas, such as litate village and a part of Kawamata town, have been designated as "planned evacuation areas." To assess the health risks and impact on food production in Fukushima Prefecture and neighboring prefectures, the spatial distribution of the radionuclides is of critical importance.

**AIRBORNE MONITORING OF LAND CONTAMINATION**

Airborne monitoring of radioactivity by the Ministry of Education, Culture, Sports, Science and Technology (MEXT) and the U.S. Department of Energy (DOE) was conducted four times in Fukushima between March and November 2011 (MEXT and DOE 2011; MEXT 2011a). Airborne monitoring is done using large sodium iodide (NaI) scintillator detectors installed in an aircraft. These instruments can quickly measure γ-rays emitted from radioactive materials on the ground and determine the distribution of radionuclides over large areas. The first airborne monitoring was done by DOE using 40 hours of flying time between March 17 and 19 (DOE 2011); this survey revealed a highly contaminated area northwest of the Fukushima plant.

Three subsequent surveys, conducted by MEXT and DOE, provided details on the distribution of radioactive materials, generally consistent with the results of the first DOE survey, and showed that the area in which deposition of $^{134}\text{Cs}$ and $^{137}\text{Cs}$ totaled more than 3000 kBq/m$^2$ (kilobecquerels per square meter) extended from the plant towards the northwest, affecting Namie town, Minami-Soma city, Katsurao village, Kawamata town, and litate village (Fig. 1). Several areas in which $^{134}\text{Cs}$ and $^{137}\text{Cs}$ totaled more than 300 kBq/m$^2$ were also found, such as at Date city in the Naka-dori region (Fig. 1). Very high radioactivity (>3000 kBq/m$^2$) extended from the power plant to the Naka-dori region through the Abukuma Highland, whose elevation is ca 1000 m (Figs. 1 and 2).

The highly contaminated area (>60 kBq/m$^2$) extends into the northern parts of Tochigi and Gunma prefectures (compare this value with that originating from global fallout around Japan, namely, a few kBq/m$^2$ level; Aoyama et al. 2001). In particular, the highly contaminated area is clearly evident along the fronts of the Ohu, Shimotsuke, and Echigo mountainous regions. A three-dimensional image (Fig. 2) confirms the close relationship between the distribution of the radionuclides and the higher elevations (MEXT 2011b).

**RADIONUCLIDE DISTRIBUTION IN SOILS**

Endo et al. (2012) sampled soils in March 2011 in areas northwest of the Fukushima plant to study the radioactive distribution at ground level. They detected the following radionuclides (with maximum depositional density values in parentheses, decay corrected to 17:00 on March 15, 2011): $^{129}\text{Te}$ (2.97 × 10$^3$ kBq/m$^2$), $^{132}\text{Te}$ (1.80 × 10$^3$ kBq/m$^2$), $^{131}\text{I}$ (1.25 × 10$^4$ kBq/m$^2$), $^{132}\text{I}$ (7.53 × 10$^3$ kBq/m$^2$), $^{134}\text{I}$ (6.98 × 10$^4$ kBq/m$^2$), $^{134}\text{Cs}$ (9.78 × 10$^2$ kBq/m$^2$), $^{136}\text{Cs}$ (3.95 × 10$^2$ kBq/m$^2$), $^{137}\text{Cs}$ (1.01 × 10$^4$ kBq/m$^2$), 

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*Elements, Vol. 8, pp. 201–206*
After the accident at the Fukushima plant, volatile radionuclides, such as $^{134}\text{Cs}$, $^{137}\text{Cs}$ (the boiling points of Cs, I, and Te may have been, respectively, Cs+; I$_2$, CH$_3$I, F, and IO$_3$; and HTeO$_4$ (Santschi et al. 1988).

The MEXT team collected soil samples from 2200 locations throughout Fukushima Prefecture and in northern Ibaraki and southern Miyagi prefectures. The depth of the sampled soil can affect the measured radioactivity, since the analytical result is reported as becquerels per kilogram (Bq/kg) after homogenization of the soil sampled between the surface and the given depth. Thus, the soil sample up to 5 cm depth was collected using a 5 cm core sampler with a specific cross-sectional area, since more than 90% of the $^{131}\text{I}$, $^{134}\text{Cs}$, and $^{137}\text{Cs}$ was found above this depth; after analysis, the radionuclide concentrations were converted to the unit Bq/m$^2$. Maps showing the distribution of $^{134}\text{Cs}$, $^{137}\text{Cs}$, $^{129m}\text{Te}$, and $^{110m}\text{Ag}$ were prepared (MEXT 2011c, d).

The distribution of $^{137}\text{Cs}$ in soils (MEXT 2011c; Fig. 3) showed that the highly contaminated area was to the northwest of the power plant; this result was consistent with measurements from the airborne survey. The activity of $^{137}\text{Cs}$ was highest in Okuma town (15,500 Bq/m$^2$; point 1 in Fig. 3), close to the plant (<3 km), where the radiation dose at 1 m height was 480 mSv/y (millisieverts per year) as measured at each sampling site by the MEXT team. The activity of $^{137}\text{Cs}$ was second highest around the border between Namie town and Iitate village (7900 Bq/m$^2$; point 2 in Fig. 3), about 30 km northwest of the plant. Moderate radioactivity (100–600 Bq/m$^2$) was found in the Naka-dori region. The 2 km scale sampling mesh used in this MEXT project revealed that there was a heterogeneous distribution even within small areas, which was not evident in the airborne survey. For example, point 2 mentioned above was located near a low-activity region (870 Bq/m$^2$; point 3), as shown in the inset of Figure 3.

The distribution of $^{129m}\text{Te}$ (MEXT 2011d; data not shown) was similar to that of $^{137}\text{Cs}$, suggesting that $^{129m}\text{Te}$ was also emitted as a gas. A larger concentration of $^{129m}\text{Te}$ was found south of the plant, possibly because of the migration of radioactive plumes with different $^{129m}\text{Te}/^{137}\text{Cs}$ ratios. However, the distribution of $^{110m}\text{Ag}$ (data not shown) was not similar to that of $^{137}\text{Cs}$. The emission and distribution mechanisms of $^{110m}\text{Ag}$ may be different from those of $^{137}\text{Cs}$ and $^{129m}\text{Te}$, because $^{110m}\text{Ag}$ may not be emitted as a gas on account of its refractory nature (boiling point of Ag = 2164°C).

Determination of the concentrations of $^{129}\text{I}$, $^{131}\text{I}$, $^{89}\text{Sr}$, and $^{90}\text{Sr}$ in soil is in progress (e.g. MEXT 2011e, f). Since the soil sampling and analysis by MEXT were conducted between June 4 and 29, data for short-lived nuclides, such as $^{131}\text{I}$, were obtained only for about 20% of the sites (MEXT 2011e). It is assumed that the $^{129}\text{I}/^{131}\text{I}$ ratio is constant.
for the radiiodine emitted during the accident, the determination of $^{129}$I using accelerator mass spectroscopy (Matsuzaki et al. 2007) allows one to estimate the distribution of $^{131}$I. Thus, the analysis of $^{129}$I is important as a complement to the $^{131}$I mapping.

Kinoshita et al. (2011) collected soil samples from shortly after the accident until the end of April 2011 and determined the distributions of short-lived nuclides, such as $^{131}$I (half-life = 8.0 days), $^{129m}$Te (34 days), and $^{136}$Cs (13 days) (Fig. 4). In addition, the sampled area extends from Fukushima through all of Ibaraki Prefecture. The ratios of the three radionuclide isotopes ($^{134,136}$Cs, $^{137}$Cs) were constant over the whole area. On the other hand, the distributions of $^{129m}$Te, $^{131}$I, and $^{137}$Cs were different, especially in Ibaraki Prefecture. Also, $^{129m}$Te was more concentrated immediately south of the power plant, as compared to $^{137}$Cs (see $^{129m}$Te/$^{137}$Cs activity-ratio map in Fig. 4). A similar tendency is also shown by the $^{131}$I/$^{137}$Cs ratio (Fig. 4).

According to previous studies of radionuclide emissions from the Chernobyl reactor (Muramatsu et al. 1987), most radionuclides are distributed as wet deposition (rainfall events). The main wet-deposition events after the Fukushima accident occurred on March 15–16 in northern Fukushima Prefecture and on March 21–23 in Ibaraki and Chiba prefectures, south of Fukushima, when transient cyclones entered these areas (Figs. 4, 5). Kinoshita et al. (2011) pointed out that the air mass around the power plant stayed in northern Fukushima Prefecture and that the radionuclides were deposited with rainfall and snowfall in the area on March 15 and 16 (Fig. 4). On the other hand, from March 21 to 23, air flowed from the plant southwards to Ibaraki and Chiba prefectures, accompanied by rainfall.

Different spatial distribution patterns for $^{129m}$Te, $^{131}$I, and $^{137}$Cs can be generated by variable air movements and rainfall patterns, coupled with variable $^{131}$I/$^{137}$Cs and $^{129m}$Te/$^{137}$Cs ratios in the plume, as seen from the contrasting ratios of I and Cs released from the power plant (Fig. 5). Considering the possibility that $^{131}$I can cause more serious health effects, as was seen at Chernobyl (Cardis et al. 2005), the distribution of $^{131}$I obtained by Kinoshita et al. (2011) is very important, particularly for the radiological dose assessment of the accident. The $^{129}$I mapping planned by MEXT is expected to confirm the $^{131}$I results obtained by Kinoshita et al. (2011).

Plutonium isotope ratios different from those of the global fallout were found in a sample collected 1.7 km from the power plant and in three soil samples taken northwest and south of the plant in the 20–30 km radius zone (Zheng et al. 2012; Yamamoto et al. 2012). Further studies on the distribution of plutonium within 20 km of the plant are needed.

**COMPARISON OF SIMULATED AND OBSERVED RESULTS**

In order to understand the temporal variation of radionuclide deposition and the mechanisms of contamination, numerical models that consider the meteorological conditions, the concentration and depositional amounts of radionuclides, and the resulting radiation doses have been developed. Such simulations have been done for radionuclide distributions on land (Chino et al. 2011; Morino et al. 2011; Katata et al. 2012; Yamamoto et al. 2012). Details about simulation studies of the atmospheric and oceanic dispersion of radionuclides are given by Mathieu et al. (2012) and Masumoto et al. (2012), respectively, in this issue. Here, we focus on simulation studies of the temporal variation of radionuclide emission and deposition over land.

Katata et al. (2012) estimated temporal variations in the release rates of radionuclides, in plume movement, and in the spatial distributions of radionuclides at various times after the accident (Fig. 6). Briefly, the dispersion from the nuclear plant on March 15–16 can be attributed to two main processes: (1) release on the morning of March 15 by a plume moving southwards from the plant, which created high radioactivity in the Naka-dori region; (2) release in the afternoon of March 15 from another high-concentration plume flowing northwards from the plant, which, coupled with rainfall, resulted in high activities in the northern part of Fukushima Prefecture (i.e. Iitate village).

Temporal variations in the deposition and emission rates from the power plant in March are summarized in Figure 5 (Morino et al. 2011). On March 15–16, high emission rates of $^{137}$Cs and $^{131}$I, coupled with easterly winds and precipitation, caused the deposition of large amounts of radionuclides in Fukushima, Miyagi, Ibaraki, and Tochigi prefectures. On March 21–23, although the emission rates were lower, large amounts of radioactive materials were transported over land by easterly or northeasterly winds, during periods of continuous precipitation, resulting in the second-largest event of radionuclide deposition over land.

Dry deposition contributed to the concentration of $^{131}$I much more than to the concentration of $^{137}$Cs, a fact that can be explained by differences in their chemical properties (Fig. 5). Under ambient conditions, radioesium cannot be present as gas, suggesting that all radioesium was transported in aerosol form. These aerosols can be readily
washed out during rainfall. However, a part of the radioiodine can be present as gas (I₂, CH₃I) that cannot be readily dissolved in water. Thus, dry deposition on land can be important in the removal of radioiodine from the atmosphere. The dry deposition fraction was larger near the power plant, in both the southwestern and northwestern directions (Katata et al. 2012). However, radionuclides in the Iitate village and Naka-dori regions were supplied mainly by wet deposition. Katata et al. (2012) also noted that topography is important in the distribution of radionuclides resulting from wet deposition.

In summary, simulations of the temporal variations of emission, deposition, and distribution of radionuclides are basically in good agreement with measured distributions obtained by airborne surveys and soil sampling.

**VERTICAL SOIL PROFILES**

Examination of the vertical migration of the radionuclides in soils after deposition has shown that more than 90% of the radiocesium and ¹³¹I deposited on the soil surface was retained in a surface layer no more than 5 cm thick and that ¹³¹I penetrated to greater depth than radiocesium (Kato et al. 2012; Tanaka et al. 2012). The depth of radiocesium infiltration in the Fukushima area was deeper than that reported for cultivated soil near the Chernobyl nuclear power plant, which may be related to the smaller clay content in the Japanese soil (Kato et al. 2012). Information on vertical migration is obviously useful for present and future decontamination strategies and also for modeling the migration of radiocesium into groundwater.

Direct evidence of the fixation mechanisms of the radionuclides in the top layer of the soil is limited, because the molar concentrations of the radionuclides are far below the level that can be measured by normal physicochemical methods. Indirect methods can be used only to estimate the chemical processes and to determine the host phases of the radionuclides in the soil; such methods include sequential extraction and particle size analysis, followed by radioactivity measurements and imaging techniques that measure radioactivity (autoradiography). Tanaka et al. (2012) suggested that less than 1% of the radiocesium in soils can be leached either with water at various pH values or even with 2 M HCl solution (soil: 5 g; solution: 15 mL). With the addition of 1.0 M NH₄Cl solution, the leached fraction increases to 5–15%, which suggests that radionuclides are strongly adsorbed into the interlayer of clay minerals (Wauters et al. 1996). Bostick et al. (2002) employed X-ray absorption spectroscopy (XAS) to show that Cs⁺ ions are strongly bonded with oxygen atoms within the SiO₄ sheets in the interlayers of clay minerals (montmorillonite and vermiculite); thus, an inner-sphere complex is formed between Cs⁺ and the clay structure. Cations that are smaller than Cs⁺, such as Na⁺ and Ca²⁺, are adsorbed by clays through the formation of outer-sphere complexes, the stability of which is much lower than that of inner-sphere complexes. Thus, these small cations are readily exchangeable through ion-exchange reactions. On the other hand, Cs⁺ and other cations (e.g., K⁺ and Tl⁺) are not readily exchanged because of the formation of inner-sphere complexes with the clay structure. Most likely, the Cs⁺ species in the Fukushima soils also forms inner-sphere complexes with clays, which reduces the mobility of Cs⁺ in soil.

Less than 10% and about 30% of the ¹³¹I were leached by water and an NaOH solution (pH 10.5), respectively, from soil collected one month after the accident (Tanaka et al. 2012). The NaOH solution, with its contained ¹³¹I, was subsequently acidified to pH 2; more than 60% of the ¹³¹I in the solution precipitated, possibly with humic materials that can bind iodine to the phenyl group in the polyorganic structure (Schlegel et al. 2006). This leaching–precipitation behavior suggests that part of the iodine is associated with organics in the soil, which may be the cause of the slow rate of leaching of ¹³¹I from the soil by water. The formation of organic iodine in natural soil has been suggested...
previously by XAS and by X-ray fluorescence analysis using an X-ray microbeam (Shimamoto et al. 2011). The formation of organo-iodine species in soil with a high organic-matter content proceeds over a relatively short period, even within a day (Yamaguchi et al. 2010; Shimamoto et al. 2011). Thus, the formation of organo-iodine is possible for $^{131}$I in the soil within about a month after it is deposited.

**FUTURE MIGRATION IN THE ENVIRONMENT**

In addition to determining the initial distribution of the radionuclides at ground level, it is equally important to follow the migration of the radionuclides in various environments via the atmosphere and hydrosphere (Yoshida and Kanda 2012). Redistribution of radionuclides through the atmosphere has been suggested (e.g. MEXT 2011a). In particular, the secondary transport of radioactive dust that has been resuspended and redeposited by wind and/or rain has been monitored in Fukushima. This effect may be responsible for the apparently more rapid decay of the measured activity in the highly contaminated areas, that is, by the removal of highly radioactive dust particles and their redistribution into moderately contaminated areas (Yamauchi 2012). In addition, the dispersion of radionuclides by pollen is being followed during the pollen season, February to May, because it is suspected that a part of the radioesium in soil can be absorbed by plants and trees and dispersed via the pollen from these plants.

However, the main pathway for the redistribution and migration of radionuclides must be through the hydrological system. Considering the strong adsorption of radioesium onto soil particles, the migration of radioesium into groundwater as a result of the infiltration of water through the soil layer is unlikely (e.g. Ohta et al. 2012). On the other hand, strong adsorption to soil particles facilitates the migration of radioesium, mainly as particulate matter, in rivers that receive the runoff from the contaminated area. A high content of particulate matter, such as colloids, results in the redistribution of radioactivity from highly contaminated areas into the fluvial environment, and finally into lake and ocean sediments. Migration through river systems has been suggested by results from airborne monitoring within 80 km of the Fukushima plant.
REFERENCES


Masumoto Y and 10 coauthors (2012) Oceanic dispersion simulations of 137Cs released from the Fukushima Daiichi nuclear power plant. Elements 8: 207-212


ACKNOWLEDGMENTS

We thank Y. Morino and D. Saito for providing results from their studies. We are also grateful to Profs. T. Murakami and R. C. Ewing for their constructive comments and suggestions about this manuscript. Two anonymous reviewers are also thanked for their helpful comments.
Five models have been used to estimate the oceanic dispersion of $^{137}$Cs from the Fukushima Daiichi nuclear power plant during March and April 2011, following the accident on March 11, 2011. The total discharged activity of $^{137}$Cs is estimated to be 2 to 15 petabequerels. A weak southward current along the Fukushima coast was responsible for the initial transport direction, while mesoscale eddy-like structures and surface-current systems contributed to dispersion in areas beyond the continental shelf. Most of the discrepancies among the models in April are caused by differences in how the mesoscale current structures off the Ibaraki coast are represented.

INTRODUCTION

A devastating earthquake and huge tsunami struck the Tohoku area, Japan, on March 11, 2011, causing major damage to the cooling systems of reactors in the Fukushima Daiichi nuclear power plant, operated by Tokyo Electric Power Company (TEPCO). In order to cool the reactor cores and the spent fuel in storage pools, large amounts of seawater and freshwater were used. A significant part of this radioactivity-contaminated water was discharged into the Pacific Ocean close to the power plant. In addition, several hydrogen explosions between March 12 and 15 resulted in the release of significant radioactivity into the atmosphere, some of which was deposited onto the sea surface over a wide area of the Pacific Ocean. Careful monitoring combined with modeling of the dispersion of the radioactivity provide critical information (1) on the processes responsible for dispersion of the radionuclides, (2) for simulation and prediction of the spread of radioactivity in the seawater, and (3) for the evaluation of the impact on the health of marine ecosystems and humans.

Since the accident at the Fukushima plant, several groups have been conducting numerical dispersion simulations of radionuclides discharged into the ocean, each group having different objectives. Some of the results from the simulations have been used to determine locations of monitoring observations off the east coast of Japan. This article reviews the present status of such simulations, without considering atmospheric deposition, and describes common aspects and discrepancies among the simulated results. The article also points out potential problems and provides guidance for future studies. This is the first attempt to conduct an intercomparison of models for the oceanic dispersion of $^{137}$Cs from the Fukushima plant.

DISPERSION SIMULATION MODELS

Numerical simulations of the dispersion of radionuclides in the ocean basically consist of two parts: an ocean circulation model and a radionuclide dispersion model. The ocean circulation model provides evolving circulation patterns for the dispersion model, while the dispersion model calculates the movement and spread of radionuclides in the ocean. In this article, we compare results from five groups: the Central Research Institute of Electric Power Industry (CRIEPI), the Japan Atomic Energy Agency (JAEA), the Japan Coastal Ocean Predictability Experiment (JCOPE) group at the Japan Agency for Marine-Earth Science and Technology (JAMSTEC), the Simulation Réaliste de l’Océan Côtier (Sirocco) group from the Observatoire Midi-Pyrénées, Centre National de la Recherche Scientifique and Toulouse University, and the National Oceanographic and Atmospheric Administration (NOAA) group.

Each group utilized a different set of models (Table 1). All of the models have their finest regional domain resolution focused on the area close to the nuclear plant, with various grid spacings in both the horizontal and vertical directions. Lateral boundary conditions of the circulation models are typically obtained from larger domain ocean circulation models, with relatively coarse resolutions, into which observed data, such as temperature, salinity, and sea-surface height, are assimilated to provide realistic upper-ocean conditions. With these assimilation schemes, mesoscale eddies and meandering of ocean currents, which are crucial
for the radionuclide dispersion in the open ocean, are adequately represented. Tidal currents are also included in several models in order to reproduce realistic spatial-temporal current variations near the coastal regions.

Although most of the groups are conducting dispersion calculations for several radionuclides, such as $^{131}I$, $^{134}Cs$, and $^{137}Cs$, we focus only on $^{137}Cs$ in this article, since it has a significantly long half-life of ~30 years and is observed in a wide area of the northwestern Pacific Ocean. All five groups are now considering both direct discharge and atmospheric deposition in their calculations, but we discuss here only the results without atmospheric deposition.

**SOURCE ESTIMATION**

The temporal evolution and amount of radioactivity released to the ocean and atmosphere from the plant are key pieces of information for dispersion simulations. In general, the source conditions are not readily available for this kind of accident, leaving a large uncertainty in the simulated results. One of the main purposes of the oceanic dispersion simulations is, therefore, to estimate the source information, using inversion techniques, as accurately as possible. So far, several estimates of the amount of $^{137}Cs$ discharged into the ocean have been reported, which are summarized in Table 2 and Figure 1. Note that the values come not only from peer-reviewed scientific papers but also from unreviewed articles.

TEPCO reported that the estimated total amount of $^{137}Cs$ discharged directly into the ocean through a crack in the concrete wall near the reactor of Unit 2 during April 1–6 was 0.94 petabecquerels (PBq), which is equivalent to about 25 kilocuries (kCi) (TEPCO 2011a). In Figure 1, this amount is indicated by a gray bar, assuming that the discharge occurred constantly for five days from April 1. On a few other occasions, TEPCO reported discharges of contaminated water into the ocean, but those were two to five orders of magnitude smaller in terms of radioactivity than the amount released during April 1–6.

Kawamura et al. (2011) estimated the amount of $^{137}Cs$ discharged into the ocean (red line in Fig. 1) using radioactivity data measured near the power plant by TEPCO (2011b) (black line in Fig. 1); they assumed that the contaminated water of the observed concentration occupied an area of 1.5 km$^2$ in front of the plant and was 1 m deep. After adjustment to the values reported by TEPCO for the period of April 1–6, a value of 4 PBq was obtained. The time series of the source information thus estimated (red line in Fig. 1) shows two peaks of release at the end of March and the beginning of April, with a magnitude of about 0.4 PBq day$^{-1}$. After April 7, the discharge diminished exponentially to about 0.001 PBq day$^{-1}$ at the end of April.

On the other hand, Tsumune et al. (2011) estimated a source function of $^{137}Cs$ by multiplying by a factor to adjust their model results, with a unit release of the radionuclide, to the observed values, giving a total of 3.5 PBq of $^{137}Cs$ discharged directly into the ocean (Fig. 1, blue line). They provided a simple scenario for the time evolution of the radionuclide discharge, in which they assumed that the time fluctuation of the observed radioactivity is associated with dispersion processes after entering the ocean. Indeed, Tsumune et al. (2011) are successful in reproducing a detailed time evolution similar to that observed at several locations along the coast south of the plant, including $^{137}Cs$ maxima observed on March 30 and April 6 near the plant.

**Figure 1** Time series of source information for $^{137}Cs$. The black line with solid circles is the time series of $^{137}Cs$ radioactivity in the open ocean near the Fukushima plant (right scale, in becquerels per liter). The values were obtained by averaging the radioactivity observed by TEPCO at the northern and southern drainage points of the plant. The red and blue lines are the time series of $^{137}Cs$ released into the ocean as estimated by Kawamura et al. (2011) and Tsumune et al. (2011), respectively (left scale, in petabecquerels per day). The gray bar indicates the $^{137}Cs$ discharge estimated by TEPCO, assuming a constant discharge between April 1 and 5 (left scale). 1 petabecquerel (PBq) = $10^{15}$ Bq

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**Table 1 Model Specifications**

<table>
<thead>
<tr>
<th>Model name</th>
<th>Base model</th>
<th>Resolutiona</th>
<th>Nesting (parent model)</th>
<th>Winds</th>
<th>Data assimilation</th>
<th>Tides</th>
<th>Integration period</th>
<th>Reference</th>
</tr>
</thead>
<tbody>
<tr>
<td>JAEA</td>
<td>Kyoto U./ JMSFb</td>
<td>1/72$^\times$1/54$^b$</td>
<td>2-step, (1/24$^\times$1/18$^b$ near Japan, 1/8$^\times$1/6$^b$ North Pacific, Kyoto U./JMSF$^b$)</td>
<td>NCEP reanalysis 2$^a$ and JMA- MSM$^c$</td>
<td>4D-VAR</td>
<td>No</td>
<td>March 11–April 30</td>
<td>Kawamura et al. (2011)</td>
</tr>
<tr>
<td>CRIEPI</td>
<td>ROMS$^d$</td>
<td>Passive tracer 1 km</td>
<td>1-step, (1/12$^e$ HYCOM$^f$)</td>
<td>NuWEAS$^g$</td>
<td>Included in HYCOM</td>
<td>Yes</td>
<td>March 1–May 31</td>
<td>Tsumune et al. (2011)</td>
</tr>
<tr>
<td>JCOPE$^b$</td>
<td>Passive tracer 1/36$^f$</td>
<td>2-step, (1/12$^g$ Northwest Pacific, 1/4$^h$ North Pacific, JCOPE$^e$)</td>
<td>NCEP analysis and JMA- MSM</td>
<td>3D-VAR in JCOPE$^e$</td>
<td>Included in HYCOM</td>
<td>Yes</td>
<td>March 21–May 6</td>
<td>Toulouse University (2011)</td>
</tr>
<tr>
<td>Sirocco</td>
<td>Passive tracer 600 m</td>
<td>1-step, (NCOM$^i$)</td>
<td>ECMWF forecast</td>
<td>Included in NCOM</td>
<td>Yes</td>
<td>March 11–to present</td>
<td>Toulouse University (2011)</td>
<td></td>
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<tr>
<td>NOAA</td>
<td>ROMS$^j$</td>
<td>Passive tracer 1 km</td>
<td>1-step, (NCOM$^k$)</td>
<td>US Navy’s COAMPS$^l$ (via NCOM)</td>
<td>Included in NCOM</td>
<td>Yes</td>
<td>March 10–June 27</td>
<td>Toulouse University (2011)</td>
</tr>
</tbody>
</table>

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Several other estimates, including those by the Sirocco, NOAA, and JCOPE groups, were basically obtained from numerical models using the TEPCO data. The values obtained by Sirocco and NOAA, about 3 to 4 PBq of $^{137}$Cs discharged directly into the ocean, are similar to those derived by Kawamura et al. (2011) and Tsumune et al. (2011). The second report from the Institut de Radioprotection et de Sûreté Nucléaire (IRSN) on the impact of radioactivity released from the plant on the marine environment (IRSN 2011a) estimated the amount of radioactivity discharged until April 11 to be 2.3 PBq, which is somewhat smaller than other estimates. Another IRSN report shows a significantly large value of 27 PBq of $^{137}$Cs (IRSN 2011b), which seems to have been derived by simple interpolation of sparsely observed data and assuming constant radioactivity within a relatively thick surface mixed-layer in March. A relatively large estimate of 14.8 PBq from JCOPE is mainly due to relatively coarse horizontal resolution with a simple boundary condition, in which the simulated $^{137}$Cs concentration at the sea surface in front of the plant is forced to adjust toward the observed value.

Most of the above estimates rely on radioactivity measurements by TEPCO near the nuclear plant. Errors in the TEPCO data, if any, can propagate into these estimates directly. Another factor affecting the value of estimated source information is the vertical distribution of radionuclides, especially in the oceanic surface layer. The surface mixed-layer defined by temperature or water density can be relatively thick in March due to winter cooling at the sea surface and subsequent vertical convective motion. We do not know at this stage, however, whether or not the radionuclides are also evenly distributed vertically within the surface mixed-layer. In this regard, the values in Table 2 should be considered to have large uncertainties.

**DISPERSION SIMULATIONS**

With the above-mentioned source information for simulating the dispersion of radionuclides in the ocean, time series of the three-dimensional distribution of $^{137}$Cs were obtained from each model. In this section, we compare these results, focusing on the surface distribution of $^{137}$Cs in the coastal and continental shelf regions during the first two months after the accident. We present 10-day averaged surface horizontal-velocity fields and $^{137}$Cs distributions for two periods, from March 22 to 31 (Fig. 2) and from April 21 to 30 (Fig. 3). These periods correspond, respectively, to a time of southward dispersion along the Fukushima coast and to a time of gradual dispersion toward the margin of the continental shelf. Monitoring of the radionuclides was conducted by the Ministry of Education, Culture, Sports, Science and Technology (MEXT) and TEPCO during March and April, 2011 (MEXT 2011; TEPCO 2011b), and comparisons of the simulated results with the observations are also made for the two periods.

**March 22–31**

A lack of observational data prevents us from providing a detailed description of the $^{137}$Cs distribution at the end of March. The monitoring observations, however, indicate high concentrations of $^{137}$Cs along the coast, near the nuclear plant (Fig. 2c). The data along a line 30 km offshore from the coast also show $^{137}$Cs contamination, with a magnitude of about 10 to 15 Bq L$^{-1}$. These observed values are significantly higher than those observed in Japanese coastal waters before the accident, a typical value of which is about 0.003 Bq L$^{-1}$ (Kasamatsu and Inatomi 1998).

In general, the surface current fields in all the models show a strong eastward or northeastward flow—the Kuroshio current—along the coast of Japan south of Inubo Peninsula. The current separates from the coastal area off Inubo Peninsula. The models also show a broad southward flow, with a speed of 0.2 to 0.5 m s$^{-1}$, in the region east of 141.5° E and north of the Kuroshio current (Fig. 2a–i). All models demonstrate a weak southward flow, with a speed of 0.1 m s$^{-1}$ or less, along the coast in front of the Fukushima plant. This southward current along the coast is responsible for the southward distribution of $^{137}$Cs at the end of March. The southward flow along the coast can be traced back up to 38° N in all the models, while the speed of the flow varies among the models and, in the JCOPE model, is partially associated with a cyclonic circulation off the coast of Fukushima. The local flow pattern in this region is susceptible to wind forcing, which shows higher temporal variability associated with synoptic weather disturbances.

All the models fail to simulate the relatively high concentration of $^{137}$Cs along a line 30 km offshore. Since the results shown here are the dispersions of $^{137}$Cs released directly from the plant, it is reasonable to expect that this offshore contamination at the end of March was due to deposition from the atmosphere. This is consistent with the conclusion of Tsumune et al. (2011), who showed the importance of deposition from the atmosphere by checking the $^{131}$I/$^{137}$Cs activity ratio.

Another important surface current pattern is eddy-like structures off the coast of Ibaraki in the region between 36.7° N and the Kuroshio current; in this region, the differences among the models are rather large. A clear example is an anticyclonic circulation centered at 36.4° N, 141° E in the CRIEPI result. A similar eddy structure can also be seen in other model results, but it is relatively weak and shifted slightly to the east in the JCOPE model, and it appears as a part of a strong dipole eddy structure in the

<table>
<thead>
<tr>
<th>Table 2</th>
<th>ESTIMATED AMOUNT OF $^{137}$Cs DISCHARGED DIRECTLY INTO THE OCEAN</th>
</tr>
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<tbody>
<tr>
<td>Institution</td>
<td>Period</td>
</tr>
<tr>
<td>TEPCO</td>
<td>April 1–April 6</td>
</tr>
<tr>
<td>IRSN</td>
<td>Up to April 11</td>
</tr>
<tr>
<td>IRSN</td>
<td>March 25–July 18</td>
</tr>
<tr>
<td>JAEA</td>
<td>March 21–April 30</td>
</tr>
<tr>
<td>CRIEPI</td>
<td>March 26–May 31</td>
</tr>
<tr>
<td>JCOPE</td>
<td>March 21–May 6</td>
</tr>
<tr>
<td>NOAA</td>
<td>March 10–June 27</td>
</tr>
<tr>
<td>Sirocco</td>
<td>March 20–June 30</td>
</tr>
</tbody>
</table>

*a In petabecquerels (1 PBq = 10$^{15}$ Bq)
The JAEA model. The Sirocco and NOAA models show relatively broad southward flow off Ibaraki. Satellite images of the sea-surface temperature distribution indicate a weak, warm-core, eddy-like feature off the coast of Ibaraki at the end of March and in early April (not shown). The 137Cs concentration had not reached the region of these eddies by the end of March.

An ensemble mean of the five model results, giving equal weight in the averaging (Fig. 2F), captures most of the above-mentioned velocity and 137Cs distributions. It is rather difficult, however, to show that the ensemble mean field is better at representing the observed distribution, since the observational data are so sparse and limited to a region close to the plant.

April 21–30

The high 137Cs concentration had spread offshore by the end of April, while the radioactivity along the line 30 km offshore diminished slightly to a value of around 10 Bq L\(^{-1}\) or less, except for two locations, where values of more than 20 Bq L\(^{-1}\) were detected (Fig. 3c). New monitoring stations were installed in the region off Ibaraki, but the observed values were all under the detection level of about 10 Bq L\(^{-1}\) for this time period.

All the models show southward or southeastward dispersion of the 137Cs in the latter part of April (Fig. 3d–e). The offshore dispersion seems to be associated with a nearshore, northeastward surface flow broadly distributed near the power plant in all models. The southward or southeastward movements of 137Cs in the offshore region south of 37\(^{\circ}\) N, however, show large differences among the models. While the anticyclonic circulation brings the 137Cs distribution southeastward in the CRIEPI and JCOPET models, the JAEA, Sirocco, and NOAA results show southward dispersion along the coast associated with a weak southward flow near the coast. The NOAA results indicate strong eddy features beyond the coastal region, but the radionuclide distribution was not affected by the eddies at the end of April. The differences among the models suggest that the surface circulations in the region between 37\(^{\circ}\) N and the Kuroshio current are susceptible to mesoscale eddy activity and to variability of the Kuroshio, and the modeled Kuroshio current is in turn strongly affected by data-assimilation processes in the larger domain models. In addition, the radionuclide distribution is affected by velocity fields not only during April 21–30 but also before that period. Again, the ensemble mean fields capture reasonably well the main features of the 137Cs distribution and the velocity characteristics off Fukushima and Ibaraki (Fig. 3f).

In addition to the mesoscale eddy activity, the magnitude of horizontal and vertical mixing processes in the ocean may strongly influence the 137Cs distribution. For example, the CRIEPI and NOAA results show relatively weak values of less than 10 Bq L\(^{-1}\) in most of the region affected by radionuclide contamination as compared with other model results. One possible reason for this discrepancy could be differences in the magnitude of the vertical diffusivity; in general, the larger the vertical diffusivity, the weaker the surface concentration of the 137Cs. However, it is not straightforward to deduce this effect in a simple comparison among the models in Figures 2 and 3, since each model uses different schemes for advection and diffusion as well as different diffusion coefficients.
Another possible cause for the discrepancy is the degree of horizontal movement of the radionuclides within the 10-day-average window. When the radionuclides move around in a large area, the averaged concentration becomes smaller as compared with a case where radionuclides stay in the same location. This aspect strongly depends on the variability in the current system and should be evaluated in the future in order to clarify the detailed dispersion processes in this region.

At the end of April 2011, the relatively strong southward flow in the offshore region had strengthened as compared with the end of March. A major part of the $^{137}$Cs distribution, however, was confined within the region between the coast and the offshore southward flow. The $^{137}$Cs dispersed to the south or southeast was eventually captured in early May by the northern flank of the Kuroshio current and spread rather quickly to the east into the Pacific Ocean. This eastward movement of $^{137}$Cs can be seen in all the model outputs, and one example for the JCOPET model is shown in Figure 4.

**FUTURE ISSUES**

Comparison of the surface horizontal distributions of $^{137}$Cs among the dispersion models for the Fukushima accident demonstrates general agreement of the flow fields and associated $^{137}$Cs distributions at the end of March and April 2011. However, there are noticeable differences among the models as well, in particular for the region between 37 °N and the Kuroshio current, where cyclonic or anticyclonic eddy-like circulations can be seen in some models. Accurate representation of such mesoscale structures and associated radionuclide dispersion near the coast is an important challenge for simulations on the regional scale.

The degree of vertical mixing in a model, as well as the vertical distribution of the source term, may also affect the surface distribution of the radionuclides. During March and April, several low-pressure systems passed through the Fukushima region, and these could have produced relatively large vertical mixing in this region. We need to...
To describe what happened and is happening in terms of the dispersion of radionuclides such as 137Cs from the Fukushima Daiichi Nuclear Power Plant, 137Cs radioactivity at the end of April 2012 was of the order of 1 Bq L⁻¹. Results from recent observations and numerical models indicate that the distribution of 137Cs has expanded and shifted to the east into a large portion of the North Pacific Ocean, while the radioactive activity in most of the area is of the order of, or below, 0.01 Bq L⁻¹. In order to describe what happened and is happening in terms of the dispersion of radionuclides from the Fukushima plant, research-based, accurate observations and analyses in a wide area of the North Pacific Ocean for more than a few decades are needed; as well, detailed comparisons and a synthesis of the simulated results and observations are strongly required.

ACKNOWLEDGMENTS

YM and YM thank Drs. Sergey M. Varlamov, Ruochao Zhang, Toshimasa Doi, and Toru Miyama for their support for JCOPE simulations. LL is deeply grateful for support from Dr. John Cortinas, Dr. Frank Bub, Mr. Robert Daniels, Mr. Richard Patchen, and Ms. Hong Lin for NOAA dispersion simulations.
Interactions between Nuclear Fuel and Water at the Fukushima Daiichi Reactors

1811-5209/12/0008-0213$2.50 DOI: 10.2113/gselements.8.3.213

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KEYWORDS: corium, spent fuel, radionuclide release, environmental impact, radiotoxicity, Fukushima Daiichi nuclear power plant

CHARACTERISTICS OF THE REACTORS AND NUCLEAR FUELS

There are six boiling water reactors (R1–R6) at the Fukushima Daiichi nuclear power plant. Four reactors (R1–R4) were destroyed by the accident: the three reactors (R1–R3) operating at the time of the earthquake and the neighboring reactor, R4, whose fuel had been removed and stored in cooling ponds. The cores of R1–R3 contained about 256 metric tons of nuclear fuel (400 fuel assemblies in R1 and 548 assemblies in each of R2 and R3; one assembly contains 60 fuel rods, each 3.70 m long, and each assembly weighs about 170 kg). Reactors R5 and R6 were shut down for routine inspection. In September 2010, 32 of the fuel assemblies in the core of reactor R3 were mixed-oxide (UO2 + PuO2) MOX fuel (IAEA 2011) totaling about 5.5 tons. The other assemblies were uranium oxide fuels, UO2 (named UOX fuels). The spent fuel storage tanks located in the four destroyed reactor buildings contained an additional 461 tons of nuclear fuel, including 395 tons of discharged irradiated fuel and 66 tons of unirradiated UO2 fuel waiting to be loaded into the reactors.

When reactors 1–3 shut down automatically after the earthquake, about 89% of the 6.1 gigawatts (GWth) of thermal nuclear fission energy being produced was immediately interrupted, i.e. the kinetic energy of fission products, neutrons, and photons. However, 11% of the energy remained in the cores of R1–R3 after shutdown, 6% (360 megawatts) in the form of beta decay heat essentially from fission products (see Fig. 1a) and 5% in the form of antineutrinos. Initially, this energy was rapidly released, and later, more slowly. Indeed, spent nuclear fuel is considered to be an important heat source for thousands of years in most concepts of geological disposal (Fig. 1a).

The radiotoxicity of the used fuel is in part due to the accumulation of the radioactive isotopes (“fission products”) that were generated by the nuclear fission of uranium and plutonium atoms during reactor operation. It is also due to the transuranium elements (actinides beyond uranium in the periodic table) created by neutron capture on 238U in the fuel. These radionuclide inventories depend on the length of time the fuel was “burned” in the nuclear reactor, i.e. on the “burnup,” which is the energy released expressed in gigawatt-days per metric ton of uranium and plutonium (GWd/t). After a typical burnup during reactor operation for some years, the radioactivity of the fuel has increased by a factor of a million (10^7 becquerels/metric ton of fuel). One year after discharge from a reactor, the dose rate measured one meter from the fuel assembly is one million millisieverts per hour (for comparison, the natural background dose is on the order of three millisieverts per year). A person exposed to this level of radioactivity at a distance of one meter would receive a lethal dose in less than a minute (Hedin 1997; Bruno and Ewing 2006). Fission-product inventories are roughly proportional to burnup, while actinide-element inventories (Pu, Am, Np, Cm) are more complicated functions of burnup because the fissile transuranium elements are partly consumed at high burnups and the production rates of higher actinides (Am, Cm) increase with burnup.

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Typical end-of-life burnups are about 40 GWd/t, which are achieved after 3 to 4 years in the reactor. Due to the replacement of only a part of the used fuel by unirradiated UO₂ fuel in normal reactor operation, a reactor core is always a mix of old and rather fresh fuel, and burnups for individual fuel assemblies range from 3 GWd/t to 41 GWd/t. The average burnup of the Fukushima Daiichi reactors is assumed to be about 20 GWd/t. The average burnup has not been reported “officially,” but the “official” total 137Cs inventory of reactors 1–3 can be calculated from the release fractions and total releases given in IAEA (2011) as 7.1 × 10¹⁷ Bq. This would correspond to an average burnup of about 23 GWd/tU. Endo et al. (2011a) estimated an average burnup of 17.2 ± 1.5 GWd/tU, based on the average ratio of 134Cs/137Cs (0.996 ± 0.07) measured in soils within a radius of 100 km. Average core burnups were reported in the same publication as 25.8, 23.2 and 21.8 for reactors R1, R2, and R3, respectively, closely matching the value of 23 GWd/tU derived from the IAEA (2011) data. The lower burnup calculated by Endo et al. (2011a) may be due to the postulated core meltdown (i.e. differences in the degree of damage and associated Cs release for the fuel in the center of the core versus at the periphery) or to greater damage of once-burned fuel due to its higher temperature. The presence of MOX fuel in reactor 3 was considered in the world press to be a strong additional risk factor due to the higher plutonium content. For a given burnup, MOX fuel is more toxic than conventional fuel, but the short residence time in the reactor—only 5 months—means that the average fission-product inventories and associated toxicities of this type of fuel are probably lower than the average inventories of a pure UO₂ fuel. But the Pu inventory of MOX fuel is much higher. Endo et al. (2011a) report a value of 3.9 wt% Pu in the MOX fuel in reactor 3. Considering that UOX fuel with an average burnup of 23 GWd/tU contains about 0.8 wt% Pu and that only about 6% of the fuel in reactor 3 was MOX fuel, the total loaded inventory of Pu in this reactor was about 0.98 ton, roughly 30% greater than the 0.75 ton (0.8% of 95 tons of fuel) in reactor 2, which contained a similar total fuel mass but without MOX.

As an example of the evolution of toxicity over time, Figure 2 shows the toxicity inventory of one ton of spent nuclear fuel (UO₂) for a rather high burnup of 47.5 GWd per ton of the initial uranium inventory (calculations were made as part of the MICADO project; Grambow et al. 2010). Indeed, even for this UO₂ fuel, the Pu inventory dominates the long-term toxicity; therefore, the greater Pu inventory of the MOX-containing reactor would increase the long-term toxicity by about 30%. However, this does not directly represent the potential impact since the toxicity also depends on the mobility of plutonium, which can be very low depending on the chemical conditions (for instance in a reducing environment or in the presence of organics).

Considering that the dose limit for ingestion according to regulations in Europe is 1 mSv/y (millisievert per year), the high toxicity of the radionuclides in the damaged fuel cores requires isolation well beyond hundreds of thousands of years in order to avoid exposing the fuel cores to natural waters, which might lead to the release of toxic radionuclides into the food chain. Isolation for such long times is also necessary to avoid exposing people in the vicinity of the damaged cores to lethal doses of external gamma radiation.
HOW MUCH WAS RELEASED FROM THE REACTORS? HOW MUCH REMAINS?

Toxicity is not identical to risk. Risk depends on the accessibility of radionuclides to humans and to their mobility in the environment. In the future, important measures will have to be taken in order to reduce the short- and long-term risks of the highly toxic inventory of the reactors, for example, by strict confinement and/or geological disposal of the fuel. Today, the largest risk stems from those elements (Pu, Am, Np, Cm). These elements are responsible mainly for long-term toxicity (see Fig. 2) since they are long-lived alpha emitters (in case of ingestion, alpha particles, 4He2+, cause more damage to human cells due to their larger size). But the actual risk originating from these nuclides is much lower since, even in the immediate vicinity of the damaged reactors, for example, at a distance of 500 m, Pu concentrations in the soil (239/240 Pu activities of 500 m, Pu concentrations in the soil (239/240 Pu activities of 0.055 ± 0.029 Bq/kg) are identical to the Pu concentrations in Japanese soil that resulted from atmospheric testing of nuclear weapons (0.02–0.4 Bq/kg for 239/240Pu) (Hirose et al. 2003).

The activities of plutonium and other nuclides measured by the Tokyo Electric Power Company (TEPCO) over a period of 8 months are shown in Figure 3 (original data taken from a series of Web references from TEPCO 2011: www.tepco.co.jp). These data can be used to compare the ratios of the measured activities to the activity ratios of fission products and actinides in the nuclear fuel in the reactor. The large symbols in Figure 3, corresponding to the date of the accident, represent reference values (see explanation in the caption). As can be seen, the measured activities still have, with an uncertainty of about a factor of 2, the signature of the inventory ratios in the original fuel as far as the releases of 137Cs, 131I, 110mAg, and 129mTe are concerned, when corrected, as in the case of 131I, for radioactive decay since the date of release (March 15) from the reactor. In contrast, measured activities of the alkali earth element nuclides, such as 140Ba and 90Sr, are about a thousand times lower than the reference value of the activity ratios in the fuel. Finally, for the actinides 241Am, 242Cm, and 239Pu, the measured activities are about 5 orders of magnitude lower than the reference values in the nuclear fuel. Comparing the concentrations of the actinides with each other, their measured activity ratios correspond to their inventory ratios in the fuel, indicating a similarly slow mechanism of release for all actinides.

Thus, for the Pu inventory in the reactor, about 10^3 times less is released to the environment as compared with the Cs inventory. Considering this low release of Pu, even fuels of higher Pu content, such as MOX fuel, will release very little Pu. Thus, no significant additional short-term risk will arise from Pu release from the MOX fuel. In contrast, long-term risks depend on Pu inventories, particularly if Pu release from the reactor is increased by oxidizing groundwater coming into contact with the fuel.

Recently, careful activity measurements were reported at 15 soil-sampling locations between 5 and 60 km from the Fukushima plant (Endo et al. 2011b). Using these data, the activity ratios 129mTe/137Cs, 131I/137Cs, and 140Ba/137Cs were calculated to be 1, 20, and 0.06, respectively, which can be compared with the same ratios in the original spent fuel, i.e. 0.7, 12, and 22, respectively. This corroborates the previously discussed measurements made in close proximity to the Fukushima plant: 129mTe, 131I, and 137Cs show similar release behaviors, whereas about 1/400th as much 140Ba is released as Cs. These findings confirm that the data obtained in the vicinity of the Fukushima plant are representative of the general release patterns.

The relative behavior of the different nuclides near the Fukushima plant also matches very well with experimental results. In a Knudsen cell experiment, spent nuclear fuel fragments were heated stepwise in a closed, confined space to temperatures in excess of 2000 °C, and the stepwise volatilization of the various elements were measured by mass spectrometry (Rondinella et al. 2008). Figure 4 presents a typical result obtained from MOX fuel samples. Volatilization starts at 1000 °C with the release of Te and He (produced by alpha decay), while Cs and I start to volatilize at 1100 °C. Finally, uranium begins to volatilize above 1600 °C. Interestingly, Ba shows an intermediate level of volatility. From these data, temperatures in the Fukushima reactors were probably high enough to cause the volatilization of most of the Xe inventory and a large fraction of the Cs, but certainly not the actinides (U, Pu, and minor actinides such as Am, Cm, and Np).

The confinement of most of the actinides within the reactors is, on one hand, reassuring, as these elements carry the highest long-term toxicity burden. On the other hand, a direct consequence of this confinement is that the long-term risk assessment requires the evaluation of the fate of

![Graphical representation of radioactivity measurements, reported periodically by TEPCO (2011) between March and November 2011 for the Fukushima plant at soil-sampling locations (denoted “Playground”) located about 500 m north-northwest of the stacks of Units 1 and 2. The large symbols at the date of the accident represent reference values, which correspond to hypothetical activities for the case in which all nuclides have been released to the same extent (i.e. the same fraction of reactor core inventory of a given nuclide) as that of Cs. Measured values lower than the reference value indicate a much lower extent of release than Cs.](image-url)
the remaining fuel in the reactor. How can we proceed with this assessment, considering the fact that due to high radiation fields direct access to the fuel will probably not be possible for at least a few decades? Some indirect information on the release behavior of the radionuclides in the reactor core can be derived from chemical analyses of the cooling water collected from the three damaged reactor cores. A cooling circuit was installed by TEPCO in July 2011, which runs decontaminated water through the three destroyed reactor cores and collects outflowing contaminated water for decontamination and desalination, after which the decontaminated water is re-injected. Decontamination factors for $^{137}$Cs were $10^6$, meaning that Cs activity in the water was a million times lower after a decontamination cycle than before. About 180,000 m$^3$ of highly contaminated water were collected for decontamination with a specific activity for $^{137}$Cs varying between 1.8 Bq/mL in July 2011 to 0.7 Bq/mL in November 2011 (data on the volumes collected and the associated activities are from TEPCO reports; TEPCO 2011). These data indicate a total release to the water of $1.7 \times 10^{17}$ Bq or about 27% of the total $^{137}$Cs inventory in the cores of reactors 1–3. However, some fraction of the volatile elements, such as Cs, may have recondensed in the coldest parts of the primary cooling circuits during the accident. This figure is therefore a minimum amount of Cs release from the fuel. Specific activities for the nuclides $^{89,90}$Sr were $6 \times 10^5$ Bq/mL in July 2011. No data were reported for longer contact periods. The Cs/Sr activity ratio in water collected in July is about 10 times higher than in the fuel, indicating reduced mobility of Sr as compared with Cs.

Due to the very high temperature during the meltdown, fuel pellets, as well as the zircaloy cladding and steel, melted and mixed, yielding an ill-defined material called corium. Earlier work, as in the French VULCANO experiments or the characterization of the core of reactor 2 at Three Mile Island, demonstrated that corium consists of several phases: an oxic phase and one or two metallic phases, depending on the accident conditions, which can cause the separation of the heavier and lighter metallic elements. How can we estimate the long-term stability of corium? In laboratory experiments performed on simulated corium, Pontillon and Durcos (2010) identified four groups of released elements:

1. Volatile fission products, including fission gases (Xe, Kr), I, Cs, Sb, Te, Cd, Rb, and Ag
2. Semivolatile fission products, including Mo, Rh, Ba, Pd, and Tc
3. Low-volatility fission products, such as Ru, Ce, Sr, Y, Eu, Nb, and La
4. Nonvolatile radionuclides, including Zr, Nd, Pr, and some of the actinides (U, Pu, Np, Am, Cu)

These laboratory results are consistent with the behavior of the measured radionuclides at the Fukushima plant: group 1 corresponds to radionuclides that have been significantly released (30 to 100%) into the cooling water (Cs) and into the environment (Xe, Cs, I, Te); groups 2 and 3, as indicated by Ba and Sr, seem to have been significantly released from the fuel (0.01%; see the discussion related to Fig. 3), but only a small part of these elements has reached the environment, probably due to their lower volatility and their propensity to recondense within the primary circuit (see Fig. 3); and group 4 essentially was not released from the fuel (99.9999% retained).

**LONG-TERM CORIUM ALTERATION IN WATER**

**Characteristics of the Two Main Alteration Mechanisms**

Oxic corium is a solid solution with a tetragonal structure. Although it has not been demonstrated that corium is a single phase, it may be possible to consider the oxic corium as hyperstoichiometric $\text{UO}_2+x$; stoichiometric deviations of the fuel were about $x = 0.14$ for samples obtained from the molten core of the Three Mile Island Unit 2 reactor (Bottomley and Coquerelle 1989). This value is lower than the threshold value of $x = 0.25$, which corresponds to $\text{UO}_3$. Corium compositions obtained from fuel treated in the PHEBUS severe-accident facility (Barrachín et al. 2008) were close to $\text{U}_{0.99}\text{Zr}_{0.01}\text{O}_{2.23}$ and $\text{U}_{0.86}\text{Zr}_{0.12}\text{Fe}_{0.005}\text{Cr}_{0.001}\text{Nd}_{0.006}\text{Pu}_{0.004}\text{Ce}_{0.004}\text{O}_{2.42}$ for irradiated fuel and to $\text{U}_{0.95}\text{Zr}_{0.04}\text{Fe}_{0.001}\text{O}_{2.32}$ for nonirradiated fuel. In the latter cases, these compositions correspond to an average deviation of $x = 0.33$ from the normal stoichiometry.

Considering corium as hyperstoichiometric $\text{UO}_2+x$ allows the use of certain analogue materials for assessing the long-term behavior of corium in contact with natural waters. Indeed, many studies have been performed worldwide over at least 30 years on different types of uranium oxides in order to assess the long-term behavior of spent nuclear fuel under geological repository conditions. For instance, solid-water reactions have been studied for different solid solutions, such as $\text{UO}_2$; partly oxidized or fresh spent nuclear fuel; pure $\text{UO}_2$; oxidized $\text{UO}_2$; alpha-doped $\text{UO}_2$ simulating long-term irradiation fields; and natural uraninite (Forshy 1995; Grambow et al. 1996, 2000; Stroes-Gascoyne et al. 1997; Röllin et al. 2001; Ollila et al. 2003; Werme et al. 2004; Poinssot et al. 2005; Ollila 2008). The European-funded MICADO project (Grambow et al. 2010) recently assessed the uncertainties in the different models describing the dissolution processes of spent nuclear fuel disposed of in a deep repository for geological periods. Based on this knowledge, some key issues can be considered.

First, as for $\text{UO}_2$-derived solids, two radionuclide fractions can be distinguished: (1) fast-dissolving radionuclide inventories (the so-called “instant release fraction,” or IRF), which correspond to radionuclides that are not bound into

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**Figure 4** Knudsen cell analysis of the volatile release of radionuclides during heating of irradiated MOX fuel beyond normal conditions, from the European project NF-PRO. “M.S.” means “mass signal”; for the present discussion, only relative values are of importance. The left scale applies to all radionuclides except Xe and UO$_2$, which are plotted against the scale on the right. Modified from Rondinella et al. (2008)

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**Table 1** Corium compositions obtained from fuel treated in the PHEBUS severe-accident facility (Barrachín et al. 2008) were close to $\text{U}_{0.99}\text{Zr}_{0.01}\text{O}_{2.23}$ and $\text{U}_{0.86}\text{Zr}_{0.12}\text{Fe}_{0.005}\text{Cr}_{0.001}\text{Nd}_{0.006}\text{Pu}_{0.004}\text{Ce}_{0.004}\text{O}_{2.42}$ for irradiated fuel and to $\text{U}_{0.95}\text{Zr}_{0.04}\text{Fe}_{0.001}\text{O}_{2.32}$ for nonirradiated fuel. In the latter cases, these compositions correspond to an average deviation of $x = 0.33$ from the normal stoichiometry.
the matrices (either corium or spent fuel); (2) a slow-release fraction of radionuclides, which are located in the matrices (corium or spent fuel) and released as the corium matrix dissolves.

**Instant Release Fraction (IRF)**

The so-called IRF release is not governed by any mechanism but corresponds to radionuclides that are dissolved fast upon fuel–water contact. Therefore the only issue to address is the quantity of fast release upon water contact. No experimental data are available for corium. For spent fuel, IRF values are in the range of 5–10% of the total inventory, depending on the radionuclides (Ferry et al. 2007). Considering the typical corium-formation scenario (a transient event at very high temperature, >2300 °C, followed by a decade-long phase during which the corium is cooled under water), it is likely that a large part of the unbound radionuclides has already been released in the reactor core and to the cooling water and that these radionuclides are no longer retained in the fuel matrix. The remaining long-term IRF fraction in the corium is therefore anticipated to be very limited.

**Slow-Release Fraction**

The dissolution process of the corium matrix in water is likely to be electrochemically controlled, as for spent fuel (see Figure 5 for spent fuel). Due to the large difference in uranium solubility under oxidizing and reducing conditions (roughly $10^{-6.5}$ and $10^{-9.5}$ mol L$^{-1}$, respectively), the corium matrix will probably undergo two competing dissolution mechanisms: (1) under oxidizing conditions, a relatively fast surface-interaction-controlled dissolution and (2) under reducing conditions, a slow solubility-controlled dissolution.

Under **oxidizing conditions**, spent fuel or UO$_2$ leaching requires, first, a surface oxidation of UO$_2$ to a mixed U(IV)/V) oxidation state of hyperstoichiometric UO$_{2+x}$, with $x > 0.33$ (UO$_2$), and then complete oxidizing dissolution as dissolved U(VI) species. As measured on synthetic samples, the corium matrix is likely to be already oxidized so that its stoichiometric deviation is given by $x = 0.33$, and no additional surface-oxidation step prior to oxidative leaching is probably necessary. One can anticipate a faster oxidation rate than for spent nuclear fuel. Oxidant influx is however necessary for transforming the remaining U(IV) into U(VI):

$$\text{U}^{IV} + \text{O}_2 \rightarrow \text{U}^{VI}$$

Temperature, the metal of the disposal containers.

Whether oxidizing or reducing conditions prevail in the damaged reactor cores may be assessed by analyzing the concentrations of U and Pu in the cooling water and by studying solubility controls: high concentrations ($>10^{-5}$ mol/L) are, for example, typical of oxidizing conditions. The experimental database on the interaction of UO$_2$-derived solids with water shows that temperature, the solubility limits of radionuclides, fuel-damage conditions, burnup, and the presence of remaining cladding play major roles in the effective radionuclide release from the corium matrix. Furthermore, the dissolution rates are not expected to be directly proportional to the specific surface areas. As far as water chemistry is concerned, redox potential and carbonate concentrations are key parameters (Bruno and Ewing 2006), whereas salinity (seawater versus freshwater) will play only a minor role in radionuclide release (Loida et al. 1994). Colloidal particles and dissolved organic matter are important for the transport of sparingly soluble radioelements such as Pu and Am (Kim and Grambow 1999).

**Potential Influence of Radiation Fields**

The temporal evolution of the redox conditions at the corium–water interface has an important effect on the radionuclide release behavior. The evolution of this behavior will be quite different under oxic surface conditions than under the reducing conditions in a deep geological repository. Air ingress is indeed omnipresent under oxic surface conditions, but in a geological repository, it only occurs during the operations phase, and thereafter all remaining air is consumed by redox reactions, in particular, with the metal of the disposal containers.

Spent nuclear fuel and the corium short-term radiation field mainly give off oxidizing gamma radiation, while over the very long term (>100 years) the radiation field is characterized mainly by alpha-decay radiation. During the first few hundred years, gamma radiation may strongly increase
The 131I content in soil samples is much larger than the samples correspond to inventory ratios in the reactors, and it is consistent with the absence of a significant release of actinides around the Fukushima site. The ratios of the activities of 137Cs, 131I, 110m Ag, and 129m Te reported for soil samples correspond to inventory ratios in the reactors, and the 131I content in soil samples is much larger than the value that would be expected if a large contribution came from the fuel storage ponds. The large quantity of radionuclides released from the three reactors probably masks any contribution from the fuel storage ponds, which confirms a much lower fuel alteration in the ponds.

Furthermore, from the large data set that has been acquired in the last few decades about the long-term evolution of spent nuclear fuel in water, some insights may be gained about the behavior of the oxic corium, whether in a geological repository or in long-term storage (such as within a protective sarcophagus). By comparison with spent nuclear fuels, after the passage of cooling water, oxic corium is anticipated to have a much lower IRF, potentially zero, and its radionuclide release behavior should be dominated by matrix alteration, which should be faster than for spent nuclear fuel. Three main options are therefore possible for corium management:

- **Recovery of the corium in order to condition it inside suitable containers without further treatment,** as was done with reactor 2 at Three Mile Island, while waiting for subsequent disposal in a deep geological repository. However, the amount of fuel lost in the melted core at Three Mile Island in 1979 was about 30 tons, less than one-twentieth the inventory at Fukushima (reactors and pools). In this case, the long-term release behavior of the corium is anticipated to be less desirable than that of spent nuclear fuel, since the long-term alteration rate of the corium will be higher. However, little or no IRF is anticipated, which would be favorable since the IRF dominates the long-term impact of spent fuel in a repository.

- **Treatment, in order to decrease long-term toxicity and to optimize the stabilization of corium in dedicated waste matrices.** Indeed, the most toxic elements, such as the actinides, could be recovered by separation processes, such as hydrochemistry or pyrochemistry. Pyrochemical processes may be of great interest due to the presence of numerous metallic components and the anticipated refractory behavior of part of the corium. Such treatment may allow confining the most mobile radionuclides in a stable matrix instead of having them dispersed in the ill-defined corium matrix. In this option, the long-term release performance of the waste will depend on the specific matrix to be used. If vitrification of corium is chosen, good performance for up to 10^6 years can be anticipated.

- **Finally, the site can be stabilized by creating some kind of protective sarcophagus.** During a period lasting hundreds of years, natural waters will probably find access to the corium inside the sarcophagus, and the corium will likely corrode and release radionuclides; these would have to be recovered and managed. This is not a long-term option (thousands of years), but it may be a solution for a time period during which institutional control can be assured, which is intrinsically difficult to assess (what about the stability of current societies over hundreds of years?).

Whether option 1 or 2 is chosen, only a preliminary estimate of the long-term performance is possible based on the present knowledge of spent nuclear fuel behavior. Studies of real corium samples from Fukushima will have to be performed, either to develop a treatment process or to characterize the radionuclide release properties of untreated corium. In the absence of relevant and robust experimental data, conservative assumptions in performance assessment will probably lead to prohibitively expensive solutions.

Upper limits for radionuclide release predictions from the corium matrix can be obtained by developing a site-specific performance model for the Fukushima corium. Such a model could be created based on actual observations of the corium in the reactors in the presence of water. In the present study, we used the reported activities of 137Cs and 90Sr in the outflowing cooling water to conclude that about 30% of the Cs inventory and about 3% of the Sr inventory were mobilized from the three reactors. In a similar way, one could analyze the evolution of the activities of other radionuclides (239Pu, etc.) in the cooling water of the reactor to assess the mobility of these nuclides in the core and to quantify source terms for water contact for the various conditioning and disposal scenarios. The continued flushing of the molten cores with water will in the long term also reduce the inventories of radionuclides that can be mobilized rapidly during disposal.

**CONCLUSION**

Comparison of radionuclide release from the reactors with the radionuclide inventories remaining in the reactor and estimation of corium–water interaction from known spent fuel–water interaction provide important insight for developing assessment and management strategies for the molten fuel in the reactor cores. If corium is to be disposed of without treatment, models for corium stability and for radionuclide release from corium upon contact with water will have to be developed based on (1) analyses of radionuclide activities in actual cooling waters, (2) chemical modeling of the analytical results in the context of the kinetics and thermodynamics of actinide and fission product release (solubility constraints, redox states, etc.), and (3) comparison with spent fuel behavior and experimental corium databases. If corium treatment is being considered in view of either confining it in a more stable matrix or even recovering the most radiotoxic radionuclides, specific processes will have to be developed based on the corium properties and the wide knowledge available about fuel treatment.
REFERENCES


IRSN (2011) Synthèse actualisée des connaissances relatives à l’impact sur le milieu marin des rejets radioactifs du site nucléaire accidenté de Fukushima Dai-ichi, 26 octobre 2011


TEPCO (2011) Data source: measurements at Fukushima Daiichi nuclear power station at periodic soil sampling point of activities “Playground” at about 500 m from stacks of Unit 1 and 2 in direction west/north-west. Updated periodically on the Web


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Call for Session Proposals for IMA 2014

Preparations are well under way for the 21st meeting of the International Mineralogical Association (IMA) in South Africa. The overall theme of the IMA 2014 meeting is “Delving Deeper – Minerals as Mines of Information.” The logo is symbolic of South Africa’s rich mineral resources, from which has sprung its dynamic mining heritage, also the backbone of the country’s economy. The meeting will take place on 1–5 September 2014 at the Sandton Convention Centre, in the heart of Johannesburg, the City of Gold.

The IMA 2014 meeting will be held under the auspices of the Geological Society of South Africa and the Mineralogical Association of South Africa, and is already generating sponsorship from the mineral industry, which will enable a professional, vibrant atmosphere for a memorable conference. South Africa’s sizeable community of mineralogists will contribute to the hosting of this first IMA meeting on African soil, and all aspects of mineralogy will be covered. The Organizing Committee is headed by Dr Sabine Verryn as conference chair, along with Dr Desh Chetty as scientific committee chair and Dr Craig Smith as finance chair.

Proposals for sessions and topics to be covered are invited (e-mail: info@ima2014.co.za), and further information is available on the conference website (www ima2014.co.za). Please register to receive updated information if you are not already on the communications list. The Organizing Committee looks forward to welcoming everyone to South Africa in September 2014.
FROM THE PRESIDENT

With my two vice-presidents, Guy Libourel and Javier Escartin, and the support of a renewed Council composed mainly of young scientists, it is a true pleasure and great honour for me to be the president of the SFMC for the term 2012–2013. I am convinced that, in France and in Europe, these two years will be known in the future as the beginning of the “renaissance” of the idea that minerals are key products for the development of our civil societies, as occurred in the past during the Stone, Bronze and Copper ages. A milestone for this new age happened in February 2012, when the European Commission identified non-energy, non-agricultural raw materials as one of the three societal and economic challenges for the future, along with health and agriculture. This is a response to the ever-growing pressure on industry’s access to critical elements, like the rare earths. Minerals and materials of natural or artificial origin are thus at the heart of the scientific and technical issues raised by the global management of our raw-materials resources. The issues involve extracting, recycling and substitution processes, and they require consideration of the whole chain of environmental impacts and the necessity to reinforce, and rebuild in some cases, research, education, training centres and networks. This renewal coincides with the emergence of nanomaterials, which, because of their novel properties, may help to reduce material consumption; but they also bring many disturbing questions about their impacts on the environment and human health. So it is an exciting time for mineralogical societies in general and the French community in particular to be involved in these two crucial issues. We must work on maintaining bridges between academic research on one hand and industry and the public on the other.

I am convinced, as were SFMC past-presidents Anne Marie Karpoff and Patrick Cordier before me, that societal and economic questioning will provide our community with many opportunities to increase the visibility, attractiveness and notoriety of our discipline worldwide.

Bruno Goffé, SFMC President

SFMC ELECTION RESULTS FOR 2010–2012

President: Bruno Goffé (CEREGE, Marseille)
1st vice-president: Guy Libourel (CRPG, Nancy)
2nd vice-president: Javier Escartin (IPGP, Paris)
Secretary general: Marc Blanchard (IMPMC, Paris)
Assistant secretary general: Maryse Ohnenstetter (CRPG, Nancy)
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Councilors: Muriel Andréani (UCBL, Lyon), Anne Line Auzende (IMPMC, Paris), Etienne Balan (IMPMC, Paris), Sylvain Bernard (MNHN, Paris), Delphine Charpentier (UFC, Besançon), Valérie Chavagnac (LMTG, Toulouse), Alain Cheilletz (CRPG, Nancy), Stéphanie Duchêne (CRPG, Nancy), Mathieu Roskosz (UMET, Lille), Denis Testemale (Institut Neel, Grenoble)

WELCOMING NEW COUNCIL MEMBERS FOR 2012–2014

Bruno Goffé, CNRS, senior scientist at CEREGE Aix-Marseille, was the head of the Earth sciences division at the National Earth and Astronomy Institute (INSU) from 2006 to 2011. He is a mineralogist, petrologist and geologist specialized in mountain building, metasediments, experimental mineralogy and materials science. He has supervised 30 PhD and 50 master’s students and is the author or co-author of 150 peer-reviewed publications and 17 patent publications.

Alain Cheilletz is a full professor at the École Nationale Supérieure de Géologie de Nancy, Lorraine University. As an economic geologist, he has worked on tungsten, copper, lead–zinc and gold deposits around the world. He is the co-holder of three international patents devoted to determining the geographic origin of emeralds and was an associate editor of Mineralium Deposita (2001–2005).

Sylvain Bernard is a CNRS research scientist at the Muséum National d’Histoire Naturelle (Paris). During his PhD in 2008 at the Laboratoire de Géologie de l’ENS, he documented the preservation of traces of life in rocks that had experienced intense metamorphic conditions. His scientific goals can be synthesized in a single question: How do biomolecules (and biominerals) evolve during fossilization processes?

Javier Escartin is a CNRS senior scientist at the Institut de Physique du Globe de Paris and adjunct scientist at Woods Hole Oceanographic Institution. His main areas of interest are the formation and evolution of the oceanic lithosphere and the use of experimental rock mechanics to understand the rheology and mode of deformation of alteration products (e.g. serpentinites) in the oceanic environment.

Mathieu Roskosz is an assistant professor at Lille 1 University. He is an experimentalist in the field of mineral physics and chemistry, with applications in astrophysical and magmatic environments. Recently, he has been applying an experimental approach to the study of isotopic fractionation and equilibration processes.

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- Rheology, Deformation
- Thermodynamics
- Origin of Life, Primitive Planets
- Societal Implications
- Magnetic Properties
- Geodynamics

2-6 September, 2012
Porquerolles Island, 83412 Hyères, France
http://www.sfmc-fr.org

Contact: serpentines2012@sfmc-fr.org
In this President’s Letter, I want to talk about global climate change science and opinion, which I believe can help inform us about a transformation that is happening today in the science of mineralogy and all the other sciences that mineralogy touches.

Recently, I saw reported in the New York Times the results of an opinion poll that had been very carefully designed and commissioned by academics at Yale and George Mason University. By roughly a 2-to-1 margin, the poll reports that Americans perceive that weather extremes have increased in recent years and that “global warming is affecting weather in the United States.” Contrast this apparent sea-change with the deep aggravation that most scientists have experienced (at least in the United States) over the last several years, where a vanishingly small number of vocal scientists with alternative opinions to standard scientific views on global climate change have had the bulk of public opinion on their side. I was also impressed by an article published in Physics Today (March 2012) by Jane Lubchenco and Thomas Karl, administrator and director, respectively, of the U.S. National Oceanic and Atmospheric Administration. In that article, they lay out the quantifiable evidence for the increase in extreme weather events over the last few decades, and they remind us that this is a prediction of mainstream global climate change science, which climatologists are continuing to refine. I believe that we are far from a general public understanding of the views that we are conducting a very dangerous experiment by burning fossil fuels as fast as they can be pulled from the ground, that the cost of energy in the near term is not nearly as important as the cost to the planet in the long term, and that debating these issues in the political arena can only break down into dramatic counterproductivity. But I am delighted that at least there is a move to wake up the general public about topics that people must (eventually) understand, for this really is one of the very most important issues of our time.

How could this possibly have anything to do with the way we, as mineralogists, currently perceive our science, and where it is going in the future? There are many ways to answer this question, and I have already written, albeit indirectly, about this kind of thing in my previous presidential letters, Elements editorials, and certain published articles. However, here, we will take a slightly different tack to see the connection. Richard Harrison at Cambridge is currently leading a remarkable initiative, sponsored by the Mineralogical Society of Great Britain and Ireland, known as the “100 Most Important Questions in Mineralogy.” The stated purpose? “We aim to identify 100 mineralogical questions that, if answered, would have the greatest impact on resolving current and future challenges in the Earth, planetary, and environmental sciences.” With input from mineralogists the world over (including, undoubtedly, many of you, and, for better or worse, myself), they are well on their way to doing this. Well over 200 questions have been proposed to date, and we have been challenged to assess these entries according to several criteria, including by considering the following question: “What does the list convey to funding agencies and the wider public about the research we are doing as a community?” This is where global climate change comes back into the picture. Several submitted mineralogy-based questions speak to the heart of the global climate change research picture. Here are just two, whose answers are largely missing in climate change science, but sorely needed:

What gas phase reactions are catalyzed on mineral–dust surfaces in the atmosphere, and what is their impact on atmospheric chemistry?

Which abundant airborne minerals, if any, have important radiative properties and thus affect climate change?

These and related questions put mineralogy squarely in the core of future, critical climate change science, and as a result, into the public (and political) eye. But clearly, that is exactly where we want mineralogy to be, helping to understand these critical issues relevant to Earth sustainability. Answering questions like the two above take large numbers of interdisciplinary scientists, who are at least in part serious mineralogists, working for many years to sort through these challenges. In the process, if done well with skill and patience, the great questions of our time are answered, along with attracting the public and political support that is ultimately so important.

This example is just one of many. Within the “100 Most Important Questions in Mineralogy” exercise to date, many deeply insightful questions have been submitted. In several cases, revealing mineralogical questions addressing key issues have been put forward, spanning the fundamental and applied sciences, in fields from the origin of life to aspects of geophysics, from plate tectonics to heat transfer. For example: What does the temporal distribution of minerals through >4 billion years of Earth history reveal about global tectonics and the supercontinent cycle?

Other areas addressed by these questions have to do with everything from ocean science to nanogeoscience. For instance: What is the inventory of mineral nanoparticles in the world’s oceans, and what biogeochemical role do they play, including the role they play in supplying limiting nutrients to the vital photosynthetic microorganisms of the oceans?

The science of mineralogy has moved to the fore. It is a science that is now sophisticated enough to integrate with other advanced disciplines to gain valuable insight into the most pressing fundamental, as well as practical, questions of this age. For a mineralogist, what could be more valuable and rewarding than that? Let’s do our job effectively, and contribute.

Michael F. Hochella Jr. (Hochella@vt.edu), Virginia Tech, President, Mineralogical Society of America

**VOTE 2012 MSA ELECTIONS**

MSA members should have received voting instructions at their current e-mail addresses. Those who do not wish to vote online can request a paper ballot from the MSA business office. As always, the voting deadline is August 1.

The MSA had a booth at the Tucson Gem and Mineral Show, Tucson, Arizona, on 9–12 February 2012, a show celebrating Arizona’s “Centennial” with the theme of “Minerals of Arizona.”

The Dana Medal will be presented to Roberta L. Rudnick at the 2012 Goldschmidt Conference in Montreal, Québec, Canada, to be held on 25 June–1 July 2012. There will be a special session in her honor, “Formation, Evolution, and Destruction of Cratons and Their Lithospheric Roots,” during which she will give her Dana Lecture.

MSA will have a booth at the GSA Annual Meeting in Charlotte, North Carolina, USA, on 4–7 November 2012. During that week, MSA will hold its Awards Lunch, MSA Presidential Address, Joint Reception among MSA, GS, and GSA’s Mineralogy, Geochemistry, Petrology, and Volcanology Division, annual business meeting, Council meeting, and breakfasts for the past presidents and associate editors. Do not forget the lectures by Roebling Medalist Harry W. Green II and MSA Awardee recipient Karim Benzerara. More information will be available through the MSA website.

MSA has in stock the newly published Landmark Paper Number 4 (2012): *Classic Papers in Granite Petrogenesis*. The volume includes the selected papers and a commentary by John Clemens and Fernando Bea. MSA also has the previous 3 volumes of the series. Descriptions, tables of contents, and ordering of these and other volumes can be accessed on the MSA home page, www.minsocam.org/MSA/Mineralogical_Society.html#landmark.

J. Alex Speer, MSA Executive Director
jaspeer@minsocam.org

**50- AND 25-YEAR MSA MEMBERS**

The following individuals will reach 50 or 25 years of continuous membership in the Mineralogical Society of America during 2012. Their long support of the Society is appreciated and is recognized by this list and by 25- or 50-year pins, mailed in early January. If you should be on this list and are not, or have not received your pin, please contact the MSA business office.

**50-Year Members**

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**25-Year Members**

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**MINERALOGICAL SOCIETY OF AMERICA UNDERGRADUATE PRIZES FOR OUTSTANDING STUDENTS**

The Society welcomes the following exceptional students to the program’s honor roll and wishes to thank the sponsors for enabling the Mineralogical Society of America to join in recognizing them. MSA’s Undergraduate Prizes are for students who have shown an outstanding interest and ability in mineralogy, petrology, crystallography, and geochemistry. Each student is presented a certificate at an awards ceremony at his or her university or college and receives an MSA student membership, which includes a subscription to *Elements* and a *Reviews in Mineralogy Monograph* volume chosen by the sponsor, student, or both.

Past Undergraduate Prize awardees are listed on the MSA website, as well as instructions on how MSA members can nominate their students for the award.

**Jenifer Axler**
Smith College
Sponsored by Dr. John Brady

**Marisa Davies**
University of Victoria
Sponsored by Prof. Dante Canil

**Nicholas Davis**
Texas A & M University
Sponsored by Dr. Robert Popp

**Lauren Finkelstein**
George Washington University
Sponsored by Dr. Richard Tolio

**James C. Gossweiler**
Towson University
Sponsored by Dr. David Vanko

**David W. Hawkins**
George Mason University
Sponsored by Dr. Julia Nord Cooper

**Kathryn Kumamoto**
Williams College
Sponsored by Prof. Reinhard Wobus

**Thao P. Le**
University of Oklahoma
Sponsored by Dr. David London

**Kara E. Marsac**
Eastern Michigan University
Sponsored by Dr. Christine Clark

**Benjamin S. Murphy**
Pomona College
Sponsored by Dr. Jade Star Lackey

**Abbey Nastan**
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**Nathalie Elizabeth Sievers**
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**Jacob van Wesenbeeck**
Indiana University
Sponsored by Prof. David Bish

**IN MEMORIAM**

Friedrich Liebau – Senior Fellow – 1962
THE PRESIDENT’S CORNER

Funding Geochemistry and Other News

For the most part, geochemistry is perceived as an academic discipline whose impact on society is limited. However, as time passes, geochemistry and its related multiple subfields have become essential in showing the way towards solutions for the major challenges that our society has to face in the future. EAG Past President Eric Oelkers, in a provocative plenary lecture at the Goldschmidt meeting in Knoxville, told us “how geochemistry can save the world.” There is no end to the list of domains where geochemists can help in this noble cause. Energy: The future depends on finding and better managing new energy resources, be they unconventional gas and oil or new sources of uranium and coal, until other more renewable and ecologically friendlier energy sources can take over. The underground capture and storage of CO₂ also require the advanced and multifaceted knowledge of geochemists. Water: Being able to predict the quality of water resources and the pathways of contaminants released by human activities clearly requires the know-how of geochemists. Mineral resources: The scarcity of several strategic materials is a challenge for geochemists involved in understanding the genesis and long-term utilization strategies for ore deposits. This list could be further expanded by adding climate change, forensic geochemistry, soil conservation, etc. However, while specific programs are targeted at these societal questions, it can be said that the geochemical community has failed at identifying itself as the prime science at the root of and leader in the applications mentioned above. From that perspective, our community should “reclaim its copyrights” and become more proactive in increasing its visibility to governments, funding agencies and the European Union. In my own subdiscipline, isotope geochemistry, it is rather obvious that the boundary between basic science and the science that funding agencies or governments include in their focused programs is very fuzzy. Many tools and approaches originally developed for understanding mantle geochemistry or the early Solar System have been used in more applied geochemical approaches. Overall, this is true for most geochemical fields, where much of the basic understanding upon which applied geosciences are based stems from more fundamental investigations that are nowadays unfortunately looked down upon by funding agencies. All this is probably rather obvious to most geochemists. Yet, I am convinced that one has to be relentless in making this message known, if we are to halt and perhaps even reverse the ever-diminishing funding stream for fundamental geochemical research. There is a clear need for raising awareness about this topic, and our societies should be at the forefront of this endeavour.

On another front, I would like to talk to you about the recently launched EAG blog (http://blog.eag.eu.com/). It is a new endeavour that started in March 2012; we have several regular geochemical bloggers and various intermittent bloggers and storytellers, and naturally, contributions from the community are highly encouraged and more than welcome. I would like to congratulate Juan Diego Rodriguez-Blanco (University of Leeds) and his team, as well as Marie-Aude Hulshoff from the EAG, for making our association even more lively through this blog.

Bernard Bourdon, EAG President
Lyon, April 2012

Goldschmidt2013 boasts cultural delights and an excellent science program. The Goldschmidt conferences, co-sponsored by the EAG and the GS, is now the foremost conference in Geochemistry, with over 3300 delegates attending the 2011 meeting in Prague.

Call for additional sessions starts September 2012
DO PUT THESE DATES INTO YOUR DIARY
AND JOIN US FOR WHAT LOOKS SET TO BE AN OUTSTANDING MEETING.
WHY JOIN A PROFESSIONAL SOCIETY?

This question was recently posed to the membership of the Geochemical Society in a survey whose goal was to ensure that the Society continues to best serve the needs of its membership. The responses were eye-opening, and reflective of scientists’ changing expectations and needs as they increasingly rely on social media for peer-to-peer communication and access to journals through library e-subscriptions. The strongest message received concerned many aspects of the journal we co-sponsor with the Meteoritical Society, *Geochimica et Cosmochimica Acta*. Some parts of this story we already knew. The number of personal subscriptions to *GCA* is becoming vanishingly small as the membership, and everyone else, gets access to the journal electronically through their library. Many respondents noted the turmoil, hopefully solved by the time you read this, that accompanied the most recent contract negotiation with the publisher and the change in editorial leadership. The role of a commercial publisher in society journal production was a particularly prickly topic among respondents, with many pointing out the diminishing society editorial control and questioning the wisdom of letting commercial publishers profit from the authors’ products and the editorial services provided, generally for free, by our community. What was less often noted is that *GCA* has been the number-one-cited full-length journal in the category of geochemistry/geophysics for many years, in part because of the fair and even-handed peer review managed by Frank Podosek and the selfless service of a large board of dedicated associate editors. Other positive features include the fact that, in most cases, authors can publish in *GCA* for free, that the web presentation of the journal, created by the publisher, allows the reader easy discovery of related papers and, in the near future, the ability to link with other related datasets. Where the balance lies between the strengths and weaknesses of the Society’s current publishing activities is front and center in the mandate given to the recently restaffed Publication Advisory Committee, which will be examining the types of publishing activities that would best address the needs of the membership. *GCA* is but one of many publications cosponsored by the Geochemical Society, one of which you are reading now.

One experiment in our publications inventory is the redesigned *Geochemical News* (www.multibriefs.com/briefs/gs), now e-mailed weekly to the membership. The GN provides the opportunity to communicate news of interest to the geochemistry community quickly and link the membership to newsworthy stories across the broad field of geochemistry. The GN is at your disposal to advertise meetings and publications and to post funding announcements and other news items of interest to the geochemical community. Also appearing in GN are job postings listed in our Career Center (www.geochemsoc.org/career-center), an economical way to have your job postings viewed by over 4000 subscribers to the GN.

Another traditional raison d’être for a professional society is conferences, and here the nearly 3000 abstracts submitted to this year’s Goldschmidt Conference in Montreal reflect the continued popularity of the Goldschmidt and its increasing ability to attract attendees from across the breadth of geochemistry. Going forward, our efforts will be focused on keeping Goldschmidt strong by looking for ways to reduce the expense of the meeting for attendees, increasing support for student participation, providing additional content, and rotating the meeting location through a larger proportion of the world, in keeping with the international nature of the Geochemical Society. As with our multiple publishing activities, the Goldschmidt Conference is not our only conference-related activity. The Meeting Assistance Program offers grants of up to $2000 to support smaller, thematic meetings (www.geochemsoc.org/programs/meetingassistanceprogram). You can read a report on a meeting we sponsored on page 236. Along these lines, we have also joined forces with the EAG in establishing an outreach program, whose goal is to bring modern approaches and interesting applications of geochemistry to audiences that have fewer opportunities to interact routinely with the international geochemical community. Perhaps the most distressing survey responses were from those who noted their desire to partake in Society activities but could not afford to do so. The US$30 membership fee of the GS is small by western standards, but not for some developing countries. We hope to address this issue with some form of sliding membership fee that ties the fee to an index of relative income. We already do something similar for students and retirees, who pay a membership fee that is just enough to cover their subscription to this magazine; so, in essence, they receive the other benefits of GS membership for free.

The ongoing programs mentioned above address the majority of member services requested by survey respondents. Beyond these, the survey responses provided a number of ideas for ways in which the GS can expand its activities to better address the needs of the geochemical community. The leadership takes these suggestions seriously and will work to implement as many as feasible. This path thus provides at least one answer to the question “Why join a professional society?” because a professional society can marshal and direct a critical mass of energetic individuals to make highly cited publications a reality, organize well-attended conferences, provide rapid reporting of news relevant to the community, connect those offering jobs to those looking for employment, and provide a variety of other services of benefit to the membership. The GS greatly appreciates the membership participation in the benefits survey and looks forward to making many of the suggested new benefits a reality.

Rick Carlson (rcarlson@ciw.edu), GS President

NOTES FROM ST. LOUIS

Remember the 15 October 2012 deadlines for the 2013 GS awards: Goldschmidt Medal, Clarke Medal, Patterson Medal, Treibs Medal, and the GS/EAG Geochemical Fellow. Nomination requirements and procedures are available online at www.geochemsoc.org/awards/makeanomination.

The GS Meeting Assistance Program (MAP) was established in 2002 to allocate up to five sponsorships of up to US $2000 each ($10,000 annually) in support of geochemistry sessions/symposia at any scientific conference of geochemical relevance. Past sponsorships and application procedures are available at www.geochemsoc.org/programs/meetingassistanceprogram/.

The GS weekly e-newsbrief, *Geochemical News*, now has more than 4000 subscribers. Subscription is included with membership, but anyone may subscribe for free at: http://multibriefs.com/option.php?gs. Archives of recent issues are also online at http://multibriefs.com/briefs/gs/.

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E-mail: gsoffice@geochemsoc.org
Website: www.geochemsoc.org
2012 METEORITICAL SOCIETY FELLOWS

Philip Bland (UK/Australia) – For original and diverse studies of important meteorite problems, helping establish the Western Australia camera network, and contributions to the society

Christine Floss (USA) – For superior ion microprobe studies of isotopes and trace elements in diverse meteorites and in presolar grains, as well as for contributions to the society

Makoto Kimura (Japan) – For outstanding studies of the mineralogy and petrology of primitive chondrites and of high-pressure minerals in shocked meteorites, and for his contributions to the society

Thorsten Kleine (Germany) – For his fundamental studies of the HF–W system and the chronology of the early Solar System

Yangting Lin (China) – For contributions to the understanding of the origins of chondritic components, most notably presolar grains and CAIs, and the petrology of Martian meteorites, for his role in the Chinese Antarctic meteorite collection program, and for his contributions to the society

Katharina Lodders (USA) – For the application of thermodynamics to our understanding of Solar System processes and the compilation of huge amounts of Solar System data so that it is readily accessible to scientists

Bernard Marty (France) – For outstanding studies on the noble gases and nitrogen in meteorites and Genesis samples, and for contributions to the society

Akira Yamaguchi (Japan) – For major contributions to our understanding of the petrogenesis of achondrites, leadership in the collection/curation of Antarctic meteorites at NIPR, and contributions to the society

Edward Young (USA) – For significant studies of C, O, and Mg isotopes in meteorites and protoplanetary disks, for studies of the hydrology of asteroids, and for contributions to the understanding of isotopic fractionation during evaporation of silicates

Hisayoshi Yurimoto (Japan) – For innovative isotopic studies of chondritic components, particularly CAIs and fluid inclusions, and the mentoring of many students

Jutta Zipfel (Germany) – For significant research on a range of differentiated meteorites and on planetary missions to understand igneous processes on asteroids and Mars, for work on meteorite curation and classification, and for contributions to the society

The Meteoritical Society wishes Marc Norman great success as executive editor of *Geochimica et Cosmochimica Acta*. Read about his appointment on page 186.

NOMENCLATURE COMMITTEE REPORT

The purpose of the Nomenclature Committee (NomCom) is to approve new meteorite names, and to establish guidelines and make decisions regarding the naming of meteorites. We are also charged with keeping the community apprised of new meteorites through the *Meteoritical Bulletin* and the Meteoritical Bulletin Database (www.lpi.usra.edu/meteor/metbull.php). Since the last report, *Meteoritical Bulletin* (MB) 99 has been completed; it contains 1075 meteorites, 468 of which are non-Antarctic. MB99 will be published shortly in the new online format. A further 1509 meteorites have been approved thus far for MB100.

The type specimen (TS) repository review process is underway, with curators of TS repositories now required to update their contact information in an online database. Any new meteorite submission will not be considered if the information about the TS repository listed in the submission is incomplete.

Our guidelines for meteorite nomenclature continue to be revised to keep up with the times. A recent addition is a section entitled “Meteorites Found on Celestial Bodies Other than Earth!” The complete, up-to-date guidelines can be found at www.meteoriticalsociety.org/bulletin/nc-guidelines.htm.

Please do not hesitate to contact me (herd@ualberta.ca) with questions or concerns about NomCom and especially with suggestions for improvement. As always, essential information on meteorite nomenclature, instructions, and the template for reporting new meteorites can be found on our homepage: http://meteoriticalsociety.org/simple_template.cfm?code=pub_bulletin.

A list of current NomCom members can be found at www.meteoriticalsociety.org/bulletin/TermExpirations2011.htm.

Chris Herd
Chair of the Nomenclature Committee

http://meteoriticalsociety.org
The people of sub-Saharan Africa, a region with rapidly growing population, will need to import the surplus food produced in the Americas. My concern is that as their economies continue to grow they will be able to afford to buy more meat and dairy products as their economies grow, and it takes 3 to 10 calories of grain to produce one calorie of meat. Thus global economic growth is accelerating growth in demand for grain far faster than the effect population growth is having on this demand. My children and as yet unborn grandchildren have little risk of facing a food shortage: we live in Iowa, the greatest grain-producing region the world has ever known! For that matter, people living throughout North America, South America, and Europe have little risk of food shortages, as these regions have excess food-production capacity and their populations have either stabilized or are rapidly doing so. The people of China, India, Japan, South Korea, and Southeast Asia are also at low risk of food shortages; populations in these countries are also rapidly stabilizing, and as long as their economies continue to grow they will be able to afford to import the surplus food produced in the Americas. My concern is for the people of sub-Saharan Africa, a region with rapidly growing populations, abysmal economies, and degraded soils.

The poverty and deprivation that grips sub-Saharan Africa is rooted in the mineralogy of their soils. The young loess and glacial till soils of Iowa are dominated by smectites, illites, and randomly interstratified S/I (not really smectite/illite because the layer charge of the “illitic phase” is way too low, but that is another story). These 2:1 phyllosilicate clay minerals hold water and nutrients and help both to form and to stabilize soil organic matter by adsorbing fragments of biopolymers and physically protecting humic substances from rapid microbial decomposition. Soil organic matter in turn stabilizes soil structure and is a reservoir of slowly released nutrients that nourish crop growth. Iowa soils are incredibly productive! The soils of sub-Saharan Africa are dominated by quartz sands and old, highly weathered Fe- and Al-oxhydroxide clay minerals. Because these minerals have low-activity surfaces, they are not effective at forming and stabilizing soil-enriching humus. Furthermore, the soils of sub-Saharan Africa have little capacity for retaining plant nutrients and are easily leached and/or depleted of nutrients by cropping.

The challenges facing sub-Saharan Africa have many social, political, economic, and historical causes, but the fragility of their soils has been a major factor reinforcing the poverty trap. We are wise to remember the words of Franklin Delano Roosevelt, “A nation that destroys its soils destroys itself.” But we must also bear in mind that Iowa was endowed with resilient soils, while Africa was given fragile soils; the difference is in the mineralogy.

David Laird (Dalaird@iastate.edu) President, The Clay Minerals Society

On Earth, many clay minerals and related phyllosilicates form from reactions involving water during weathering, diagenesis, and hydrothermal alteration. Clay and phyllosilicate minerals have been detected by spectroscopy on the surface of Mars and in some classes of meteorites by analyses in terrestrial laboratories. Occurrences of phyllosilicate minerals in extraterrestrial materials are widely understood to indicate the former presence of water on some rocky bodies elsewhere in the Solar System. The landing site for the Mars Science Laboratory (MSL) mission (successfully launched in November 2011 and due to land on Mars in August 2012) was chosen largely because clay-mineral-bearing strata, in their stratigraphic context and in relation to other water-soluble minerals, will be accessible to the ten scientific instruments on MSL rover Curiosity, including the first X-ray diffractometer to be flown to another planet. NASA recently selected a mission to return samples from a primitive asteroid, of a spectroscopic class that may contain phyllosilicates, to the coming decade.

The August 2011 issue of Clays and Clay Minerals assembles five papers on clay and phyllosilicate minerals in extraterrestrial materials. Four are case studies of mineral assemblages detected by orbital spectroscopy of the surface materials on Mars; the fifth reviews the occurrence and significance of serpentine-group phyllosilicates in one class of carbonaceous chondrites. This thematic issue embodies the overlapping interests and emerging connections between planetary geologists and clay mineralogists.

Michael Velbel, Michigan State University

ElEmEnts
cycles, emphasizing their coupling to controls on atmospheric CO₂ and current research deals with computer modeling of the carbon and sulfur proxies, such as the density of stomata in fossil plant leaves. Dr. Berner's GEOCARB models. His modeling efforts have been confirmed by various this model by extending it to the beginning of the Phanerozoic in the early diagenesis, and studies of geochemical cycles.

Robert A. Berner obtained his BS and MS degrees from the University of Michigan and his PhD from Harvard University. He then went to the Scripps Institution of Oceanography as a Sverdrup Postdoctoral Fellow. In 1963 he joined the faculty at the University of Chicago and later moved to Yale University, where he was promoted to professor in 1971. He remains at Yale as an emeritus professor, after retiring in 2007. Dr. Berner is a member of the U.S. National Academy of Sciences. Among his many awards are the 1991 Doctor Honoris Causa, Université Aix-Marseille (France), the 1991 Huntsman Medal in Oceanography (Canada), the 1993 Goldschmidt Medal of the Geochemical Society, the 1995 Arthur L. Day Medal of the Geological Society of America, and the 1996 Murchinson Medal of the Geological Society of London.

One of the most internationally recognized and valuable research accomplishments of Dr. Berner, along with colleagues Bob Garrels and Tony Lasaga, has been the now famous BLAG model of atmospheric CO₂ variations through the Cretaceous. Dr. Berner has gone on to refine this model by extending it to the beginning of the Phanerozoic in the GEOCARB models. His modeling efforts have been confirmed by various proxies, such as the density of stomata in fossil plant leaves. Dr. Berner's current research deals with computer modeling of the carbon and sulfur cycles, emphasizing their coupling to controls on atmospheric CO₂ and O₂, the effect of CO₂ on paleoclimate and of O₂ on biological evolution, the role of plants in rock weathering and their controls on atmospheric CO₂ oscillations in the Phanerozoic, and weathering of kergen in fossil shales as a measure of the modulation of atmospheric O₂. Dr. Berner has tackled a number of other significant problems as well. This work includes studies of the kinetic behavior of carbonates in the ocean, experiments on the stabilities and kinetics of carbonate minerals and other sedimentary mineral types, field observations of the processes of early diagenesis, and studies of geochemical cycles.

Luca Fanfani's career as a geochemist-mineralogist has spanned more than 40 years. He has been full professor at the University of Cagliari, Italy, since 1976 and dean of the Faculty of Sciences since 2009. Luca is an active member of the committee of the Water–Rock Interaction Working Group (WRI) and, as general secretary, organized the WRI-10 conference in 2001. He served as a mentor to many young geochemists in Italy and other countries. He has authored or coauthored more than 60 scientific articles, addressing a wide range ofgeochemical issues. He recognized, long before most of his colleagues, the important connection between geochemistry and mineralogy for understanding the transport and fate of harmful and toxic elements in the near-surface environment. Luca has had a strong impact on the foundation of environmental mineralogy and geochemistry in Italy. He created a research group that became a nationwide reference, stimulating the birth and growth of similar groups around the country. Luca was also a pioneer in understanding the importance of international cooperation and interaction. He stimulated scientific cooperation with less-developed countries, giving rise to several projects in Latin America and North Africa, and he contributed significantly to the progress of environmental geochemistry.

Distinguished Service Awards to Ernest E. Angino and Luca Fanfani

The Distinguished Service Award recognizes outstanding service by an IAGC member to the Association or to the geochemical community that greatly exceeds the normal expectations of voluntary service.

Ernest E. Angino is being honored for his dedicated service to IAGC as treasurer from 1980 to 1994. He was a professor and is now an emeritus professor in the Department of Geology at the University of Kansas. Ernie did research and teaching in the area of aqueous geochemistry. He contributed significantly to the understanding of the aqueous geochemistry of trace metals and the chemistry of Antarctic lakes and participated in the development of the important research area of geochemistry and health. During his tenure as chair of the Department of Geology at the University of Kansas, he was instrumental in organizing the alumni association, which has resulted in significant gifts to the department. Ernie brought organizational and management skills to IAGC during his time as treasurer. He worked to increase the assets of IAGC, handing to his successor, D. T. Long, an association in an extremely stable financial state. He also proved to be an invaluable resource for the president and secretary of IAGC, as he contributed to negotiations with the publisher of the society’s journal, Applied Geochemistry, worked with international collaborators, and helped in the formulation of the various awards bestowed by the society. Ernie’s dedicated service to IAGC went well beyond that of being treasurer.

Luca Fanfani's career as a geochemist-mineralogist has spanned more than 40 years. He has been full professor at the University of Cagliari, Italy, since 1976 and dean of the Faculty of Sciences since 2009. Luca is an active member of the committee of the Water–Rock Interaction Working Group (WRI) and, as general secretary, organized the WRI-10 conference in 2001. He served as a mentor to many young geochemists in Italy and other countries. He has authored or coauthored more than 60 scientific articles, addressing a wide range of geochemical issues. He recognized, long before most of his colleagues, the important connection between geochemistry and mineralogy for understanding the transport and fate of harmful and toxic elements in the near-surface environment. Luca has had a strong impact on the foundation of environmental mineralogy and geochemistry in Italy. He created a research group that became a nationwide reference, stimulating the birth and growth of similar groups around the country. Luca was also a pioneer in understanding the importance of international cooperation and interaction. He stimulated scientific cooperation with less-developed countries, giving rise to several projects in Latin America and North Africa, and he contributed significantly to the progress of environmental geochemistry.

Urban Geochemistry Working Group

The IAGC is reinvigorating the Urban Geochemistry Working Group under the leadership of Dr. Berry Lyons (The Ohio State University, USA). The group will be cochaired by Dr. David Long (Michigan State University, USA). To kick off this new working group, Dr. Lyons and Dr. Russell Harmon (U.S. Army Corps of Engineers) will be guest editors of the December 2012 issue of Elements, which will feature urban geochemistry as the thematic topic. Additionally, Dr. Lyons and Dr. Long will be cochairing a session devoted to urban geochemistry at the annual Geological Society of America (GSA) meeting in November 2012 in Charlotte, North Carolina, USA. If you would like to be involved in this exciting, newly reorganized working group, please contact the IAGC business manager, Chris Gardner, at iageochemistry@gmail.com.

ElSeVier/IAGC Student Research Grants

The Elsevier/IAGC Student Research Grant Program is designed to assist PhD students in geochemistry in undertaking and acquiring geochemical analyses in support of their research. Selection is based upon a meritorious proposal. In addition to their grant stipend, each student receives a one-year membership in IAGC. This year’s recipients are:

Alice DuVivier, Durham University, UK ($2500) – “Using Ca isotopes to evaluate the weathering influx in seawater: Implications for the driving mechanisms of the Cenomanian–Turonian boundary oceanic anoxic event (OAE 2)”

Jill Gheelerter, Georgia State University, USA ($2000) – “Enhanced bioremediation of oiled salt marsh sediments using clay minerals”

Peter Tollan, Durham University, UK ($1500) – “Modern arc peridotites – Analogues for continental-root evolution”
Mineralogical Society of Great Britain and Ireland

www.minersoc.org

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All candidates need to have at least four years of postgraduate experience in the practice, application or teaching of science. Additionally applicants must have undertaken continuing professional development commensurate with the level of attainment required for a minimum of two years immediately prior to the application.

Applicants must demonstrate that their scope of practice requires them to:

- Demonstrate a systematic understanding of knowledge, and show critical awareness of current problems and/or new insights in their area of mineralogical science
- Have a comprehensive understanding of techniques applicable to their scope of practice and the ability to critically evaluate current research
- Deal with complex issues both systematically and creatively, make sound judgements in the absence of complete data, and communicate their conclusions clearly to specialist and non-specialist audiences
- Exercise self-direction and personal responsibility in solving problems, and exercise personal autonomy in planning and implementing tasks at a professional level
- Continue to advance their knowledge, understanding and competence to a high level

Visit www.minersoc.org/chartered.html for more details and an application form. Members of long standing may be particularly interested in our ‘fast-track’ method of application. There is an initial cost of £50 plus a charge of £45 per year thereafter.

MAJOR MEETINGS IN 2013

The Society will be involved in two major meetings in 2013. Details are given below below and on the Society website.

Volcanism, Impacts and Mass Extinctions: Causes and Effects

On 27–29 March 2013, London’s Natural History Museum will host an international, multidisciplinary conference that brings together researchers from across the geological, geophysical and biological disciplines to assess the state of research into the causes of mass extinction events. The main goal of this conference will be to evaluate the respective roles of volcanism, bolide impacts, sea level fluctuations and associated climate and environmental changes in major episodes of species extinction. More details are available at http://massextinction.princeton.edu/. This event is supported by the Volcanic and Magmatic Studies Group and the Mineralogical Society.

Minerals for Life: Overcoming Resource Constraints

On 17–19 June 2013, our ‘Minerals for Life’ meeting will be held in Edinburgh. The meeting is a collaborative venture with the Geological Society, the British Zeolite Association and the Institute of Materials. The key aim of this meeting is to bring together workers from academia (mineralogy, chemistry, ‘materials’ and others), industry and regulatory bodies to discuss mineralogy under the following four themes:

Strategically Important Mineral Resources includes the sustainability of mineral resources, such as strategically important elements (considering both primary and secondary sources), ethically/responsibly sourced metals and gems, and related topics such as resource recovery and management. The recycling of minerals will be addressed here as appropriate.

Functional Materials and Minerals deals with nano-, micro- and mesoporous materials (both synthetic and natural), such as zeolites, pillared clays and the like; thin films of (or on) mineral surfaces; and mineral catalysts. This topic may include any ‘functional’ mineral application (or mineral-derived material), such as sensors and transducers, sorbents, ion-exchange media, cements and others.

Minerals for Environmental Protection includes both nuclear and non-nuclear applications. It considers the use of minerals as retarding media in engineered chemical barriers, alongside physically engineered subsurface structures such as mineral liners; permeable reactive barriers; and examples of environmental remediation in which mineral technology has had significant impact. Carbon capture and storage is another important part of this theme.

Biological Processes in Mineral Science and Technology includes a range of biological processes, both naturally occurring and industrially applied. These will include biomining and bioremediation applications, and also emerging biological synthesis routes for commercially useful materials. Other geologically important biomineralization processes, in both prokaryotic and eukaryotic systems, will also be of interest.

Go to www.minerals-for-life.org for more information.

CLAYS USED IN BEADMAKING

Modern lampwork* glass beadmaking can trace its lineage back 500 years to the Italians (e.g. Murano glass), who made beads by wrapping hot glass around copper wire. After the glass cooled, the bead was cut off with the copper wire still inside. It was then dropped into a caustic solution that dissolved the copper wire, leaving a clean hole behind.

The American lampwork bead movement started around the 1970s. Glass-bead artists found they could use techniques similar to those of the Italian beadmakers by wrapping molten glass around a mandrel (a piece of stainless steel welding rod) that had been dipped in a sludge (generally a mixture of clay, water and other ingredients, called bead release) beforehand and dried so that the bead could be twisted off after cooling.

When I started making lampwork beads in 1991, I had problems getting the beads off the mandrels and I decided to try to make my own bead release. It took months of experimenting and testing to settle on a good basic formula using kaolin as the main ingredient. It’s been eight years since the first test batches of bead release were handed out in pickle jars. Now I have three formulas sold in many parts of world.

Robin J. Foster

* A type of glasswork that uses a torch to melt rods and tubes of clear or colored glass; the molten glass is then shaped with tools, gravity and hand movement.
JAPAN ASSOCIATION OF MINERALOGICAL SCIENCES AWARDEES

The Japan Association of Mineralogical Sciences (JAMS) is proud to announce the recipients of its 2011 society awards. The Japan Association of Mineralogical Sciences Award is given to a maximum of two scientists per year for exceptional contributions to the mineralogical and related sciences. The Manjiro Watanabe Award, named in honor of Professor Manjiro Watanabe, a famous Japanese mineralogist, and funded by his contribution, is presented yearly to a scientist who has contributed significantly to mineralogical and related sciences over his/her career. The Japan Association of Mineralogical Sciences Research Paper Award is given annually to the authors of two excellent papers in the Journal of Mineralogical and Petrological Sciences (JMPS) and Ganseki-Kobutsu-Kagaku (GKK) published in the last three years. Congratulations to all the winners!

Japan Association of Mineralogical Sciences Award to Tetsumaru Itaya

Tetsumaru Itaya, from Okayama University of Science, Japan, is a leading expert in the geochronology of orogenic belts around the world. His research spans a wide range of subjects, in addition to geochronology, including studies of volcanic, metamorphic, and plutonic rocks, accretionary complexes, and fault rocks for predicting earthquake activity; ore petrology and mineralogy; the development of high-quality analytical techniques; contributions to anthropology and archeology; and paleomagnetic studies related to global tectonics. Highlights of his recent research include the following:

- Discovery of a very large excess of argon in kyanite and of the regional excess argon wave occurring in a Barrovian-type metamorphic belt
- Elucidation of the mechanism underlying argon depletion from phengites during ductile deformation accompanying the exhumation of high-pressure metamorphic rocks and the formation of excess-argon-free phengites in ultrahigh-pressure metamorphism

His research has contributed to the understanding of orogenic processes around the world. The most challenging part of his research has been revealing the precise K-Ar chronology of Holocene volcanic rocks, which allows for dating island-arc volcanic rocks using a few grams of a sample with 2 wt% potassium, while applying a precise correction for the mass fractionation of argon isotopes.

Japan Association of Mineralogical Sciences Award to Kazumasa Sugiyama

Kazumasa Sugiyama, from the Institute for Materials Research (IMR), Tohoku University, Japan, is a mineralogist whose research concerns the development of new functional materials. He started his scientific career by focusing on the application of X-ray diffraction to the structural analysis of natural minerals with complex structures. His research interests also include the elucidation of the structure of amorphous materials. Conventional X-ray diffraction has a drawback in that it is not useful for distinguishing between elements with similar atomic numbers. Kazumasa Sugiyama used anomalous X-ray scattering (AXS) to address the above-mentioned problem and obtained fine-structural information for materials with complex structures. This new approach is one of the most promising methods for the structural analysis of disordered materials, including nanoscale natural minerals. He also developed new equipment for the fine-structural analysis of high-temperature liquids by energy-dispersive X-ray diffraction (EDXD), and he used the equipment to obtain structural images of a variety of liquid materials. Recently, he extended his research to the structural analysis of minerals with more complex structures. He also developed an advanced AXS-RMC (reverse Monte Carlo) method and solved the structures of complex and disordered materials. His research has contributed significantly to the advancement of fundamental Earth science knowledge and the development of new functional materials.

Manjiro Watanabe Award to Fumiyuki Marumo

Professor Fumiyuki Marumo started his scientific research studying the crystal structure of harmotome by single-crystal X-ray diffraction under the supervision of Prof. R. Sadanaga at the University of Tokyo in 1955. In 1961, he moved to the University of Bern in Switzerland and pursued structural research on sulfosalt minerals from Lengenbach. He solved many complicated structures and contributed to the determination of the structural scheme of arsenic-bearing sulfosalts. He also reported three new sulfosalts minerals from Lengenbach. He returned to Japan in 1966 and continued structural research at the Institute for Solid State Physics at the University of Tokyo. He was engaged in the structure determination of crystals of metal complexes, charge-transfer organic complexes, and natural organic materials, and he obtained valuable results in these fields. In 1972, he was offered a faculty position at the Tokyo Institute of Technology, where he started a structural investigation of crystals of ferroelectrics, ferroelastics, ionic conductors, transition metal silicates, etc. Most importantly, he confirmed the anisotropic distribution of 3d electrons, which was suggested by crystal-field theory, by determining accurate electron-density distributions in a series of spinel-type transition metal silicates using X-ray diffraction. This research attracted the attention of numerous inorganic crystal chemists. He also succeeded in growing high-quality nonlinear optical crystals of the low-temperature form of BaB$_2$O$_4$ from a supercooled melt of pure BaB$_2$O$_4$ by making the melt temperature about 100 °C higher than the phase transition point between the low- and high-temperature forms of BaB$_2$O$_4$.

JAPAN ASSOCIATION OF MINERALOGICAL SCIENCES RESEARCH PAPER AWARDS


Tetsuo Kawakami Tomokazu Hokada
THE DISCOVERY OF CHIBAITE

Koichi Momma, a mineralogist from the National Museum of Nature and Science, has found and described a new silica clathrate species, “chibaite,” in collaboration with other members of JAMS. The new mineral incorporates hydrocarbon molecules such as CH_4, C_2H_6, C_3H_8, and i-C_4H_{10} in its silica framework. In 1998, Chibune Honma, a fossil collector, discovered white quartz in tuffaceous sediments of Early Miocene age (Hota Group) in the southern Boso Peninsula, Chiba Prefecture, Japan. Naoki Takahashi from the National History Museum and Institute, Chiba, analyzed the quartz specimen, which had an unusual, thick, hexagonal, platy shape; however, electron microprobe analysis revealed the presence of ordinary, simple silica. A few years later, Katsumi Nishikubo, a mineral collector from Chiba, collected more specimens. Masayuki Takada, a mineralogist from Kyoto, studied the crystal morphology of the distinctive quartz and revealed it to be a pseudomorph composed of (111) twins of octahedral crystals with cubic symmetry. Nishikubo sent some transparent euhedral crystals to Tohoku University, where Momma was studying silica minerals under the supervision of Toshiro Nagase and Yasuhiro Kudoh. Momma carried out Raman spectroscopic analyses on the crystals and detected methane and other hydrocarbons occluded in the crystals. X-ray investigations revealed that the crystal structure of Nishikubo’s sample is different from that of melano phlogite, the only silica clathrate mineral hitherto known. Chibaite has been approved by the IMA Commission on New Minerals, Nomenclature and Classification (#2008-067) and is described in detail in Momma et al. (2011).1

Chibaite is isotopological to the cubic structure II gas hydrate. It is epoxially intergrown with a minor amount of another, as-yet-unnamed silica clathrate mineral, which is isotopological to the hexagonal structure H gas hydrate. Chibaite is colorless, has a vitreous luster, and has no cleavage. Its refractive index, Mohs hardness, and calculated density are 1.470(1), 6.5–7, and 2.03(1), respectively. The empirical formula derived from the electron microprobe data is Na_{0.99}(Si_{134.53}Al_{1.63})O_{272}, with n_{max} = 3/17.

The Hota Group includes fore-arc sediments related to the Paleo-Izu accretionary arc deposited near the plate margin at the triple junction of the Pacific, Philippine Sea, and North America plates. Veins containing chibaite fill fissures related to minor faults, in which thermogenic hydrocarbons were deposited from fluids originating from deeply buried sediments. Silica clathrate minerals store hydrocarbons that have vanished from sedimentary rock and, therefore, provide new evidence for geological carbon cycling at active plate boundaries.

The fourteenth Experimental Mineralogy, Petrology, and Geochemistry (EMPG) Conference took place between March 4 and 7 at the Christian Albrechts University in Kiel and was organized by the Department of Mineralogy of that institution. More than 260 participants from 30 countries found their way to northern Germany, thus fulfilling the organizers’ intention to bring together researchers from all fields of experimental geosciences. Altogether, 230 abstracts were submitted (104 posters and 126 oral presentations). The whole range of experimental research, including geochemical, mineralogical, and petrological aspects, was covered. Because of the long distance to Kiel, the participation of some attendees was made possible with the support of the European Mineralogical Union (EMU) and the German Mineralogical Society (DMG); this support is gratefully acknowledged by the organizers.

A wide range of topics was covered during the conference, including the evolution of terrestrial planets and the early Earth, subduction zone processes, and the deep Earth. Another theme concentrated on new frontiers and developments in experimental applications and applied geosciences. Examples were found in sessions dealing with the capture and storage of CO₂ and the exploration and disposal of energy-related and hazardous materials.

During the last EMPG Conference, in Toulouse in 2010, an effort was made to encourage closer links between theoretical simulations and experimental approaches. Especially in topics like diffusion, reaction kinetics, and small-scale deformations, stronger collaborations might have great potential. During EMPG XIV, researchers with numerical backgrounds presented their research in at least two sessions. Hopefully, this effort will be continued or even enlarged in future conferences.

The organization of this conference was exemplary. From the efficient online registration, through the icebreaker event, to the conference itself and the conference dinner, many helping hands made sure that everything was working perfectly. Let’s not forget the many small details, like continuously available coffee and cake, the friendly staff in the cloakroom, and the speakers’ ready room. Special thanks go to Philipp Kegler, Astrid Holzheid, their team, and all the helpers.

**Bastian Joachim**

The First **European Mineralogical Conference** will be held at the Goethe-University in Frankfurt, Germany, **2-6 September 2012**.

The contributing societies are:
- **DMG** Deutsche Mineralogische Gesellschaft
- **MinSoc** Mineralogical Society of Great Britain & Ireland
- **MinSocFin** Mineralogical Society of Finland
- **ÖMG** Österreichische Mineralogische Gesellschaft
- **PTMin** Mineralogical Society of Poland
- **RMS** Russian Mineralogical Society
- **SEM** Sociedad Española de Mineralogía
- **SFMC** Société Française de Minéralogie et de Cristallographie
- **SIMP** Società Italiana di Mineralogia e Petrologia
- **SSMP** Swiss Society of Mineralogy and Petrology

The themes for the conference are as follows: Mantle petrology and geochemistry; Magmatism and volcanology; Metamorphism; Applied mineralogy; Mineral physics; Mineralogical crystallography; Planetary materials; Mineral deposits and raw materials; Low T geochemistry; Geochronology; Geobiochemistry; Advanced analytical techniques; Archaeometry, care and preservation; Open session.

Invited lectures will be given by Hilary Downes, Thomas Stachel, Rod Ewing, Tim Elliott, and the IMA medallist David Green.

The scientific committee consists of one representative of each society.

The local organizing committee: Gerhard Brey, Heidi Höfer
GAC-MAC WINNIPEG 2013

The 2013 joint annual meeting of the Geological Association of Canada and the Mineralogical Association of Canada will be held from May 22 to 24 at the Convention Centre in downtown Winnipeg. The city is located 29 km west of the longitudinal center of North America and sits on the sediments of the immense glacial Lake Agassiz. It is just a short distance from one of the world’s largest rare-metal pegmatites at Tanco, spectacular outcrops of Paleozoic carbonate rocks in the Interlake area, Precambrian rocks of the Superior craton and Trans-Hudson orogen, and a score of other geological attractions. As is customary at a GAC-MAC meeting, the field trip offering is exceptional. Here is a great opportunity to discover the Tanco pegmatite, the Flin Flon mining district, the Thompson nickel belt, for example. Several short courses will be offered before and after the meeting.

Details on registration, programs, and events are available at: www.gacmacwinnipeg2013.ca

Here are some of the symposia, special sessions, and field trips that will be of great interest to the mineralogy–geochemistry–petrology community. Check the website for the full list.

**Symposia**

**Earth Materials, Petrological and Geochemical Processes**

*In Honor of Frank C. Hawthorne*

Elena Sokolova, Norman Halden

**Granitic Pegmatites – From Fascinating Crystals to High-Tech Elements**

*In Honor of Petr Černý*

Milan Novák

**Special Sessions**

**Diamond: From Birth in the Mantle to Enplacement in Kimberlite**

Maya G. Kopylova, Yana Fedortchouk

**Uranium: Cradle to Grave**

Peter Burns

**Rare Earth Elements in Melts, Fluids, and Crystal Structures**

Anton Chakhmouradian, Ian Coulson

**Precious and Rare Metals in the Volcanogenic Massive Sulfide Environment**

Patrick Mercier-Langevin, Harold Gibson, Simon Gagné

**Testing Links among Large Igneous Provinces, Iron Formations, and Volcanogenic Massive Sulfide Deposits**

Andrey Bekker, Richard Ernst

**Layered Intrusions: New Paradigms and Approaches to Understanding Magmatic Processes**

James S. Scoates, Jim Miller

**Field Trips**

The Tanco Mine: Geological Setting, Internal Zonation, and Mineralogy of a World-Class Rare Element Pegmatite Deposit

Tania Martins, Paul Kremer, Peter Vanstone, Gary Poetschke, Blair Skinner

Neoarchean Mafic-Ultramafic Intrusions in the Bird River Greenstone Belt: Tectonic Setting and Economic Significance

Paul Gilbert, James Scoates, Jon Scoates, Erik Yang, Caroline Mealin, Michel Houé, Carey Galeschuk

The Volcanological and Structural Evolution of the Paleoproterozoic Flin Flon Mining District: The Anatomy of a Giant VMS System

Harold Gibson, Bruno Lafrance, Sally Pehrsson, Michelle Dewolfe, Kelly Gilmore, Renée-Luce Simard

Metamorphosed Alteration Zones and Regional Metamorphism: Examples from the Trans-Hudson Orogen

Chris Couëslan, Doug Tinkham, Al Bailes, Simon Gagné

Tectonic Evolution of the Thompson Nickel Belt, Manitoba: Sedimentation, Structure, and Magmatism in a Continent-Continent Collisional Zone

Josef Macek, Hermann Zwanzig, Chris Couëslan

**Magmatic Ni-Cu-PGE-Cr Deposits: Ore-Forming Processes with Implications for Exploration**

Michel Houé, Valérie Bécu, Doreen A. Ames, Xue-Ming Yang, Paul Gilbert

**Metamorphism in the Ore Environment**

Chris Couëslan, Doug Tinkham, David Pattison, Simon Gagné

**Geomicrobiological and Biogeochemical Advances in Environmental Systems**

Ian Power, Lachlan MacLean

**Impact Cratering: A Geological Process**

Gordon Osinski, Richard Grieve

**Terrestrial Analogues for Comparative Planetary Geology and Astrobiology**

Ed Cloutis, Gordon Osinski

**Post-Detonation Nuclear Forensics**

Antonio Simonetti, University of Notre Dame

**Pre-Detonation Nuclear Forensics**

Mostafa Fayek, University of Manitoba

**Thermochemistry of Uranium Minerals and Compounds**

– Alexandra Navrotsky, University of California–Davis

**Aqueous Geochemistry of Uranium**

– Jeremy Fein, University of Notre Dame

**Materials at the Nanoscale**

– Peter Burns, University of Notre Dame

**Mine Tailings Characterization and Remediation**

– Michael Schindler, Laurentian University

**Ceramic Waste Forms for Actinides**

– William Weber, University of Tennessee, and Rodney Ewing, University of Michigan

**Subsurface Uranium Mobility**

– Zachara, Pacific Northwest National Laboratory

**Spend Nuclear Fuel**

– David Shoesmith, Western University of Ontario

**Actinide Borate Waste Forms for Actinides**

– Thomas Albrecht-Schmitt, University of Notre Dame

**Pre-Detonation Nuclear Forensics**

– Ian Hutcheon, Lawrence Livermore National Laboratory

**Post-Detonation Nuclear Forensics**

– Antonio Simonetti, University of Notre Dame

**Mineralogy and Crystallography**

– Sergey Krivovichev, Saint Petersburg State University

**Ore Deposits and Economic Geology**

– Mostafa Fayek, University of Manitoba

**Uranium: Cradle to Grave**

Mineralogical Association of Canada Short Course

Winnipeg, Manitoba, Canada

May 20–21, 2013

**Content**

The focus of this short course, which will immediately precede the GAC-MAC meeting, will be the many aspects of uranium, an element that changed the course of the world like no other. Content will span the mineralogy, geochemistry, and ore deposits of uranium, and will include nuclear waste challenges and solutions, weapons proliferation, and nuclear forensics for attribution and nuclear security. The short course will bring together a panel of international experts focused on educating graduate students, early-career scientists, and researchers seeking a deeper involvement in the field. We invite you to join us and enjoy topics central to this fascinating element’s history, complexity, environmental impact, and importance in global security. Topics and confirmed speakers/authors include:

**History of Uranium** – Jessica Beard, University of Notre Dame

**Mineralogy and Crystallography** – Sergey Krivovichev, Saint Petersburg State University

**Ore Deposits and Economic Geology** – Mostafa Fayek, University of Manitoba

**Thermochemistry of Uranium Minerals and Compounds** – Alexandra Navrotsky, University of California–Davis

**Aqueous Geochemistry of Uranium** – Jeremy Fein, University of Notre Dame

**Materials at the Nanoscale** – Peter Burns, University of Notre Dame

**Mine Tailings Characterization and Remediation** – Michael Schindler, Laurentian University

**Ceramic Waste Forms for Actinides** – William Weber, University of Tennessee, and Rodney Ewing, University of Michigan

**Subsurface Uranium Mobility** – Zachara, Pacific Northwest National Laboratory

**Spend Nuclear Fuel** – David Shoesmith, Western University of Ontario

**Actinide Borate Waste Forms for Actinides** – Thomas Albrecht-Schmitt, University of Notre Dame

**Pre-Detonation Nuclear Forensics** – Ian Hutcheon, Lawrence Livermore National Laboratory

**Post-Detonation Nuclear Forensics** – Antonio Simonetti, University of Notre Dame
STUDENT TRAVEL GRANTS

Thirteen travel grants worth 200 € each and financed by the Spanish Mineralogical Society (SEM) will be available to help qualified master’s and PhD students, as well as recent PhDs, attend the following meetings:

SEM-SEA 2012 (5 grants). This conference is the joint scientific meeting of the Spanish Mineralogical Society (SEM) and the Spanish Clay Society (SEA). It will be held in Bilbao (Abandoibarra Paraninfo, Bizkaia Aretoa Building) from 27 to 30 June 2012. This conference will be the 32nd meeting of the SEM and the 22nd meeting of the SEA. The local organizing committee is composed of members of the Department of Mineralogy and Petrology of The Basque Country University (UPV/EHU). An international seminar entitled “Archaeometry and Cultural Heritage: The Contribution of Mineralogy” will be held on 27 June 2012. Two optional post-congress geological field trips in the Bizkaia region will be organized: “Intracretaceous Volcanism in the Basque Cantabrian Basin” and “Mineralogy of the Carranza Valley.”

Fourth EuCheMS (3 grants). This conference will be the 4th congress of the European Association for Chemical and Molecular Sciences. It will take place in Prague, Czech Republic, on August 26–30, 2012. More information is available on the 4th EuCheMS website, http://euchems-prague2012.cz.

The travel grants will be awarded on the basis of the quality of the submitted abstract, the absence of other sources of support available to the recipient, and previous travel grants provided to attend meetings. Applicants must send a copy the submitted abstract, their CV, and a copy of the registration fee bank receipt to SEM Secretary Salvador Morales (smorales@ugr.es).
FIRST CIRCULAR

The Brazilian Clay Group of the Brazilian Geochemical Society, on behalf of AIPEA, Association Internationale pour l’Étude des Argiles, invites you to attend the 15th International Clay Conference – XV ICC, in Rio de Janeiro, Brazil.

CONTACT: www.15icc.org  |  info@15icc.org

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WHO SHOULD ATTEND:
Scientists and technologists involved in all aspects of clays and clay minerals, including:
- Geology
- Petroleum Geology and Engineering
- Mineralogy and Geochemistry of Clay Minerals
- Ceramics
- Catalysts
- Polymers and Nanocomposites
- Soil and Crop Science
- Environmental Technology
- Medical Care and Health
- Astronomy
- Meteoritics and Compared Planetology
- Physics and Chemistry of Surfaces
- Origin of Life
- Analytical Techniques
- Climate and Climatic Changes
- Materials Science and Technology

ACTIVITIES:
- Keynote lectures by distinguished scientists
- Both oral presentations and separate poster sessions
- ASYS (AIPEA School for Young Scientists)
- Field trips
- Short courses

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IMPORTANT DATES
- Open now to Proposal of topics for sessions and symposia
- Aug-Dec 2012 to Preparation and submission of abstracts

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The Gordon Research Seminar and Conference on Isotopes in the Biological and Chemical Sciences met in Galveston, Texas, USA, on February 5–10, 2012. The conference celebrated both the centennial of the first observation of a stable isotope, the detection of Ne-22 by Francis Aston, and the contributions of Jacob Bigeleisen to the calculation and interpretation of isotope effects on physical and chemical processes. Isotopes in biogeochemical processes were prominently featured in sessions organized by Thomas Hofstetter and Ariel Anbar. In the initial session, devoted to biogeochemistry and pollutant dynamics, Thomas Hofstetter provided an introduction to the types of studies that employ isotope-effect measurements. Martin Elsner (Institute of Groundwater Ecology, Helmholtz Zentrum München) and Daniel Hunkele (University of Neuchâtel) presented research on isotopic fractionation in the environment attributable to microorganisms and the interpretation of the mechanisms of decomposition. Alex Sessions (Cal Tech) and Karen Casciotti (Stanford University) communicated data on the use of H and N isotope fractionation to infer pathways of microbial metabolism.

On the second day, the presentations veered more towards the geochemical. Edwin Schauble (University of California, Los Angeles) gave a talk on isotope thermometry requiring high-precision measurements. This was followed by presentations by Laura Wasylenki (Indiana University) on metal ion coordination and David Johnston (Harvard University) on sulfur fractionation.

The Gordon Research Conference on isotopes has long focused on the development and application of the theory of isotope fractionation. The introduction and adaptation of the “Bigeleisen equation” was covered by Alex van Hook, and other contributions toward the calculation of isotope effects were presented by Steven Schwartz and Piotr Paneth. The synergy of studying isotope fractionation in the environment coupled with the determination of isotope effects on enzyme systems was apparent during the discussions at this meeting.

The Geochemical Society (through its Meeting Assistance Program), the Biological Chemistry Division of the American Chemical Society, and Thermo Fisher Scientific provided support for the conference. The next planned meeting will be held in early February 2014 in Galveston.

Vernon Anderson
Conference Chair

GEORGES PÉDRO DAY

The Société Française de Minéralogie et de Cristallographie sponsored a day of talks on the theme “Georges Pédro and Soil Clays,” in Paris on December 15, 2011. The meeting was organized by Christian Feller, director of research at the Research Institute for Development (IRD), on behalf of the French Association of Soil Studies (Association Française pour l’Étude du Sol, AFES) and the French Clay Group (Groupe Français des Argiles, GFA). About 100 colleagues and former students from near and far came to share this special day. Georges Pédro is a world-scale figure in clay mineralogy and soil science. He was a precursor in the domains of nanoparticles, biogeochemical cycles and light chemistry. He is a member of several academies, among which are the Academia Europaea, the French Academy of Sciences and the Agriculture Academy of France. He has long been a scientific advisor in agronomic sciences at the OECD and a member of the DGXII Committee at the EEC. A close friend of George Brindley and Jacques Mering, Georges Pédro made pioneering contributions in clay science, including (1) the crystal structure of clay minerals, (2) the spatial organization of weathering profiles, (3) the global distribution of soils and weathering covers with their specific mineral composition as related to the major climatic processes and (4) the protection of the soil resource and the role of soils in sustainable development. He was the first to use extensively experimental approaches to constrain the physicochemical parameters governing weathering. He was among the first to use modern mineralogical techniques to understand the nature, crystal chemistry and state of hydration of clays and associated minerals in soils. He demonstrated how the texture of soils, defined as an organized system, is directly connected to environmental conditions and affected by anthropic actions.

During the morning session, colleagues spoke of their interactions with Georges Pédro at various stages of his 55-year-long career: Christian Feller, André-Bernard Delmas, Daniel Tessier, Hélène Paquet, Alain Ruellan, Adrien Herbillon, Jean-Paul Legros and Jean-Claude Leprun. The morning session ended with a talk by Georges Pédro entitled “Vision on a Life Devoted to Investigating Clays and Soils.” The afternoon session illustrated some recent developments: properties of soil clays (Laurent Caner, University of Poitiers), interactions among clays, organic matter and biological activity (Claire Chenu, AgroParisTech, Grignon; Christian Feller, Institut de Recherche pour le Développement), clays and health (Hervé Quiquampoix, Agronomic Research Institute, Montpellier; Nicole Liewig, University of Strasbourg; Michel Rautureau, University of Orléans), and clays as nanomaterials (Claudine Noguera, University Pierre and Marie Curie). With a cocktail reception at lunch time and extensive discussions at the end of the meeting, this special day was an occasion for transmitting experience among generations of scientists working on clays, soils and the environment.

Georges Calas and Hélène Paquet
BOOK REVIEW

NATURE’S NANOSTRUCTURES*

The Earth system, comprising geologic, hydrologic, biologic, atmospheric, and anthropic subsystems, cannot be studied effectively without crossing many traditional disciplinary boundaries. Nature’s Nanostructures is a strategically named volume, edited by Amanda S. Barnard and Haibo Guo, that exemplifies not only the ease with which boundaries can be crossed but also the necessity of doing so.

There is a natural tendency in nanogeoscience to want to show how nanoparticles are “special” in that their chemical behavior differs from that of their macroscopic structural counterparts. While interesting and important, this can sometimes lead to the impression that nanoparticles are merely idiosyncratic, an oddity. Overall, this book gives a different impression—that nanoscale materials and structures are a major part of the world we live in. Nature’s Nanostructures includes explorations into biomaterials, photonic crystals, extraterrestrial particles, aerosols, and anthropogenic/engineered particles in the environment. The book consists of an introductory overview and 20 chapters grouped into four categories: Nanomaterials and Mineral Nanoparticles (with an emphasis on inorganic nanomaterials and aqueous settings), Biomaterials, Nanoparticles in Space and in the Atmosphere, and Engineered Nanoparticles in the Environment. Covering these subjects in about 550 pages is a feat of brevity, considering that there are about 130 pages of references, along with a 9-page index and 20 blank or title pages between chapters. Separate from the 550-page text is a 32-page section at the end consisting of color versions of many of the figures in the text. The book is thus an unusually broad overview and not a deep exploration of one subject (though certain chapters might be considered exceptions). While some chapters delve into moderate mathematical detail, for the most part the chapters are relatively short and liberally referenced to encourage further reading.

An initial chapter attempts a rough quantification of global nanoparticle reservoirs and fluxes, akin to an elemental geochemical cycle. Following this are several chapters on oxides, particularly iron oxides and hydroxides, and a chapter on pyrite surface energies. Proceeding along largely inorganic lines, subsequent chapters deal with noble metal nanoparticles (including so-called “invisible gold” in sulfide ore minerals), diamondoids, and “negative curvature” nanoparticles (nanoscale pores) with a focus on uranium transport. The section on biominerals then starts with an overview of nanoscale biominerals of many different types (from shell and bone minerals to biogenic magnets). The next two chapters are concerned with magnetic biominerals, including nanoscale magnetoreceptors in birds and bird navigation. A theory-based chapter deals with ways in which organisms can direct nucleation and growth of nanominerals. The last chapter in the section notes that “all iridescence in nature arises from photonic crystals” and discusses the case of photonic crystals in beetles. Anyone who has taught an introductory course in which the origin of the Solar System is related to literally nebulous “dust clouds” will appreciate the three chapters at the beginning of the section on nanoparticles in space and in the atmosphere. These chapters treat everything from vapor condensation models and aggregation to dust that enters the Earth’s atmosphere. The discussion gradually comes down to Earth (sorry, I couldn’t help it) in the form of a chapter on the formation of atmospheric aerosols. Aerosol-formation events mostly occur in the daytime, emphasizing the importance of photochemistry in such processes.

The final section covers engineered nanoparticles, although the degree to which nanoparticles are intentionally (as opposed to inadvertently) “engineered” is open to debate. The section essentially deals with anthropogenic nanoparticles in the environment. Diesel engines and bioparticles (including everything from viruses to pollen) exemplify inadvertent nanoparticle production. Chemical processes in industry taking advantage of chemical vapor deposition, particle deposition, and aggregated particle deposition result in nanomaterials that can also enter the environment. The final paragraphs in this chapter deal with the relatively new field of nanotoxicology. Allophane and imogolite in soils are treated next (with relevance to soil organic matter and carbon sequestration), followed by a final chapter focusing largely on organic nanomaterials in the environment and their transformations (one section even deals with engineered quantum dots and their effect on algal photosynthesis).

This is not a textbook in which one will find separate chapters on the chemical and physical underpinnings of nanoscience. No chapters are devoted to the origin of quantum size effects, to the nature of the aqueous electric double layer around nanoparticles, or to the lack of band bending and potential differences between the surface and interior of small particles. Some of this information is scattered throughout the chapters, of course, but the book largely assumes basic familiarity with physical chemistry.

*Carnick M. Eggleston (carrick@uwyo.edu) Center for Photoconversion and Catalysis and Department of Geology and Geophysics 1000 E. University Ave. University of Wyoming, Laramie, WY 82071, USA

CALENDAR

2012


June 24–29  Goldschmidt 2012, Montreal, Canada. E-mail: helpdesk@goldschmidt2012.org; website: www.goldschmidt2012.org


July 2–6  4th International Congress Eurosoil 2012, Bari, Italy. Website: www.eurosoil2012.eu


July 15–20  9th International Symposium on Synchrotron Environmental Geochemistry, Aveiro, Portugal. Web page: http://9iseg.web.ua.pt


October 7–11  MS&T’12: Materials Science & Technology Conference and Exhibition, combined with ACER’s 114th Annual Meeting, Pittsburgh, PA, USA. Web page: www.matsitech.org


October 15–19  19th Annual Short Course: Fluids in the Earth, Naples, Italy. E-mail: claudia.cannatelli@unina.it; web page: www.fluidenv.unina.it


November 4–7  Geological Society of America (GSA) Annual Meeting, Charlotte, NC, USA. Web page: www.geosociety.org/meetings


November 16–17  10th Swiss Geoscience Meeting, Bern, Switzerland. Web page: http://smsp.sncatweb.ch

November 18–23  Cities on Volcanoes 7, Colima, Mexico. E-mail: cov7@citiesonvolcanoes7.com; website: www.citiesonvolcanoes7.com

November 25–27  3rd International School on Experimental Crystallography, Uberlandia, Brazil. E-mail: Mathcry.Combisition@cm2. uhp-nancy.fr; web page: www.crystallography.fr/maths/uberlandia2012.php

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CALENDAR

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**November 26–30**  MRS Fall Meeting, Boston, MA, USA. Web page: www.mrs.org/s/mrs/index.asp

**December 1–8**  International Workshop on Magmatic Ore Deposits, Karnataka, India. E-mail: sisk.mondal@gmail.com; web page: www.sites.google.com/site/ptsymposium

**December 3–7**  AGU Fall Meeting, San Francisco, CA, USA. Details forthcoming

**December 5–8**  13th European Meeting on Environmental Chemistry, Moscow, Russia. Web page: www.europeanace.com/about/meetings

**2013**


**January 27–February 1**  37th International Conference and Expo on Advanced Ceramics and Composites, Daytona Beach, FL, USA. Webpage: http://ceramics.org/meetings/akers-meetings

**February**  International DTTG-Workshop on Qualitative and Quantitative Analysis of Clays and Clay Minerals, Karlsruhe Institute of Technology (KIT), Germany. Web page: www.dttg.ethz.ch/Analysis of Clays and Clay Minerals

**March 3–7**  TMS Annual Meeting, San Antonio, TX, USA. Web page: www.tms.org/Meetings/Meetings.aspx

**March 18–22**  44th Lunar and Planetary Science Conference (LPSC 2013), Houston, TX, USA. Web page: www.lpi.usra.edu/meetings/lpsc2013


**April 1–5**  MRS Spring Meeting & Exhibit, San Francisco, CA, USA. Web page: www.mrs.org/spring2013

**April 7–11**  24th American Chemical Society (ACS) National Meeting & Exhibition, New Orleans, LA, USA. Web page: www.acs.org

**April 24–28**  Basalt 2013 – Cenozoic Magmatism in Central Europe, Göttingen, Germany. E-mail: basalt2013@senckenberg.de; web page: www.senckenberg.de/root/index.php?page_id=15387&prev=true

**May 5–8**  Canadian Institute of Mining, Metallurgy, and Petroleum 2013 Conference & Exhibition, Toronto, Ontario, Canada. Web page: www.cim.org/calendar/calender.cfm?Year=All

**May 19–22**  AAPG 2013 Annual Convention & Exhibition, Pittsburgh, PA, USA. Web page: www.aapg.org


**June 9–14**  Water-Rock Interaction (WRI 14), Avignon, France. E-mail:contact@wri14-2013.fr; web page: www.wri14-2013.fr/en/home.html

**July 20–24**  IAVCEI General Assembly 2013: Forecasting Volcanic Activity, Kagoshima, Japan. Details: Masato Iguchi, e-mail: iguchi@svo.dprl.kyoto-u.ac.jp; web page: www.iavcei.org/IAVCEI.htm

**July 29–August 2**  Annual Meeting of the Meteoritical Society, Edmonton, Alberta, Canada. Web page: www.meteoriticalsociety.org

**August 4–8**  Microscopy & Microanalysis 2013, Indianapolis, IN, USA. Web page: www.microprobe.org/events

**August 25–30**  Goldschmidt 2013, Florence, Italy. Website: www.goldschmidt2013.org


**September 2–10**  10th International Eclogite Conference, Courmayeur, Aosta Valley, Italy. Web page: www.iec2013.unito.it

**September 8–12**  246th American Chemical Society National Meeting & Exhibition, Indianapolis, IN, USA. Web page: www.acs.org


**October 1–5**  MRS Fall Meeting & Exhibit, Boston, MA, USA. Web page: www.mrs.org/fall2013

**October 12–16**  MS&T’14: Materials Science & Technology Conference and Exhibition, Pittsburgh, PA, USA. Web page: www.matscitech.org/about/future-meetings

**October 19–22**  Geological Society of America Annual Meeting, Vancouver, BC, Canada. E-mail: meetings@geosociety.org; web page: www.geosociety.org/meetings

**November 18–21**  26th International Applied Geochemistry Symposium 2013 Incorporating the New Zealand Geothermal Workshop, Rotorua, New Zealand. Web page: www.gns.cri.nz/iags

**December 1–6**  MRS Fall Meeting & Exhibit, Boston, MA, USA. Web page: www.mrs.org/fall2013

**January 26–31**  38th International Conference and Expo on Advanced Ceramics and Composites, Daytona Beach, Florida, USA. Details forthcoming

**February 19–22**  247th ACS National Meeting & Exposition, Dallas, TX, USA. Web page: www.acs.org

**September 1–5**  21st General Meeting of the International Mineralogical Association (IMA2014), Johannesburg, South Africa. E-mail: info@ima2014.co.za; web page: www.ima2014.co.za

**September 7–14**  Annual Meeting of the Meteoritical Society, Casablanca, Morocco. Webpage: www.meteoritical-society.org

**2014**

**January 26–31**  38th International Conference and Expo on Advanced Ceramics and Composites, Daytona Beach, Florida, USA. Details forthcoming

**March 16–20**  247th ACS National Meeting & Exposition, Dallas, TX, USA. Web page: www.acs.org

**June 9–13**  Goldschmidt Conference, Sacramento, CA, USA. Details forthcoming

**August 10–14**  248th ACS National Meeting & Exposition, San Francisco, CA, USA. Web page: www.acs.org

**September 1–5**  21st General Meeting of the International Mineralogical Association (IMA2014), Johannesburg, South Africa. E-mail: info@ima2014.co.za; web page: www.ima2014.co.za

**September 7–14**  Annual Meeting of the Meteoritical Society, Casablanca, Morocco. Webpage: www.meteoritical-society.org

**PART QUOTE**

It is not enough to have a good mind; the main thing is to use it well

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The photograph shows the ruin of a local government castle of the Jogan era at Tagajo, located just north of Sendai, approximately 5 km from the present coastline. It was damaged during the Jogan earthquake in 869 AD. This earthquake had an estimated magnitude of 8.3 and caused a tsunami that seriously damaged the northeastern coast of Japan. The record of this tsunami and its effects are not only evidenced by the tsunami deposits but are part of the historical record of that time (see Minoura et al. 2001). The Jogan tsunami sediments can be found up to four or even five kilometers inland from today’s coastline in the deposits of the Sendai and Ishinomaki plains (Satake et al. 2008). Tagajo is an old castle town and was one of the cities hit by the Jogan earthquake and tsunami; 1000 lives in the old town were lost due to the tsunami (Minoura et al. 2001).

According to the Miyagi Prefectural Research Institute of the Tagajo site (www.thm.pref.miyagi.jp/kenkyusyo/explanation_tagajoato.html, in Japanese), buildings, including the ruined castle, of the local government of Tagajo were first constructed in 724 AD (first stage), repaired in 762 (second stage), and reconstructed in 780 after fire damage caused by a local war (third stage). In 869, the local government buildings were destroyed by the Jogan earthquake and possibly by the subsequent tsunami, but they were reconstructed afterwards (fourth stage). In 869, the local government district (about 1 km × 1 km) was destroyed in the middle of the 11th century. The photo, therefore, may not show the ruin after the Jogan earthquake. The ruin in the photo is almost in the center of the district. A road gutter that was probably destroyed by the Jogan tsunami can be observed near the south gate of the district (Miyagi Prefectural Board of Education Report No. 167, 1995, in Japanese), about 300 meters south of the ruin shown in the photo.

Flood waters from the 2011 tsunami came within one kilometer of the southern edge of the district (Geospatial Information Authority of Japan, www.gsi.go.jp/common/000061572.pdf). As the coastline was 1 km inland from today’s coast during the Jogan era, we can conclude that the tsunamis of 869 and 2011 were comparable in size because the difference in their flood fronts corresponds to the difference in the coastline between 869 and today.

REFERENCES


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