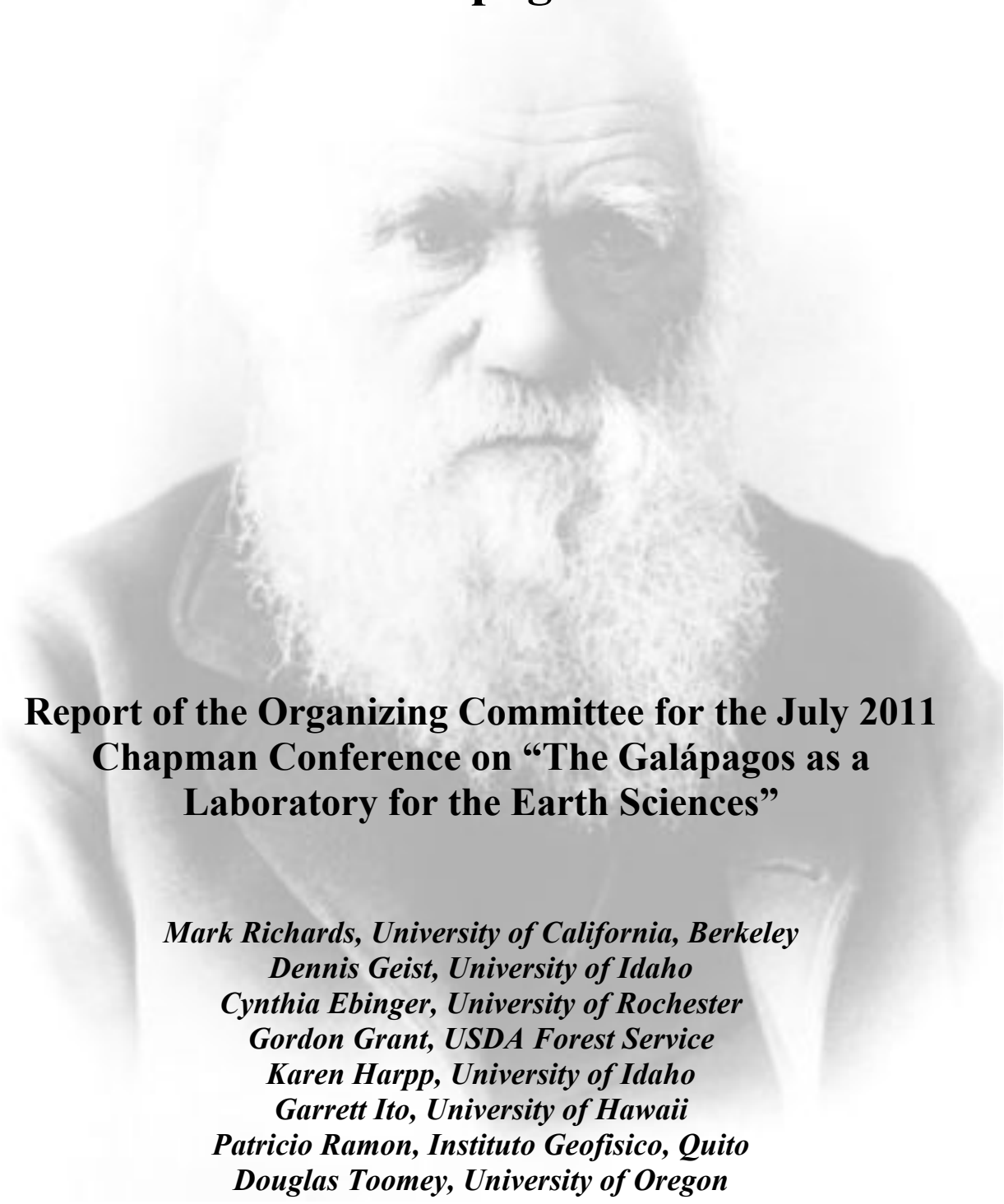
The Evolution of Ocean Island Systems: A New Community Perspective from the Galápagos



Report of the Organizing Committee for the July 2011 Chapman Conference on "The Galápagos as a Laboratory for the Earth Sciences"

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Setting the Stage

Ocean islands hold a uniquely important position in our understanding of geological phenomena, ranging from the core-mantle boundary to the largest volcanoes on Earth. Ocean islands are also central to our understanding of speciation, extinction, the evolution of isolated ecosystems, and the impacts of climate change. The Galápagos Archipelago in particular has played a key role in shaping our ideas about the co-evolution of geological and ecological systems. Indeed, it is often lost that Charles Darwin's *Origin of Species* grew from an essentially geological perspective, spurred famously by both geological and biological observations in the Galápagos. The insular setting continues to provides a rich environment for interdisciplinary scientific research, including: 1) opportunity to substitute space for time (in the case of time-transgressive archipelagos); 2) the ability to capture the full geological cycle of ocean islands from formation and emergence through erosion and submergence; 3) the complex interplay between biological and geological processes; and 4) the wide range of natural hazards present on ocean islands, including volcanism, earthquakes, large landslides, and tsunami inundation.

Ocean islands provide the best opportunity to enhance our understanding between the interplay of life and the physical earth.

Despite this profound legacy of interdisciplinary insight and discovery, modern research on ocean islands has tended to proceed along disciplinary lines, and hence opportunities for advancing a systems-level understanding are being missed. For example, the emergence/subsidence histories of volcanic island archipelagos exercise first-order controls on biological, hydrological, geomorphological, and ecological evolution, yet relatively little research has exploited this rich intersection of science; the necessary data are either missing or lacking in integration. A more complete understanding of these connections is possible with modest investment, given modern observational and modeling capabilities. Applied to the Galápagos and other ocean island systems, such a complete picture of physiographic and ecological evolution has the potential to revolutionize virtually every aspects of ocean island science, and to pave the way for major advances in understanding processes from the deep earth to the oceans and atmosphere.

The Galápagos Symposium

In July 2011, the National Science Foundation Directorate of Geosciences, the American Geophysical Union, and the Charles Darwin Foundation co-sponsored a symposium in Puerto Ayora, Galápagos (Ecuador) entitled "The Galápagos as a Laboratory for the Earth Sciences." The main purpose of this conference was to assemble researchers in diverse fields to identify key problems that require new collaborative and individual studies to advance our understanding of the evolution of volcanic ocean islands. The conference was interdisciplinary by design and included geodynamicists, geochemists, volcanologists, seismologists, hydrologists, geomorphologists, and ecologists, many focused on the Galápagos, but an equal number of experts on other ocean island systems such as Samoa, Hawaii, Iceland, the Canaries, the Azores, and Juan Fernandez.

Volcanic islands constitute one of Earth's most dynamic geologic environments and uniquely sample parts of the earth's mantle that are otherwise inaccessible.

The symposium consisted of 3 days of scientific presentations and plenary talks, 3 days of field excursions, and 2 days of workshops designed to plan future directions for scientific exploration and public outreach. The approximately 80 conference attendees included an international group of leading senior scientists, many early-career scientists and students (including 15 attendees from South America, especially Ecuador), a number of Ecuadorian officials responsible for research and conservation in the Galápagos National Park, and five NSF program directors. Perhaps due in part to the venue, many participants remarked that this was the most exciting conference they had ever attended. Indeed, the symposium was marked by a consistent exploratory dialogue across disciplinary boundaries that produced many new insights and avenues for research.

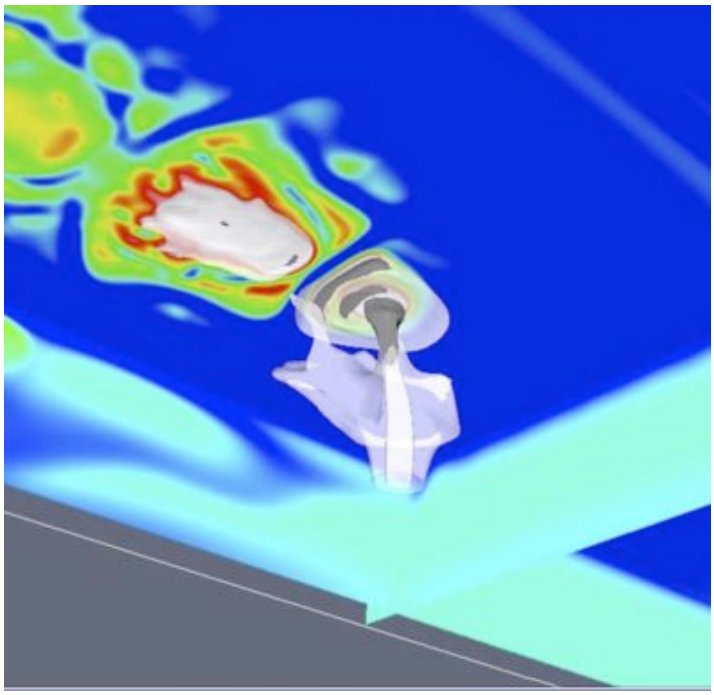
Recommended Initiatives

The major outcome of the workshop was that both broad themes and specific proposals for future work and collaboration were identified. The consensus of the workshop was that the next generation of breakthrough research will require interdisciplinary, team-based efforts. The initiatives identified at the conference will necessitate strategic planning owing to the larger scale and cultural challenges that such cross-cutting international research will require. Perhaps the biggest surprise of the symposium was the identification of the enormous potential for progress at the boundaries of volcanology, geomorphology, hydrology, and ecology, all linked by a need for LiDAR and high-resolution bathymetric imaging. The symposium participants identified five broad

interdisciplinary initiatives, including three for collaborative science that capitalize on the unique characteristics of the Galápagos hotspot province, one for public outreach, and one for collaboration and exchange activities at the international level: 1) a virtual international ocean island observatory; (2) a large-scale seismic imaging experiment; (3) LiDAR topographic and high-resolution bathymetric mapping (particularly in shallow water); (4) volcanological studies, including geophysical measurements and hazards assessment; and (5) an outreach effort that includes writing and illustrating a geological guidebook and new designs for training naturalist guides. These initiatives and specific action items are described in the following sections.

An International Ocean Island Observatory

The broadest outcome of the symposium is the possibility of an International Ocean Island Observatory (IOIO), a community program comparable to, or even broader than, the successful integrative and interdisciplinary Interridge and Margins programs. A community program focusing on ocean islands would draw upon activities and research efforts around the world to achieve a more comprehensive understanding of the evolution of ocean island systems and their ecological responses to anthropogenic and natural hazards, including climate change and water resources. Such an effort would require collaboration with ecologists, evolutionary biologists, and environmental scientists working in various ocean island archipelagos, and could yield untold fundamental scientific rewards. The 2011 Galápagos symposium demonstrated not only that interdisciplinary work by earth scientists is promising, but also that collaborative efforts to study island ecosystems using a holistic approach are the future.



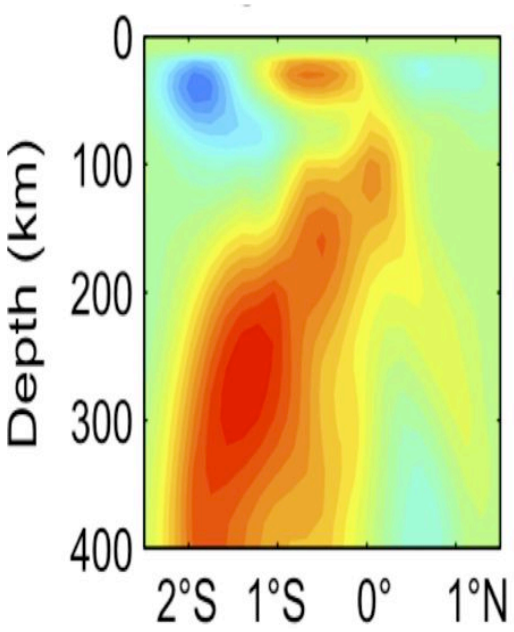
This sophisticated computational model of the Hawaiian plume viewed from below aids in our understanding of worldwide geodynamic processes (courtesy of G.Ito).

The IOIO initiative would result in the first-ever network of geological/ecological investigators studying these critical habitats, and could begin modestly by creating a virtual ocean island research community relying upon modern tools of information technology, a few focused international symposia, and the initiation of an outreach effort that builds on current efforts. The proposed IOIO could also draw upon numerous opportunities to secure support for virtual communities, such as NSF's Research Coordination Networks (RCN) program. The IOIO could also be a

strong candidate for a future NSF Frontiers of Earth System Dynamics proposal with sufficient preparatory groundwork.

Integrated Geophysical, Geochemical, and Geodynamic Imaging

In many ways, the Galápagos Archipelago is an ideal location for carrying out an ambitious program of seismic tomography and other subsurface imaging experiments. Most importantly, the Galápagos is one of the best places on the planet for observing the geochemical and geophysical manifestations of hotspot-ridge interaction, and the region has a remarkable richness of clues as to how these processes function at the level of mantle flow and magma transport. Just as the Galápagos formed the crucible for the theory of evolution, the Galápagos Archipelago and Galápagos Spreading Center system is one of just several key locations for understanding hotspot-ridge interactions, and hence the dynamics of upper mantle flow. Enormous progress has been made in the last two decades in unraveling the remarkable patterns of geochemical signatures in the Galápagos, both from terrestrial and shipboard studies. Complementary geophysical observations and modeling have also elucidated much about lithospheric structure and yielded quantitative models for mantle dynamics. Despite these advances, the picture is tantalizingly incomplete, and there was an overwhelming consensus at the Galápagos Symposium that a new generation of seismic imaging could provide key information for integrating the various sources of information to obtain a much more complete understanding of mantle and magma dynamics in the Galápagos system as well as in other related systems globally. Such an understanding would also be key to developing robust models for the emergence/subsidence history of the islands, invaluable information for landscape and ecological studies.



This seismic tomographic image is of the Galapágos hotspot and clearly delineates the anomalous mantle responsible for the islands (courtesy D. Toomey and D. Villagomez.

In addition to being a premier site for studying hotspot-ridge interaction, there are several additional reasons that the Galápagos Archipelago offers an almost ideal setting for seismic imaging: (1) The islands themselves span most of the bathymetric swell, thus offering an unusually broad aperture for mapping regional geochemical variations and imaging to greater depths than is typical for oceanic archipelagos. (2) Because of well-established relations with the Ecuadorian Navy, Ecuador's Instituto Geofisico, and the Galápagos Marine Reserve (National Park), a good collaborative relationship is already in place for conducting OBS and active seismic investigations. (3) The thin lithosphere

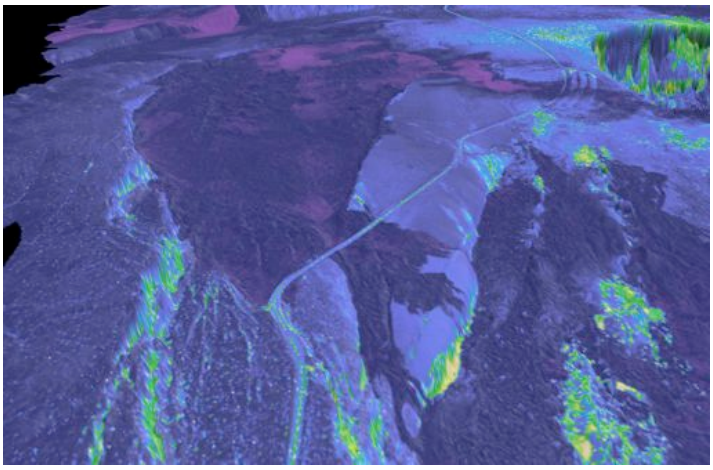
facilitates seismic imaging of magma source regions and magma conduits to crustal magma reservoirs and surface vents. (4) A number of singular structural features of the Galápagos are ripe for explanation in terms of underlying mantle and deep-crustal processes, including the still unexplained "Darwinian" structural alignments of volcanoes and islands, the enormous and enigmatic escarpment bounding the southwestern margin of the Galápagos platform, and the remarkably contrasting character of volcanic construction between the eastern and western islands. Answering these questions in Galápagos could lead to a watershed shift in our understanding of ocean island systems worldwide.

Two onshore seismic imaging studies of the Galápagos have been completed, one that used combined surface- and body-wave tomography to map seismic velocities between about 100-400 km depth and a second, higher-resolution study imaging the crustal structure beneath Sierra Negra and Cerro Azul volcanoes. Without ocean bottom seismometers, however, the critical region of the crust and upper mantle between 10 and 40 km will remain mostly unknown, and this is the critical region for melt extraction and processing. Thus, onshore-offshore seismic imaging is critical to quantify the time and length scales of hotspot-influenced magmatic processes, and to test models for the extraction and retention of melt beneath ocean islands at plume-ridge intersections. The combined data set from these two seismic studies lacks the resolution and stations off plume to reference the anomalous mantle structure. A network utilizing both land-based and OBS instruments is required to create both the requisite density and aperture to image velocity variations throughout this critical region. A marine wide-angle multichannel survey is also needed to understand the velocity structure of the lower crust and uppermost mantle in order to test models for magma emplacement and evolution.

The working group on seismic imaging concluded that a focused international workshop should be held in the coming year (2012) to begin organizing and planning for a major set of Galápagos seismic imaging experiments. This workshop should involve not only the international community of seismologists interested in imaging various aspects of ocean island and spreading ridge dynamics, but also a healthy contingent of volcanologists, petrologists, geochemists, marine geophysicists, and geodynamic modelers to ensure that the seismic imaging work provides the measurements to maximize the potential for forging a much more complete understanding of the entire geological evolution of the Galápagos plume-ridge system.

LiDAR and Bathymetric Imaging

High-resolution topographic data, as measured by LiDAR, has revolutionized geomorphologic studies of the few ocean islands where it has been obtained. Some of the major questions that arose from the symposium involve the mechanisms of growth of ocean islands from abyssal depths to their maximum elevation, the mechanisms and rates of erosion, and the interplay between magmatic and erosional processes. LiDAR imagery is extremely useful for volcanological studies, especially in lava terrains, where the margins of individual flows can be elucidated on the centimeter scale, the distribution of surface morphologies mapped, and cross-cutting structures identified. Furthermore,



Airborne LiDAR has revolutionized geomorphological and ecological studies, owing to cm-scale resolution. It has been underutilized in volcanology, as demonstrated by this image of Kilauea's caldera, where lavas of different ages stand out clearly, as do caldera-related structures and the vegetative canopy (image courtesy of S. Soule and K. Cashman).

LiDAR data will permit collaboration with ecologists to develop an understanding of the fine-scale associations between species distribution and topography, both in the sense of baseline studies and for monitoring change. Little use of LiDAR has been made for measuring deformation features related to caldera ring fault systems, caldera floor deformation, and fissuring, but the potential is great. LiDAR data are also useful for monitoring vegetation changes, one of the most important issues in the Galápagos, owing to the islands' susceptibility to climate change and invasion by introduced plants.

The Galapagos Archipelago represents an end-member of ocean islands due to their semi-arid climate in a tropical setting. The lack of fluvial erosion on most of the islands means that evidence for volcanic construction and structural evolution is preserved to extraordinary degrees. In addition, dramatic differences in precipitation between windward and leeward sides of the high islands create strong ecological and hydrological contrasts within a few kilometers, with cloud-drip forests nearly adjacent to cactuses. The range of climate zones and volcanic histories in the islands also suggests that the potential is high for shedding new light on fundamental processes in the competition between volcanic construction, fluvial dissection, and soil development and hillslope processes in driving landscape evolution over time. LiDAR will be integral for understanding the extent to which destructive processes have shaped the landscape and how they might influence the biological environment. Moreover, comparison of archipelagos presents the opportunity to assess different space-time relationships as they relate to the broader geomorphic problem of landscape evolution. Although progress toward a comprehensive picture of island formation and evolution is limited by complex and poorly understood island genesis histories, progress can be made towards understanding how volcanic landforms develop over time in arid terrains, when channels are initiated and how they evolve and incise the islands, how constructional versus destructional processes compete, and how these geomorphic processes "set the table" for life to colonize and diversify by evolution.

Most of the margins of the Galápagos Platform, including the region between the hotspot and the Galápagos Spreading Center, have been mapped by high-resolution multibeam and side-scan sonar. The shallow-water bathymetry relies on coarse navigational charts,

however, and this is the critical region for understanding the effects of eustatic sea-level change, climate change, and subsidence and erosion on the geomorphic evolution of islands. The research arm of the Ecuadorian Navy, INOCAR, is beginning a major initiative to map the shallow-water bathymetry using multibeam sonar, and has invited international collaboration.

Volcano Monitoring and Hazards Assessment

The traditional view that ocean island volcanoes only produce effusive eruptions, and are therefore relatively safe, is naïve. Almost every ocean island volcano that has been studied in detail has undergone explosive eruptions. Add to this the exceptionally high rates of magma intrusion (as measured by volcano inflation) and the high frequency of eruptions from closely spaced volcanoes, which produce a zone of considerable hazard from flows, eruptions, faulting, and flank collapse. Perhaps for the first time, volcanologists at the symposium came to recognize the importance of calderas as water catchments and the consequent hydrovolcanic activity. Potentially disastrous explosive eruptions have occurred at Kilauea (Hawaii), and even in the arid Galápagos, explosive eruptions have been documented at every caldera that has been studied in detail. The 1968 eruption of Fernandina is a classic example; the violence of this eruption was unprecedented on a worldwide basis. More obviously, explosive hydrovolcanism also occurs along coastlines, where human populations are concentrated. The lack of detailed bathymetric maps prevents the simulation of the impact of tsunamigenic landslides or Pacific tsunamis along the coastlines of the islands, as was demonstrated in the ~2 m inundation experienced in Puerto Ayora after the March 2011 Tohoku earthquake.

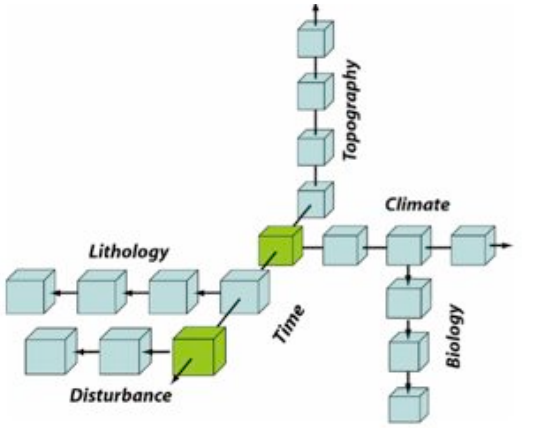
Despite these dangers, no volcanic, seismic, or tsunami hazards assessment has ever been conducted in the Galápagos. Hazards maps are greatly needed, especially as the islands grow in population and the number of tourists visiting the active volcanoes increases. The Instituto Geofisico is currently installing a telemetered 6-station seismic monitoring network on the highest-risk volcanoes as part of their national network. Because spacings will be mostly > 30 km, only regional earthquakes will be well located, and it will not include deformation monitoring by GPS. With the early demise of the EnviSAT radar monitoring system, the fate of monthly imaging of the Galapagos volcanoes with InSAR remains unclear. A denser network of seismometers and deformation monitoring would greatly improve the monitoring situation. Moreover, temporary GPS and seismic deployments at Sierra Negra volcano have shown that Galápagos volcanoes display unprecedented activity distinct from that at Hawaii, permitting an opportunity to understand the mechanics of basaltic caldera volcanoes and magma transport and storage on a more global basis.

Public Outreach in the Galápagos

The great story of the Galápagos involves the co-evolution of the geology and biology of the archipelago, yet the 200,000 plus visitors each year to the Galápagos are primarily attracted by and exposed to the biological wonders; in general, they receive little information on the geology of the islands. This situation is understandable in terms of a

number of factors, including the natural attraction of blue-footed boobies, the endemic giant tortoises and iguanas, and the ecological importance of the Galápagos as the best-preserved semi-arid island ecosystem in the world. However, another major factor is that the Galápagos National Park naturalist guides, who are required to accompany virtually all tourist excursions, have little knowledge of the geology of the islands. This is largely a matter of their training, which is currently focused almost exclusively on ecology and preservation.

The pathways for remedying this situation are straightforward: The Charles Darwin Station plays a major role in training Galápagos guides, and has already volunteered to work with Symposium participants to devote at least one week of their several-week training program to geology. Attendees of the Symposium are determined to produce a guidebook that would simultaneously fill the need for the instruction of guides. A guidebook project will be launched in 2012 as a collaboration of the Symposium participants (led by Dennis Geist, Karen Harpp, and Kathy Cashman), Darwin Station CEO Swen Lorenz, and one of the several professional photographers dedicated to the Galápagos. This production will lead to a significantly greater awareness of the interrelation of geological and ecological evolutions on the islands, and a broader understanding of science on the part of the public. The guidebook will, of course, be made available for sale to the public as well.



Even though ocean islands provide the simplest geo- and eco-systems our planet has to offer, the complex relationships and interactions between the different parts of the systems are a generation from being understood.

Action Items

1. Listserve: An ocean island researcher listserve has already been initiated to facilitate coordination among research groups. Karen Harpp (Univ. Idaho) is in charge of this effort.

2. Website: A website is being constructed to distribute materials from the Galápagos Symposium. In addition to the published meeting abstracts, the website will include all of the materials presented at the conference, including posters and visual presentations. The posting of materials from the plenary talks will be particularly valuable in fostering interdisciplinary research. We anticipate a release date of October 15. In addition to disseminating information and ideas among researchers, the website will provide a

straightforward mechanism of outreach, as it will be accessible to the naturalist guides and general public (hosted by D. Geist and K. Harpp, Univ. Idaho).

3. AGU Monograph: An AGU Monograph on ocean island research, with emphasis on Galápagos research, has been approved and is in full swing (Karen Harpp and Eric Mittelstaedt, editors). Invitations for contributions have been issued and a manuscript deadline of March 15, 2012, has been set. This volume will include results presented at the Galápagos Symposium as well as contributions from additional authors.

4. LiDAR proposals: Research teams have been organized to apply for grants from existing NSF programs to support LiDAR imaging in the Galápagos. Teams will also mobilize once future requests for proposals are issued for the Frontiers in Earth System Dynamics program.

5. Design of an Integrated Geophysical, Geochemical, and Geodynamic Study of the Galapagos Hotspot and Spreading Center System: Garrett Ito (Univ. Hawaii) and Emilie Hooft (Univ. Oregon) are organizing an international workshop to consider prospects and designs for a large-scale seismic imaging experiment in the Galápagos, including potential deployment of OBS, multi-channel marine seismics, and terrestrial instrumentation. Financial support will be sought from NSF for this workshop, which will likely convene in the latter half of 2012.

6. Volcano monitoring: At the Galápagos Symposium, Patricio Ramon of the Instituto Geofisico in Quito, Ecuador, appealed for international collaborative research to improve characterization of volcanic (and seismic) hazards in the Galápagos. Many efforts are already underway, including geodetic and seismic monitoring of Sierra Negra volcano on Islas Isabela and Fernandina (Dennis Geist, Univ. of Idaho; Cynthia Ebinger, University of Rochester; Falk Amelung, Univ. of Miami). Three Symposium participants, Yang Shen (Univ. Rhode Island), Jonathan Lees (Univ. North Carolina), and Mark Jellinek (Univ. British Columbia) intend to propose an intensive short-period seismic monitoring/imaging experiment for Sierra Negra.

7. Guidebook and guide training: Dennis Geist (Univ. Idaho), Karen Harpp (Univ. Idaho), and Kathy Cashman (Univ. Oregon) will lead an effort to write a guidebook on the geology of the Galápagos Archipelago, with contributions sought from Symposium participants. This will be a collaborative effort with the Charles Darwin Foundation, and will seek to achieve a high quality of production, aiming for the burgeoning tourist market in the Galápagos. This guide will also be designed to serve as a "textbook" for training the many official naturalists who are required to accompany all tourist expeditions in the Galápagos National Park. The Darwin Foundation is responsible in part for training these guides, and has welcomed this effort to enhance their program. Three-dimensional visualizations of the seismic and deformation activity at Sierra Negra are in their final stages of development and will be distributed to the Park guides soon (Cynthia Ebinger, Univ. Rochester).

8. Ocean island observatory: There was a strong consensus at the meeting that further integration with the international ecology and evolutionary biology community was needed to realize the full potential for ocean island systems research, and several different approaches to an International Ocean Island Observatory were discussed, including a global virtual network as well as a Pacific Basin-focused network of existing research stations. Shortly after the Galápagos Symposium, representatives from the Darwin Research Station (Galápagos), the Gump Research Station (Tahiti), the University of California, Berkeley, Field Stations, and the California Academy of Sciences met and discussed sponsoring an international symposium on "Evolution and Sustainability of Ocean Island Systems" (tentative title), as well as a potential approach to several private foundations for financial support for the symposium. It is also possible that a subgroup of the Galápagos Symposium attendees may appeal to NSF for support via a Research Coordination Networks proposal. If successful, these initiatives could have a far-reaching influence on the future of all scientific research focused on ocean islands, and go a long way toward facilitating the kind of interdisciplinary research necessary to both understand ocean island systems and to protect their vulnerable ecologies.