The Galápagos as a Laboratory for the Earth Sciences

American Geophysical Union Chapman Conference

Puerto Ayora, Galápagos, Ecuador

25 – 30 July 2011

AGU Chapman Conference on The Galápagos as a Laboratory for the Earth Sciences

Puerto Ayora, Galápagos, Ecuador
25 – 30 July 2011

Conveners

Mark Richards, University of California Berkeley
Dennis Geist, University of Idaho

Program Committee

Gordon Grant, USDA Forest Service
Patricio Ramon, Escuela Politecnica National
Karen Harpp, Colgate University
Doug Toomey, University of Oregon
Garrett Ito, University of Hawaii
Cynthia Ebinger, University of Rochester

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Cover photo

Top left: Galapagos tortoises at the Charles Darwin Research Station. Top right: Rounded olivine and plagioclase crystals from a northern Floreana beach. Bottom left: A blue-footed booby on Espanola Island. Bottom right: View up a clastogenic flow during the 2005 Sierra Negra eruption.

AGU Chapman Conference on The Galápagos as a Laboratory for the Earth Sciences

Meeting At A Glance

Saturday, 23 July 2011

0630h–1830h	Sierra Negra Pre–Meeting Field Trip

Sunday, 24 July 2011

0730h–1530h	Sierra Negra Pre–Meeting Field Trip (continued)
1830h–2000h	Icebreaker

Monday, 25 July 2011

0830h–0900h	Welcome and Introduction
0900h–1000h	Surface Processes at Ocean Islands
1000h–1015h	Break
1015h–1215h	Surface Processes at Ocean Islands (continued)
1215h–1345h	Lunch
1345h–1545h	Active Processes at Ocean Islands
1800h–2000h	Evening Plenary and Poster Session I

Tuesday, 26 July 2011

0830h–0930h	Mantle Processes at Ocean Islands
0930h–0945h	Break
0945h–1145h	Mantle Processes at Ocean Islands (continued)
1145h–1315h	Lunch
1315h–1515h	Surface Processes in the Galapagos
1730h–1930h	Evening Plenary and Poster Session II

Wednesday, 27 July 2011

0830h–0930h	Plume–Ridge Interaction in the Galapagos
0930h–0945h	Break
0945h–1145h	Plume–Ridge Interaction in the Galapagos (continued)
1145h–1315h	Lunch
1315h–1515h	Active Processes in the Galapagos
1730h–1930h	Evening Plenary and Poster Session III

Thursday, 28 July 2011

0800h–1700h	Santa Cruz Field Trip

Friday, 29 July 2011

0830h–0930h	Future Directions: Active Processes
0930h–0945h	Break
0945h–1200h	Future Directions: Active Processes (continued)
1200h–1330h	Lunch
1330h–1615h	Future Directions: Deep Earth Processes
1800h–2000h	Evening Plenary and Poster Session IV

Saturday, 30 July 2011

0830h–0915h	Future Directions of Surface Processes
0915h–0930h	Break
0930h–1110h	Future Directions of Surface Processes (continued)
1110h–1200h	Perspectives on Collaborative Projects
1200h–1330h	Lunch
1330h–1700h	Key Scientific Questions and Strategies
1930h–2130h	Conference Banquet

SCIENTIFIC PROGRAM

SATURDAY, 23 JULY

0630h – 1830h **Sierra Negra Pre-Meeting Field Trip - Saturday**

SUNDAY, 24 JULY

0730h – 1530h **Sierra Negra Pre-Meeting Field Trip - Sunday**

1830h – 2000h **Conference Icebreaker**

MONDAY, 25 JULY

0830h – 900h **Welcome and Introduction**
Presiding: Mark A. Richards, Dennis Geist
Municipal Hall

Surface Processes at Ocean Islands
Municipal Hall

0900h – 0940h **William Dietrich** | The Coevolution of Geomorphology and Biology of Ocean Islands

0940h – 1000h Discussion by Taylor Perron

1000h – 1015h Break

1015h – 1055h **Anne J. Jefferson** | Top down or bottom up? Volcanic history, climate, and the hydrologic evolution of volcanic landscapes

1055h – 1115h Discussion by Kathy Cashman

1115h – 1155h **Suzanne P. Anderson** | Rock into Regolith: Earth’s Critical Zone on Volcanic Ocean Islands

1155h – 1215h Discussion by Gordon Grant

1215h – 1345h Lunch

Active Processes at Ocean Islands

Municipal Hall

1345h – 1425h	**Paul Segall** | Insights into magmatic processes from deformation and seismicity
1425h – 1445h	Discussion by Cindy Ebinger
1445h – 1525h	**Katharine V. Cashman** | The Hazards and Benefits of Volcanic Eruptions on Oceanic Islands
1525h – 1545h	Discussion by Jonathan Lees

1800h – 2000h Evening Plenary and Poster Session I

Adjoining Room, Municipal Hall

1800h – 1830h	Presentation by GNP/INOCAR
M-1	**Anne E. Carey** | Climate, dust, and soil biogeochemistry on volcanic islands
M-2	**Andrés González** | A hydro-ecological cross-section of Santa Cruz Island, Galapagos Archipelago
M-3	**Russell Yost** | Potential role of soil calcium and phosphorus on Galapagos tortoise growth and well-being
M-4	**Taylor Perron** | Origin of morphologic variability among Pleistocene coral reefs
M-5	**Kenneth H. Rubin** | Using Geochronology of Shoreline and Coral Reef Deposits to Study Uplift and Subsidence at Tropical Volcanic Ocean Islands: Examples from Hawaii with Applications to the Galapagos
M-6	**Oliver C. Shorttle** | Asymmetry of plume-ridge interaction around The Galápagos and Iceland controlled by spreading-ridge geometry
M-7	**Karen S. Harpp** | Plume-Ridge Interaction in the Galápagos I: Lithospheric Control on Volcanic Lineament Generation in the Northern Galápagos Province
M-8	**Katrina A. Garman** | Investigating Plume-ridge Interaction and its Tectonic Implications: Insights from the Distal Ends of the Galápagos Spreading Center at 86°W and 97.5°W
M-9	**Eric Mittelstaedt** | Plume-ridge interaction at the Galapagos: Insights provided by new gravity and magnetic observations
M-10	**Adam Soule** | Evaluating ridge-hotspot interaction models through crustal stress indicators in the Northern Galápagos Volcanic Province
M-11	**Jeffrey Karson** | Subaerial Seafloor Spreading in Iceland: Manifestations of Ridge-Hot Spot Interactions
M-12	**Emily L. Wilson** | Plume-Ridge Interaction in the Galápagos II: Volcanic Evolution of the Northern Galápagos Islands

M-13	**Bryndis Brandsdottir** | Plume-Ridge Interactions in Iceland and Galapagos, Crustal Buildup and Volcanism
M-14	**William Schlitzer** | Plume-Ridge Interaction in the Galápagos III: The Origins of Pinta, Marchena, and Genovesa Islands
M-15	**Kaj Hoernle** | Temporal and Spatial Variations in Galapagos Plume-Ridge Interaction
M-16	**Alice Colman** | Influence of Magma Supply on Galápagos Spreading Center Magmatic and Eruptive Processes
M-17	**Gordon E. Grant** | A framework for understanding landscape development of volcanic ocean islands

TUESDAY, 26 JULY

Mantle Processes at Ocean Islands

Presiding: Mark A. Richards
Municipal Hall

0830h – 0910h	**Matthew G. Jackson** | Ocean Islands and mantle plumes: Outstanding geochemical and petrological questions
0910h – 0930h	Discussion by Rajdeep Dasgupta
0930h – 0945h	Break
0945h – 1005h	**Yang Shen** | Geophysical constraints on oceanic islands, mantle dynamics and mantle heterogeneity: Part I
1005h – 1025h	**Yang Shen** | Geophysical constraints on oceanic islands, mantle dynamics and mantle heterogeneity: Part II
1025h – 1045h	Discussion by Gabi Laske
1045h – 1125h	**Mark Jellinek** | The Plume-Hotspot Connection, Plate Tectonics and the Remarkable Character of the CMB Region
1125h – 1145h	Discussion by Shijie Zhong
1145h – 1315h	Lunch

Surface Processes in the Galapagos

Municipal Hall

1315h – 1355h	**Taylor Perron** | Problems in the geomorphology of the Galápagos and other ocean islands
1355h – 1415h	Discussion by Dennis Geist
1415h – 1455h	**Noémi d'Ozouville** | The Galapagos Islands as a Laboratory for Hydrological Processes
1455h – 1515h	Discussion by Anne Jefferson

1730h – 1930h **Evening Plenary and Poster Session II**
Adjoining Room, Municipal Hall

1730h – 1800h Presentation by National Science Foundation

T-1 **Robert A. Duncan** | How Did the Galápagos Hotspot Begin?

T-2 **Eduardo Contreras-Reyes** | Magmatic processes beneath the Louisville and Juan Fernández hotspot tracks from wide angle seismic data

T-3 **Christopher A. Vidito** | Galápagos Plume Source Lithology: Inferences from Olivine Phenocryst Compositions

T-4 **Millard F. Coffin** | Deep structural images of the Ontong Java Plateau deduced from an active source seismic experiment

T-5 **Sally A. Gibson** | Constraints on the transition from active plume upwelling to lateral mantle flow beneath Galápagos: Geochemical evidence from Isla Santiago

T-6 **Mark A. Richards** | Petrological Interpretation of Deep Crustal Instrusive Bodies Beneath Oceanic Hotspot Provinces

T-7 **Paula M. Manriquez** | A flexure study beneath the Juan Fernandez Hotspot track

T-8 **Todd A. Bianco** | Geochemical Variations at Hotspots Caused by Variable Melting of Veined Mantle Plumes

T-9 **Gabi Laske** | The Hawaiian PLUME OBS deployment: Lessons learned and recommendations for a Galapagos deployment

T-10 **Deborah E. Eason** | Insights into melt and chemical transport rates in the mantle from the volcanic response to glacial unloading in Iceland

T-11 **Emilie E. Hooft** | Seismic Constraints on the Formation of the Galápagos and Iceland Platforms

T-12 **Dennis Geist** | A Petrologic Model of the Galapagos Plume

T-13 **Rajdeep Dasgupta** | Constraining pyroxenite component in OIB source through melt-rock reaction experiments in pyroxenite-peridotite system and partitioning of first-row transition elements during mantle melting

T-14 **Alejandro Gallego** | Analysis of surface wave azimuthal anisotropy with geodynamic models and application to the Iceland hotspot

T-15 **Shijie Zhong** | Mantle Plumes, Oceanic Islands and Their Induced Surface Vertical Motions

T-16 **Cinzia G. Farnetani** | Origin of hotspot lavas geochemical zoning: a geodynamics perspective

WEDNESDAY, 27 JULY

Plume-Ridge Interaction in the Galápagos
Municipal Hall

0830h – 0910h **Kaj Hoernle** | Petrology/Geochemistry of the Galapagos Hotspot and Hotspot-Ridge Interaction

0910h – 0930h Discussion by Sally Gibson

0930h – 0945h Break

0945h – 1025h **Douglas R. Toomey** | Upper mantle structure beneath the Galápagos Archipelago from joint inversion of body and surface waves

1025h – 1045h Discussion by Mike Coffin

1045h – 1125h **Garrett Ito** | Dynamics of Plume-Plate Interaction

1125h – 1145h Discussion by Cinzia Farnetani

1145h – 1315h Lunch

Active Processes in the Galápagos
Municipal Hall

1315h – 1355h **John M. Sinton** | Magma Migration, Storage and Evolution in the Galápagos Region

1355h – 1415h Discussion by John Maclennan

1415h – 1455h **Michael P. Poland** | Capitalizing on the Galápagos archipelago as a high-visibility natural laboratory for volcanology

1455h – 1515h Discussion by Patricio Ramon

1730h – 1930h **Evening Plenary and Poster Session III**
Adjoining Room, Municipal Hall

1730h – 1800h Talk on State of Galapagos

W-1 **James T. McClinton** | Neuro-fuzzy classification of submarine lava flow morphology on the Galapagos Spreading Center, 92°W

W-2 **Omar E. Marcillo** | Infrasound produced by degassing of shield-volcanos: Hawaii and Galapagos

W-3 **Peter M. Shearer** | Characterizing fault zones at Kilauea and Mauna Loa volcanoes by large-scale mapping of earthquake stress drops and high precision relocations

W-4 **Mark Jellinek** | The influence of diffusive convection on the longevity of hydrothermal plumes

W-5	**Helge M. Gonnermann** | Modeling the dynamics of magma flow from mantle to surface at Mauna Loa and Kilauea, Hawai'i
W-6	**Mary E. Peterson** | Volatile budget of the mantle sources of the Galapagos plume
W-7	**Michael P. Poland** | Magma Supply to Basaltic Shields: An Example from Hawaii and an Opportunity for the Galapagos
W-8	**Marco Bagnardi** | Time series of volcanic deformation in the Galapagos: A perspective from InSAR, GPS, and seismic data
W-9	**Rachel L. Walters** | Time-dependent geochemical modeling of the rift cycle applied to rift relocations at Iceland
W-10	**Andrés G. Ruiz Paspuel** | Seismic and ground deformation patterns at Sierra Negra Volcano, Galapagos- Ecuador
W-11	**Cynthia J. Ebinger** | Magmatism and faulting on Isabela Island, Galapagos interpreted from seismicity and InSAR patterns
W-12	**Patrick J. McGovern** | Structure and evolution of Galapagos volcanic edifices: Insights from lithospheric flexure models and comparisons with planetary analogs
W-13	**George W. Bergantz** | Magma Systems in the Galapagos Islands: The Dynamics of and Evidence for the Transition Between Crystal Rich and Crystal Poor Conditions
W-14	**Ricardo Ramalho** | Episodic swell growth inferred from variable uplift of the Cape Verde hotspot islands

THURSDAY, 28 JULY

0800h – 1700h **Santa Cruz Field Trip**

FRIDAY, 29 JULY

Future Directions: Active Processes
Municipal Hall

0830h – 0845h	Orientation
0845h – 0900h	Summary Presentation
0900h – 0930h	Panel Discussion
0930h – 0945h	Break

0945h – 1130h	Breakout Groups
1130h – 1200h	Summary (reconvene)
1200h – 1330h	Lunch
	Future Directions: Deep Earth Processes Municipal Hall
1330h – 1345h	Presentation
1345h – 1415h	Panel and breakout charges
1415h – 1545h	Breakout Groups: Surface Processes
1545h – 1615h	Reconvene in Plenary
1800h – 2000h	**Evening Plenary and Poster Session IV** Adjoining Room, Municipal Hall
1800h – 1830h	Presentation: Hazard Mitigation in the Galápagos
F-1	**Ricardo Ramalho** | Why have the old Cape Verde Islands remained above sea-level? Insights from field data and wave erosion modeling
F-2	**Marco Bagnardi** | Evidence of multiple magma reservoirs at Fernandina volcano
F-3	**Marco Bagnardi** | The April 2009 eruption of Fernandina volcano: onset and effects observed by Satellite Radar Interferometry
F-4	**Dennis Geist** | An Evolutionary Model of Galapagos Magma Chambers
F-5	**Patricio Ramon** | April 2009 Fernandina volcano eruption, Galápagos Islands, Ecuador: thermal mapping of the lava flows emitted
F-6	**Douglas R. Toomey** | Crustal structure beneath the Galápagos Archipelago from ambient noise tomography and its implications for plume-lithosphere interactions
F-7	**Mario C. Ruiz** | Seismic Activity and Seismic Monitoring at Galapagos Islands
F-8	**Jonathan M. Lees** | Search for Harmonic tremor in the Galapagos
F-9	**Leif Karlstrom** | Mechanical controls on the longevity and magnitude of large volcanic eruptions
F-10	**John Maclennan** | Petrological Constraints on Magma Transport and Storage under Iceland

SATURDAY, 30 JULY

	Future Directions of Surface Processes Municipal Hall
0830h – 0845h	Presentation
0845h – 0915h	Discussion
0915h – 0930h	Break
0930h – 1040h	Breakout Groups
1040h – 1110h	Reconvene for Discussion
	Perspectives on Collaborative Projects Municipal Hall
1110h – 1140h	Plenary Talk
1140h – 1200h	Discussion
1200h – 1330h	Lunch
	Key Scientific Questions and Strategies Municipal Hall
1330h – 1400h	Plenary Discussion on Project Ideas
1400h – 1600h	Planning Group Discussions
1600h – 1700h	Summary Discussion
1930h – 2130h	**Conference Banquet**

ABSTRACTS

listed by name of presenter

Anderson, Suzanne P.

Rock into Regolith: Earth's Critical Zone on Volcanic Ocean Islands

Anderson, Suzanne P.[1, 2]; Tucker, Gregory E.[3, 4]; Anderson, Robert S.[1, 4]; Langston, Abigail[3, 4]; Kelly, Patrick[1, 2]

1. INSTAAR, University of Colorado, Boulder, CO, USA
2. Dept. of Geography, University of Colorado, Boulder, CO, USA
3. CIRES, University of Colorado, Boulder, CO, USA
4. Dept. of Geological Sciences, University of Colorado, Boulder, CO, USA

Rock at Earth's surface is attacked by percolating aqueous solutions and physical stresses, an assault that transforms rock into regolith, and sets in motion processes that transport material to the ocean. The surface boundary layer of the crust, where surface water circulates, temperatures fluctuate, and organisms dwell, is the called the critical zone in recognition of its significance to life and the functioning of Earth's surface. Volcanic ocean islands provide interesting laboratories in which to explore the evolution of pristine rock, as volcanic edifices offer a rare known initial condition at a known time against which chemical, physical, and topographic evolution can be measured. Formation of regolith (weathered rock and mobile, disaggregated material including soil) begins the transformation from lava flow to a landscape. Denudation by processes ranging from chemical solution losses to mass wasting on scales from rainsplash to deep-seated landsliding contributes to the eventual submergence of the subaerial landmass. The 4 Myr Hawaiian chronosequence on flat, non-eroding surfaces, has shown how rock derived nutrients are lost over time, eventually limiting ecosystems to atmospherically derived and biologically-cycled nutrients. Chemical weathering of young volcanic rocks on oceanic islands and volcanic arcs accounts for 30% of silicate weathering globally, and hence exerts disproportionate control on the long-term carbon cycle. Less clear is how development of a mobile regolith on sloping surfaces impacts continued weathering and evolution of the system. One can reason that a layer of disaggregated regolith serves as water reservoir, increases reactive surface area, and provides substrate for biota, and these provide positive feed-backs on weathering and transport. But when does the thickness of the mobile layer limit further weathering? How does the architecture of the critical zone evolve over time? We use model simulations of vadose zone water movement, chemical alteration, fracture formation and stresses exerted by processes such as root or ice lens growth to explore how weathering and erosion processes produce different critical zone architectures. The Galapagos Islands offer dry, warm climates against which to exercise models. By comparing with a global array of volcanic ocean island sites, we could gain insight into the mechanisms, rates, and feedbacks involved in critical zone evolution.

http://czo.colorado.edu/

Bagnardi, Marco

Time series of volcanic deformation in the Galapagos: A perspective from InSAR, GPS, and seismic data

Baker, Scott[1]; Bagnardi, Marco[1]; Amelung, Falk[1]; Cote, Dustin[2]; Ebinger, Cinthya[2]; Geist, Dennis[3]

1. Univ Miami, Miami, FL, USA
2. University of Rochester, Rochester, NY, USA
3. University of Idaho, Moscow, ID, USA

The Galapagos Islands are home to some of the most active volcanoes in the world, but given their geographic location and difficult working conditions, the volcanoes have gone largely unmonitored until the last 19 years. Interferometric synthetic aperture radar (InSAR) provided surface displacement measurements across the island chain since 1992 and measurements covering six eruptions at three different volcanoes. A continuous GPS network established at Sierra Negra in 2003 provided daily three component surface displacements measurements at the volcano allowing precise measurements during the 2005 eruption and provided a comparison for the InSAR measurements. The temporary broadband seismic network established in 2009 around Sierra Negra and Cerro Azul provided unprecedented measurements of the seismicity at the volcanoes. Using InSAR from ERS-1, ERS-2, Radarsat-1, Envisat, and ALOS satellites from 1992 to 2011, we measured surface displacements at the active volcanoes in the Galapagos Islands and generated time series using the small baseline subset (SBAS) method. A time history of surface displacements was measured at Wolf, Darwin, Alcedo, Sierra Negra, Cerro Azul, and Fernandina volcanoes. Combined with the GPS and seismic data, the InSAR time series allowed us to correlate surface and subsurface activity at individual volcanoes. In addition to activity at individual volcanoes, interactions between neighboring volcanoes were also evident. A brief period of subsidence at Sierra Negra occurred during the 2008 eruption of Cerro Azul seen in both the InSAR and GPS time series. An interaction between Fernandina and Alcedo is also present in the InSAR time series, and the location of seismicity between the two volcanoes provides evidence for a subsurface linkage between them. These interactions are clearly evident in both the geodetic and seismic data, but the recorded seismicity also suggests links between Sierra Negra, Alcedo, and Fernandina further supporting an interconnected magmatic system within the island chain. By combining the InSAR, GPS, and seismic datasets, we obtain more details about the time-dependent relationship between what is being measured and the controlling processes beneath.

Bagnardi, Marco

Evidence of multiple magma reservoirs at Fernandina volcano

Bagnardi, Marco[1]; Amelung, Falk[1]

1. RSMAS - University of Miami, Miami, FL, USA

At Fernandina volcano only a fraction of the magma coming from the mantle is erupted; the remaining magma is stored in crustal reservoirs located at different depths. The increase of pressure generated by the injection of new magma in the shallow system inflates the volcanic edifice and can trigger eruptions; while the release of excess in pressure during eruptions or dike intrusions produces rapid deflation and can lead to instability of the edifice. Therefore, determining the presence of subsurface magma reservoirs, quantifying source parameters (e.g., geometry, depth, dimensions and pressure variations) is fundamental to the development of predictive models of volcano deformation and eruption. To investigate the surface displacement at Fernandina, associated with pressure changes in the magmatic system, we use Synthetic Aperture Radar (SAR) data acquired by the European Space Agency satellite ENVISAT in four different independent orbits between June 2003 and October 2010. The analysis shows temporal and spatial variations that suggest the presence of at least two distinct magma reservoirs at crustal depths. We perform a non-linear inversion of Interferometric SAR (InSAR) data and we infer the presence of a sill-like reservoir at ~1 km depth and of a deeper source at ~6 km depth. Both magmatic sources are located below the summit caldera and do not show important variations in their geometry and position through time. Connection between the two reservoirs is necessary to explain the dynamics of the deformation signal. Our results are consistent with previous geodetic and petrological studies and demonstrate the complexity of basaltic volcanoes.

Bagnardi, Marco

The April 2009 eruption of Fernandina volcano: onset and effects observed by Satellite Radar Interferometry

Bagnardi, Marco[1]; Amelung, Falk[1]

1. RSMAS - University of Miami, Miami, FL, USA

During the night between 10-11 April, 2009 a new eruption started at Fernandina volcano, the most active volcano in the Galapagos archipelago. A radial fissure about 200 meters long, opened on the southwestern flank and produced lava flows that reached the ocean and a plume that extended for more than 150 kilometers southwest of the volcano. Using Synthetic Aperture Radar (SAR) images acquired by the European Space Agency satellite ENVISAT we are able to study the onset and the effects of this eruption in terms of surface deformation. An image acquired on April 10, at 8am local time, does not show any signs of deformation except for the years-long caldera uplift. A second SAR image acquired on the same day, at 9pm and just a few hours before the opening of the first eruptive vent, shows distinct uplift (maximum displacement: ~0.35 m) of a circular area centered below the southwestern caldera rim. This pattern of deformation represents the surface displacement generated by the intrusion of a sheet-like body from a shallow magma reservoir towards the surface. The eruption ended on April 28, and the SAR interferograms produced using images acquired before, during (April 17) and after (May 5-15-16-22) the eruption, allow us to study its effects. Uplift of the eastern side of the eruptive fissure represents the surface displacement produced by the intrusion of the feeding dike. This pattern of deformation is very similar to the one generated by the January 1995 eruption. Subsidence of the caldera and of a broader elliptical area centered below the summit is produced by a rapid decrease in pressure in the magma storage system, caused by degassing and magma eruption at the surface.

Bergantz, George W.

Magma Systems in the Galapagos Islands: The Dynamics of and Evidence for the Transition Between Crystal Rich and Crystal Poor Conditions

Bergantz, George W.[1]

1. Earth Space Sciences, Univ. Washington, Seattle, WA, USA

Ocean island, mid-ocean ridge and arc magmatic systems differ significantly in their volatile contents, mass flux, thermal environment and origins of mantle melting. Yet they share a remarkable dynamic and “architectural” similarity in that they all display a temporal evolution where the dynamics and compositional evolution requires a progressive or repeated transition between crystal poor and crystal rich conditions. This interplay requires a magmatic history that is not monotonic in temperature, and produces compositions and intensive variables that are “buffered,” and reflect interaction, perhaps repeatedly, with crystal-rich magmatic domains (crystal mush) that may dominate the longer-lived domains of the magmatic basement. This physical separation of vertical magmatic systems into a subjacent crystal rich and overlying crystal poor domains can produce eruptions that are either compositionally uniform or continuously zoned. The compositional variability is controlled largely by the Peclet number for the system based on mass flux which dictates the ambient mush temperature, and the zoning is established and sustained primarily by melt extraction rate from the mush and chaotic low-Reynolds number convection associated with cooling, crystallization, degassing and/or from addition of new magma. While the most general physical principles of this process and the formation of the gradients are reasonably well understood, the Galapagos magmatic systems offer a unique opportunity to explore end-member dynamic processes. We will exemplify a multistage process that combines cooling history, composition, large-scale, but low-Reynolds number circulation as the primary degrees of freedom to produce a either a simple unmixing of the crystal cargo, or a more complex history.

Bianco, Todd A.

Geochemical Variations at Hotspots Caused by Variable Melting of Veined Mantle Plumes

Bianco, Todd A.[1]; Ito, Garrett[2]; van Hunen, Jeroen[3]; Ballmer, Maxim D.[2]; Mahoney, John J.[2]

1. Geological Sciences, Brown University, Providence, RI, USA
2. Geology and Geophysics, University of Hawaii at Manoa, Honolulu, HI, USA
3. Department of Earth Sciences, Durham University, Durham, United Kingdom

Three-dimensional geodynamic models of plume-lithosphere interaction explore the causes of spatial patterns of magmatic compositions at hotspots. The models couple mantle flow, heat transfer, and the melting of multiple components present in the mantle as small blobs or veins with different solidi and composition. At intraplate hotspots, predicted magma compositions evolve from having a strong signature from the deepest-melting component in the early stages of volcanism to a strong signature from the shallowest-melting component in the later stages. At ridge-centered hotspots, predicted compositions are more heavily influenced by the deepest-melting component at the center of the hotspot, with increasing contribution from the shallower-melting components with distance along the ridge. These predictions can explain some of the observations of variations in lava composition at locations such as Hawaii and Iceland if the deepest-melting component is associated with a source that has been relatively less depleted of incompatible elements on a long timescale. The predicted compositional trends arise by progressive melt extraction of the different components and the dynamics of plume-lithosphere interaction, as well as local variations in temperature, viscosity, and plate thickness. When melt from three or more components is sampled, the composition of the progressive melt extraction evolves along arrays in isotope space that trend toward mixed compositions of the components rather than the components themselves, in a process that is similar to pseudo-binary mixing. Using this prediction we show that binary mixing is not required to explain observed linear Pb isotope arrays at hotspots. In support of this concept, Monte Carlo simulations show that non-systematic, binary mixing is statistically unlikely to occur if the scale of the magma capture zone is significantly larger than the scale of isotopic heterogeneity. Our key finding that mantle flow and melting can lead to significant variations in magma compositions, independent of variability in the source, implies that the mantle source beneath many hotspots may be more uniform than previously thought. Thus if many hotspots are tapping deep mantle sources, the difference in composition from the ambient upper mantle may be correspondingly less.

Brandsdottir, Bryndis

Plume-Ridge Interactions in Iceland and Galapagos, Crustal Buildup and Volcanism

Brandsdottir, Bryndis[1]; Hooft, Emilie E.[2]; Menke, William H.[3]

1. Institute of Earth Sciences, Science Institute, University of Iceland, Reykjavik, Iceland
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Iceland is the subarial part of the Greenland-Iceland-Faeroe Ridge, a band of thickened basaltic crust, 25–30 km, stretching across the North Atlantic that represents the product of ridge-centered hotspot volcanism from the early Tertiary to present. The Galapagos Platform is also the product of hotspot volcanism, and while (unlike Iceland) the hotspot is not currently centered on the Galapagos Ridge, it was in that position during the recent (5-8 Ma) past. Several of the physical characteristic of the two regions are similar: Crustal thickness in Iceland, decreases from 35–40 km in central Iceland to about 10-15 km on the adjacent mid-ocean ridge segments. Crustal thickness beneath the Galapagos archipelago decreases from about 15 km beneath the archipelago to 6 km on the Nasca plate. Seismic velocity structure: In both regions, crustal seismic velocities are comparable to those in normal oceanic crust, except that the lower crust (Oceanic Layer 3), is disproportionately thick. The upper crust (Vp<6 km/s) is thicker in the Galapagos than in Iceland, possibly due to a greater role of intrusive volcanism, rift relocations or erosion in Iceland. Compensation: Crustal thickness, topographic elevation and gravity indicate that the crust is in isostatic equilibrium in Galapagos and Iceland. Style of volcanism: In both regions, volcanic systems are structurally and geochemically more complicated than along the mid-oceanic ridge system. Large, shallow crustal magma chambers beneath mature volcanoes are capable, when drained, of producing large calderas. Seismic imaging places them 2-3 km deep in the crust, mapped by local zones of intense shear wave attenuation and delayed P wave arrival times. In both regions, the plumbing systems that deliver melt from the asthenospheric mantle to shallow magma chambers are still poorly constrained. In the case of Iceland, rift-zone central volcanoes, which act as major controls on plate boundary segmentation, are commonly underlain by seismically-fast (high-density) domes of gabbroic cumulates which act as funnels for upwelling magma. In order to further our understanding of plume-ridge interactions, comparison of geophysical, geochemical and geodynamic data from existing hotspot-ridge systems is required.

Carey, Anne E.

Climate, dust, and soil biogeochemistry on volcanic islands

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The role of dust input to the landscape plays an important ecological role in many locations globally. In humid environments, volcanic rocks can be weathered very rapidly and soils developed from them can become depleted in phosphorous and base cations. Seminal work on the Hawaiian Islands over the past several decades has demonstrated that dust plays a significant role in providing nutrients for ecosystem development and maintenance in volcanic terrains (e.g., Crews et al., 1995; Vitousek and Farrington, 1997; Vitousek et al., 1997). In this presentation we review the bedrock geochemistry of some volcanic island chains (Galapagos, Azores, Canaries, South Shetlands) from different climatic regions and with different aeolian dust fluxes. We shall document fluvial chemical weathering fluxes, denudation rates, and soil geochemical profiles where they are available. We then speculate about the role of dust input into both soil and ecosystem development. We use all these data to estimate the elemental loss or gain rates and to assess rock transformation into soil through time and compare the information among these island chains and with the previously estimated values for the Hawaiian Islands.

Cashman, Katharine V.

The Hazards and Benefits of Volcanic Eruptions on Oceanic Islands

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The direct hazards posed by volcanic eruptions to oceanic islands – e.g., ash fall, pyroclastic flows, lava flows – are the same as in continental environments, and are similarly controlled by the magnitude, intensity, and duration of eruptive activity. However, both the associated hazards and the impact of those hazards may be quite different in oceanic island and continental settings. For example, fine ash generated by explosive volcanic eruptions is now widely recognized as an important hazard, particularly with regard to air traffic. The abundance of fine ash produced by an eruption depends on both magma composition and the extent of interaction with external water; magma-water interactions, in particular, can produce powerful explosions as well as abundant and extremely small ash particles. The type example of this phreatomagmatic activity is the 1963 eruption of Surtsey, Iceland, where the birth of a new oceanic island was observed. Eruptions from shallow submarine or emergent volcanoes also pose additional hazards in the form of locally generated tsunamis or, in extreme cases, destructive base surges. Even subaerial eruptions on oceanic islands have high likelihoods of magma-water interactions when rising magma encounters perched aquifers, or when volcanic flows traverse wet regions (to produce rootless cones) or reach the shoreline (to produce littoral cones). In the latter case, the explosivity of lava-ocean encounters depends on the rate of flow and the specific the geometry of the lava-water interaction. The impact of volcanic activity on island communities (human, plant and animal) is often magnified by both the small size and relative isolation of many oceanic islands, where even small eruptions can blanket an island with ash or cover much of its surface with volcanic flows. The devastating effects of island eruptions are illustrated by the ongoing activity at Soufriere Hills volcano, Montserrat, and, more dramatically, by the complete devastation of the island of Thera, Greece, by the Santorini eruption. Even lava flows, while rarely lethal, can repave extensive regions, thus substantially reducing habitable land areas for long periods of time, particularly in arid environments that are slow to revegetate. Small islands, or kipukas, stranded within lava flow fields may further isolate plant and animal communities and drive rapid evolutionary change. However, volcanic activity may also be beneficial to island environments. Most obviously, volcanic lava flows and debris flows routinely increase the land area of volcanic islands. In Hawaii, lava tubes provided both shelter and water for Polynesian inhabitants, and extensive perched aquifers supply water for extensive developments. More important, however, may be the “instant” soil produced by explosive eruptions. Recent cinder cone eruptions have shown that although thick scoria deposits are detrimental to vegetation, thin deposits (~ 3cm) may act as mulch, aiding water retention in arid environments. Additionally, the large surface area of fragmentation deposits, as compared with lava flows, will greatly accelerate weathering processes.

Coffin, Millard F.

Deep structural images of the Ontong Java Plateau deduced from an active source seismic experiment

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The Ontong Java Plateau (OJP) is one of the large igneous provinces (LIPs) located on the western rim of the Pacific Ocean and is colliding with the Solomon Island Arc. The OJP is a shallow oceanic plateau outlined primarily by the 4000-m isobath, and its area is one-third that of the contiguous United States. Shallow bathymetry suggests that OJP crust is thicker than that of normal oceanic crust. However, how the plateau formed is still under debate, with three primary models proposed: plume, bolide impact, and fast spreading ridge. Moreover, the OJP seems to have formed in a deep marine environment, which is not clearly explained. To understand the formation mechanism of the OJP, an active source seismic experiment was conducted over the central OJP by the Japan Agency for Marine-Earth Science and Technology (JAMSTEC) in February/March 2010. The active seismic source was a 7800 cu. in. tuned airgun array aiming to penetrate the OJP's entire crustal thickness down to the Moho. A 444-channel hydrophone streamer was towed to acquire multi-channel reflection seismic reflection (MCS) data. One hundred ocean bottom seismographs (OBS) were also deployed on the OJP's seafloor to acquire wide-angle reflection and refraction data. The new MCS data show clear sedimentary sequences in the shallow part of the OJP about 1 s thick in two-way travel time (TWT), and unnamed seamounts penetrate the sedimentary sequences suggesting magmatism following the main construction of the OJP. The MCS data also show a deep reflection event at about 11-12 s in TWT indicating a major acoustic impedance contrast such as the Moho. OBS data show a prominent refraction event with an apparent velocity of 7 km/s, which indicates a thick lower crust. No clear refraction events from the uppermost mantle are identified except at the northern edge of the OJP's main body. From these observations, we will discuss models for the formation of the OJP and LIPs.

Colman, Alice

Influence of Magma Supply on Galápagos Spreading Center Magmatic and Eruptive Processes

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A significant increase in the rate of magma supply to the crust with increasing proximity to the Galápagos hotspot along the Galápagos Spreading Center (GSC) makes this area ideal for studying the effects of variable magma supply on mid-ocean ridge (MOR) magmatic and eruptive processes. We have identified lava flow fields from individual eruptive episodes in two ~20-km-long study areas located at varying distances along the spreading axis from the region of maximum plume influence near 91°W: one at 95°W and the other 330 km away at 92°W. Over this interval the rate of magma supply increases by 40%, while the spreading rate remains nearly constant (52-56 mm/yr). Detailed geologic maps of each study site were prepared using observations of sediment thickness and lava morphology, sample mineralogy and chemical composition, and inferences from high-resolution bathymetry data. At the lower magma supply study area, eruptions typically produce irregularly-shaped, steep-sided clusters of pillow mounds with total eruptive volumes ranging from 0.03-1.3 km^3. Erupted lavas have relatively unfractionated compositions (6.2-9.1 wt. % MgO) and low degrees of enrichment in incompatible elements (0.04-0.09 K/Ti), and phenocryst contents are highly variable (0-20 % phenocrysts). These observations are consistent with magma residing intermittently in deep (>4 km) magma chambers, which feed relatively large-volume, low effusion-rate eruptions commonly focused to point sources. At the higher magma supply study area, lava morphologies characteristic of higher effusion rates (lobate and sheet flows) are much more common, although many eruptive edifices also include groups of pillow mounds aligned parallel to the spreading axis. Eruptive edifices here have lower relief, as do the individual mounds that make them up, and individual eruptive units are an order of magnitude smaller (0.001-0.2 km^3). There is a similar range in MgO content within individual eruptive units at both study areas (0.2-1.0 wt. % at low magma supply vs. 0.4-1.2 wt. % at high magma supply), but the variation among units within the high magma supply area is much greater (2.7-8.0 wt. % MgO) at high magma supply. In addition, the degree of enrichment in incompatible elements is both greater and more variable (0.13-0.34 K/Ti) at high magma supply. In contrast to the low magma supply study area, it appears that at high magma supply, magma resides in shallow (~1.5 km), frequently replenished, melt-rich magma chambers, from which relatively small volumes of lavas have been erupted more frequently and at higher eruption rates, primarily from eruptive fissures that range from 1.5 to 7.5 km in length. The differences in lava morphology and inferred eruption rates observed between the two areas with contrasting magma supply along the GSC are similar to those that have previously been generally related to variable spreading rates on the global MOR system. The detailed mapping of the GSC at the scale of individual volcanic eruptions will lead to a better understanding of the apparent inverse relationship between magma chamber depth and average eruption rate.

Contreras-Reyes, Eduardo

Magmatic processes beneath the Louisville and Juan Fernández hotspot tracks from wide angle seismic data

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We investigate the detailed 2D tomographic image of the crust and upper mantle structure of the Louisville and Juan Fernández (JF) seamounts that formed onto oceanic plate ~10 Ma and ~28 Ma, respectively. The Louisville volcanic edifice appears to be dominantly intrusive, with velocities faster than 6.5 km/s. In contrast, the tomographic image of JF volcanic edifice suggests a magmatic origin of the seamounts dominated by extrusive processes ($4.0 < Vp < 5.5$ km/s). In addition, the Louisville volcanic edifice overlies both high lower crustal (>7.2–7.6 km/s) and upper mantle (>8.3 km/s) velocities, suggesting that ultramafic rocks have been intruded as sills rather than underplated beneath the crust. In contrast, the JF edifice overlies typical lowermost crustal velocities of ~6.9 km/s and remarkable low upper mantle velocities of ~7.5 km/s, suggesting the presence of magmatic underplating below the oceanic Moho. Intracrustal magmatic intrusion may therefore be a feature of hotspot volcanism at young, hot, oceanic lithosphere, whereas, magmatic underplating below a pre-existing Moho may be more likely to occur where a hotspot interacts with oceanic lithosphere that is several tens of millions of years old.

d'Ozouville, Noémi

The Galapagos Islands as a Laboratory for Hydrological Processes

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Our study of the hydrogeology of the Galapagos Islands (GIIWS project) began in 2003 on the main inhabited islands: Santa Cruz, where the population relies on water from the brackish basal aquifer and San Cristobal, where the presence of permanent streams that were not explained, ensures freshwater resource to the population. Our knowledge now extends to the islands of Isabela, a younger island, and Floreana, historically known for its freshwater springs, in order to help gain a regional perspective. Field investigations involving hydrological instrumentation, climatological monitoring, geophysics, geomorphology and soil investigation have generated a unique vision of ongoing surface processes that are closely linked to the less visible subterranean processes. Our investigations show that topography, geology and climate are driving factors of hydrological processes in Galapagos. Also, between the four studied islands, ranging in age from more than 2 million years old to less than 10,000 years old, surface water availability increase and access to basal aquifer decrease with age. Two types of aquifers have been identified on the islands. The low-level basal aquifer outcrops in Santa Cruz and Isabela, and has been mapped using geophysics on Santa Cruz and San Cristobal. Due to the permeability of fractured shield series forming coastal aprons, intruding seawater mixes to discharging freshwater, and confer a high salt content to groundwater. In order to characterize the hydraulic properties of this volcanic aquifer, the propagation of the tidal signal into the basal aquifer has been investigated through water level monitoring in three open coastal fractures and the deep well on Santa Cruz. On the highlands, springs are the natural outlet of perched aquifers. These springs can be confined to small volcanic cones as is the case in Floreana, or can feed a network of permanent rivers that reaches the sea, like in San Cristobal, a unique feature in the whole archipelago. Helicopter-borne geophysics allowed the visualisation of 3-dimensional internal low-resistivity layers on the southern windward mountainsides of Santa Cruz and San Cristobal, which relate to known hydrological features. However, validation of the resistivity model, notably for Santa Cruz where no springs are known except the one associated with the volcanic cone of Santa Rosa, requires drilling of exploration boreholes. Currently focus is being placed on quantifying the water balance, and understanding surface processes such as interception of fog by the vegetation and infiltration through the soil zone in both the garúa and the invierno seasons. Understanding hydrological processes is crucial for water management but also to contribute to ecosystem restoration investigations and other branches of earth sciences.

Dasgupta, Rajdeep

Constraining pyroxenite component in OIB source through melt-rock reaction experiments in pyroxenite-peridotite system and partitioning of first-row transition elements during mantle melting

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Constraining the presence, nature, and proportion of compositional heterogeneities in the mantle source regions of intra-plate, oceanic basalts is of fundamental importance for understanding a wide range of topics including differentiation, dynamics, and geophysical properties of the Earth's mantle. While the ubiquitous presence of mantle heterogeneities is apparent from the variability of long-lived radiogenic isotopes and rare earth trace elements in OIBs, the lithologic nature of source heterogeneities is unclear for most ocean islands. The problem is worse for on- or near-ridge ocean islands such as Galápagos, Azores, Iceland, and Jan Mayen owing to greater contribution of shallow decompression melting of peridotite. Here we test whether MORB-like crustal pyroxenite can serve as the primary mantle heterogeneity in all non-EM type alkalic to alkalic-tholeiitic transitional ocean island basalts and whether we can identify its presence even for islands on young lithosphere. We first summarize our recent experiments on melt-rock reaction in the system MORB-like pyroxenite partial melts and fertile peridotite, which constrains the composition of the reacted melt as a function of eclogite melt: peridotite ratio at 2.5-3.0 GPa and 1375-1440 °C. These experiments with variable melt: rock ratio demonstrate that andesite to basaltic andesite partial melts of volatile-free MORB-pyroxenite can evolve to alkalic basalts with high Mg# (≥70), CaO (10-11 wt.%), TiO_2 (2-4 wt.%), MgO (15-17 wt.%), Na_2O (1.9-2.7 wt.%) and moderate to low SiO_2 (45-47 wt.%) similar to many primary alkalic OIBs although Al_2O_3 and FeO* of reacted melts remain respectively, high and low compared to plausible primary OIBs. There is a continuous transition observed from alkalic to high magnesian tholeiitic basalts with increasing melt: rock ratio and up to 30-40% pyroxenite-derived melt mass can react with peridotite and still produce a high-MgO reacted melt similar to plausible primary OIBs. We further performed partitioning experiments for first-row transition elements (FRTEs) Zn, Mn, Ni, Co, Fe between mantle minerals and basaltic partial melts at 1.5-2.0 GPa and 1300-1500 °C. We show that owing to mildly incompatible to moderately compatible behavior of these trace elements their concentrations are sensitive to source lithology and furthermore, olivine and opx dominated sources do not appreciably fractionate Mn, Fe, and Zn during melting whereas clinopyroxene and garnet dominated sources (e.g., MORB-like crust) fractionate Zn/Fe and Mn/Fe. Thus the presence of cpx and garnet dominated lithologies can potentially explain low Mn/Fe, Co/Fe, Ni/Co, Mn/Zn, and high Zn/Fe of many OIBs. In particular, low Co/Fe and Ni/Co ratio of basalts from Galápagos, Iceland, Azores, and Jan Mayen and high Zn/Fe of Jan Mayen possibly require the presence of pyroxenite in the mantle source of these islands. Our calculations suggest that up to 30-50% MORB-pyroxenite partial melt could mix with peridotite to explain the Zn-Mn-Fe-Co-Ni systematics of basalts from ocean islands on young lithospheres.

Dietrich, William

The Coevolution of Geomorphology and Biology of Ocean Islands

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Volcanic islands produced by mantle plumes are transient terrestrial surfaces in which landscape evolution and biotic colonization and speciation play out over a finite time. There is a clear beginning and an inevitable end to these coupled systems that makes them distinct from continental landmasses. Islands are rarely alone and the characteristic time progression of islands along some plate trajectory creates a stepping stone for life, with many examples of the "progression rule", in which speciation occurs as biota moves from older to younger islands. If there is a sufficient break in island formation, however, the chain of islands may all subside and colonization by terrestrial biota must begin again with subsequent volcanoes. This suggests linkages between speciation, plume dynamics and plate motion. Rates of island construction are impressive, but so too can be erosion rates where sufficient rain is captured. The calving of giant landslides contributes to island demise and affects the overall stress balance of the volcanic edifice. Terrestrial biota colonize islands as they emerge, and species numbers have been found to increase as a power law of island size. Island biogeography theory proposes that this relationship results from an area-dependent extinction rate offsetting immigration rates. The geomorphic evolution of volcanic islands, typically creating a network of canyons that branch into island calderas, must create a diversity of niches that invites speciation. Do biotic processes in turn significantly alter geomorphic processes and the progressive evolution of these island landscapes? Do biota accelerate erosion processes or slow them? Erosion requires breaking down bedrock, typically composed of stacked lava flows, into transportable pieces. Clearly biota, from microbes and organic acids to the penetrating roots of vegetation, contribute to rock breakage and decay. Gently inclined residual lava flow slopes can develop deep weathering profiles (and accrete dust from distant continental sources). Would this happen in the absence of biota? Steep canyon walls of dissected volcanoes shed periodic shallow landslides that may lead to distinct valley networks. Are these shallow landslides a product of vegetation-driven rock breakdown? Studies of volcanic islands have revealed key processes in biotic evolution and ecosystem development. How biotic process might influence geomorphic evolution of volcanic islands is much less studied. With certainty, however, the arrival of humans on islands leads to rapid extinction of native species.

Duncan, Robert A.

How Did the Galápagos Hotspot Begin?

Duncan, Robert A.[1]

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Hotspot volcanism is characterized by a geometric distribution and an age progression — both consistent with plate motion. Geochemical tracers also vary in simple ways that allow eruptive centers throughout the province to be related to the most recent site of activity. Using these constraints, several prominent hotspots have been tracked back to their origins as large igneous provinces (e.g., Reunion-Deccan; Iceland-North Atlantic; Tristan-Etendeka/Parana). This has led to important geodynamic models for mantle plume evolution, surface expression of volcanic products, and environmental impacts of massive eruptions. Do all "primary" [Courtillot et al., 2003] hotspots follow this life history? The Galápagos archipelago lies at the western end of an acknowledged (but, interestingly, bifurcated) hotspot trend of age-progressive volcanic centers and ridges that is abruptly terminated at the Middle America trench. This distribution of volcanic activity is consistent with known relative plate motion over a hotspot located under Isla Fernandina, over the last ~20 Ma. The earlier record of volcanism generated over the Galápagos hotspot, however, has been removed or obscured by plate collision and subduction. Geochemical and geochronological data for volcanic rocks in Central America can be used to reconstruct this earlier history (20-94 Ma [Sinton et al., 1998; Hauff et al., 2000]), and to connect the Galápagos hotspot to the Caribbean plateau. This ~10 x 10^6 km^3 submarine plateau has many of the hallmarks of large igneous province volcanism. However, several geodynamic origins for this vast province have been proposed, and its connection with the Galápagos hotspot is controversial. This presentation reviews the current state of information about the age and duration of Caribbean plateau volcanic activity, and geochemical indicators that distinguish a Galápagos connection from other origins. Such a connection confirms the Pacific origin of the plateau and subsequent eastward transport into its present location between the North and South American plates, bounded by E-W transform boundaries. Melting conditions over the Galápagos plume have changed substantially between the plateau construction phase and recent island volcanic activity [Herzberg and Gazel, 2009], in concert with plume cooling and plume-lithosphere interactions. However, these end-members and intervening centers appear to be related to a common mantle plume that has evolved since the first volcanism at 94 Ma.

Eason, Deborah E.

Insights into melt and chemical transport rates in the mantle from the volcanic response to glacial unloading in Iceland

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Short-lived melting perturbations due to glacial unloading in Iceland present a unique opportunity to examine time-dependent melt transport processes in the underlying mantle. A dramatic increase in volcanic productivity and coinciding change in magma composition immediately following the last major ice retreat (~15-10 ka) in Iceland have been attributed to enhanced decompression melting due to glacial unloading. The temporal variations in magma volume and composition that result from this process, including a markedly prolonged change in composition relative to eruptive volume, depend partly on the transport rates of melt from source to surface. We present new major and trace element data for 19 late-glacial eruptions in the Western Volcanic Zone of Iceland and use a combination of lava surface morphology, heights of transition from subaqueous to subaerial eruption environments, and ^3He exposure age dating to construct an eruption chronology for these subglacial units. These data supplement existing fini- and post-glacial data to form a detailed eruptive history for this hot-spot affected ridge segment since ~15 ka. They show a peak in productivity in the late-glacial and fini-glacial period, with decreased levels of highly incompatible to moderately incompatible element ratios as well as elevated SiO_2 and CaO concentrations, consistent with enhanced melting at shallow levels in the upper mantle as predicted by models of glacial unloading. Using conservation equations describing the generation and porous transport of melt in a viscous matrix, we model melt migration in the mantle during and after ice sheet removal, as well as trace element transport through the system for both equilibrium and disequilibrium melt transport. Notably, the predicted geochemical time series at the surface is especially sensitive to the mode of chemical transport, with trace element compositions modeled using disequilibrium transport exhibiting a greater dependency on melt ascent rate than for equilibrium melt transport. The results of this study emphasize the potential importance of the nature and rate of melt migration in controlling compositional variability at spreading centers and ocean islands.

Ebinger, Cynthia J.

Magmatism and faulting on Isabela Island, Galapagos interpreted from seismicity and InSAR patterns

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Sierra Negra is the most voluminous volcano in the rapidly deforming hotspot volcano system of the western Galápagos Islands. Space-based geodetic studies show rapid, but transient inflation of the caldera, yet the subsurface structure and physical properties of the volcanic constructs and magma reservoirs are weakly constrained. In 2009, we installed 16 broadband seismometers around Sierra Negra and Cerro Azul volcanoes, and within the 10-km-wide Sierra Negra caldera. Volcano-tectonic seismicity levels between 7/09 – 10/10 are high level (2-3 earthquakes/day). Over 1700 earthquakes ($1.5 < ML < 3$) have been located, with the majority concentrated along the Sierra Negra caldera fault system and at the 2005 eruption site. Seismicity levels are higher on the southern, drip forest side of Sierra Negra. Shallow seismicity in this area may be related to groundwater hydrology, or to detection thresholds. The hypocentral locations beneath the Sierra Negra caldera span the depth range of 0 to ~8 km subsurface beneath the 2005 eruption site, whereas events beneath the central and western caldera are shallower. Reverse fault focal mechanisms with nodal planes parallel to the prominent intra-caldera ridge system confirm earlier interpretations of InSAR and structural data. The Azufre hydrothermal system shows low levels of seismicity than the eastern section of the caldera. Linear, intense swarms of earthquakes that occurred on the north, east, and southwest flanks of Sierra Negra are interpreted as small volume, radial dike intrusions. Additional evidence for increased pressure and/or magma intrusion at shallow levels beneath Sierra Negra comes from changes in the recordings of tremor at the central caldera station. Intermittent tremor (<1 Hz) is observed at the caldera station from 2009 intensifies beginning in July 2010. Narrow zones of shallow seismicity (<2 km subsurface) mark E-W striking chains of cones on the east and west flanks of Sierra Negra, implying aqueous or magmatic fluid movement along fissure systems beneath the chains. Steep reverse and normal faults are illuminated on the SE flank by a linear swarm striking tangential to the caldera rim, dipping toward the summit. From the end of 2009, seismicity rates increase to 1-2 earthquakes/day from the SW flank of Alcedo, just north of our array, with earthquake magnitudes varying between ML 2-3. Persistent swarms offshore between Sierra Negra and Fernandina correlate with the uplift of Fernandina's SE flank seen in InSAR. Cerro Azul has remained aseismic during this period, after an eruption in 2008. The local seismicity dataset provides new constraints on the kinematics of the sinuous ridge, the state-of-stress around the volcano flanks, the role of aqueous and magmatic fluids in volcano deformation. Our work establishes a baseline for seismic hazard evaluation on Isabela Island, and hints at stress interactions between the closely-spaced shield volcano systems. Work-in-progress focuses on imaging crustal magma reservoirs with travel-time and ambient noise tomography, and receiver function analyses.

Farnetani, Cinzia G.

Origin of hotspot lavas geochemical zoning: a geodynamics perspective

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Spatial-temporal geochemical variations of hotspot lavas are well documented; however the debate continues whether their origin is sublithospheric (e.g., partial melting and melt migration processes), or if they are due to compositional heterogeneities in the lowermost mantle. Our three-dimensional numerical simulations explore the relation between a heterogeneous core-mantle boundary zone, a likely source region of plumes, and the resulting conduit structure. In a first conceptual model we consider a source region with large-scale (few thousand kilometers) geochemical variations in the latitudinal direction. This model, albeit simple, is of interest if the fraction of isotopically enriched material progressively increases from north to south, as suggested by the extent of the Dupal anomaly beneath the Pacific. We calculate the plume conduit structure and predict that two parallel chains of volcanoes (e.g., Loa and Kea for Hawaii) should be geochemically distinct. Our results support the bilateral plume structure revealed by lead isotopes, and indicate that such a structure can result from large-scale geochemical gradients at depth. In a second conceptual model we consider a source region with a vertical gradient in the helium distribution, so that the highest 3He/4He is located in the deepest part of the boundary layer. This maps into a conduit with 3He/4He ratios progressively decreasing from the center to the periphery. For an anhydrous mantle, lavas with the highest 3He/4He will thus occur during shield-stage magmatism, when the volcano samples the plume center. However, high 3He/4He volcanoes, such as Loihi in Hawaii and Fernandina in Galapagos, are situated at the leading edge of the islands, not at the center. To explain this intriguing observation we model the ascent of carbonatite melts formed at ~450 km depth in the hot plume. Small fractions of fluid can sequester most of the helium and ascend subvertically at high separation velocities, whereas the residual solid matrix upwells in the conduit tilted by plate-driven mantle flow. In such a case, the highest 3He/4He ratios are displaced upstream with respect to the center, and we predict high 3He/4He for pre-shield lavas, followed by declining ratios during the shield and post-shield stages.

Gallego, Alejandro

Analysis of surface wave azimuthal anisotropy with geodynamic models and application to the Iceland hotspot

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In this study we investigated the 3D variations in lattice preferred orientation (LPO) of olivine and enstatite in the mantle on the azimuthal anisotropy retrieved from surface waves. Following the approach of Smith and Dahlen (1975), we calculated azimuthal anisotropy from the linear combination of olivine elastic properties and the surface waves eigenfunctions. How surface waves with different periods respond to variations in LPO with depth is revealed in models of two anisotropic layers in which LPO is uniform in each layer but differs in direction between the two layers. The calculations show that the fast wave propagation direction is most influenced by the top layer when the layer is very thick compared to the bottom layer and most influence by the bottom layer when the top layer is relatively thin. The critical thickness at which this transition occurs tends to increases nonlinearly with wave period (10-100 s). We also find that this critical thickness is extremely sensitive to the direction of LPO in each of the two layer. One result is that if we found that for a range of layer thicknesses and wave periods, a case in which the vertically aligned olivine a-axes in the top layer and a horizontal a-axis in the bottom can produce the same surface wave anisotropy as a case in which the a-axis is horizontal in both layers (but in different directions). This result could be of substantial importance to interpreting anisotropy in regions were upwelling of mantle is present such as oceanic ridges, and mantle plumes. We further apply our methods to examine the radial anisotropy across the Reykjanes Ridge from inversions of surface wave data collected on Iceland (Delorey et al. 2007). Using 3D geodynamic models of plume-ridge interaction we reinterpret these inversions by considering azimuthal anisotropy, whereas Delorey et al. assumed the mantle was azimuthally isotropic.

Garman, Katrina A.

Investigating Plume-ridge Interaction and its Tectonic Implications: Insights from the Distal Ends of the Galápagos Spreading Center at 86°W and 97.5°W

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Geochemical, petrologic, and morphologic relationships at the Galápagos Spreading Center (GSC) can be used to deduce complex tectonic and magmatic processes that dominate sites of plume-ridge interaction. We analyzed rock cores and dredge samples, in addition to multibeam bathymetric data, Alvin observations and towed camera images to characterize two segments of the GSC: 86° - 89.5°W and 97.5°-98°W. These regions mark the distal ends of the GSC, on either side of the Galápagos hotspot, and provide an opportunity to determine the spatial extent of hotspot influence on ridge processes. Detailed analysis of the bathymetry data from these areas reveals the complexity of ridge structures. In regions farthest from the hotspot (near 86°W and 98°W), the ridge axis is characterized by ~5 km-wide rift valley floored by lineaments of volcanic cone structures oriented roughly parallel to the trend of the axis. West of 86°W, with increasing proximity to the plume locus, the morphology of the GSC becomes more like that of a fast-spreading ridge with shallower axial depth, domal cross-section, an overlapping spreading center (OSC) at 87°15'W, and several axial discontinuities. Observations made during Alvin dives, in conjunction with images collected by the Argo II camera system, provide information on both lava morphology and relative ages of flow units which help constrain flow rates, emplacement chronology and overall eruption dynamics. Both regions appear to be dominated by pillow lavas, which suggests that low effusion rates characterize these settings; however, occasional lobate flows were identified near the summits of small cones and rare sheet flows were observed along narrow rifts within the axial valley. K/Ti*100 values of western GSC samples fall between 5.8 and7.8, whereas eastern lavas exhibit greater variation, with K/Ti*100 ranging from 3.35-12.12; however, lavas at both of these locations lack incompatible element enrichments documented in lavas nearest the hotspot (91°W). Lavas from 97.5°are more mafic (7.89-9.22 wt. % MgO) than eastern samples (3.65-7.95 wt. % MgO), and basalts from both regions follow fractionation trends that lie well within the scatter of existing data for the GSC.

Geist, Dennis

A Petrologic Model of the Galapagos Plume

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Conventional models of plume-ridge action call on plume material flowing along the base of the lithosphere toward the ridge. This model is inconsistent with a number of seismic and geochemical observations in the archipelago: 1. Although the GSC is contaminated with plume Sr, Nd, and Pb, there is no plume He in GSC lavas. 2. Several of the northern Galapagos volcanoes have less of a plume isotopic signal than any GSC lavas from within 400 km of the Galapagos hotspot (see Harpp abstracts). 3. GSC magmas contain water from the Galapagos plume; there are no data bearing on whether the plume is richer in CO2 than the GSC or whether plume CO2 contaminates the GSC. 4. Combined surface and S-wave tomography reveals 4 velocity zones in the Galapagos plume: a 1 to 2% slow zone extending from 400 to 100 km, a normal velocity zone from 100 to 80 km, a zone 2% slow zone from 80 to 15 km, and the crust. The deep slow zone is unlikely to be due to hydrogen in olivine or temperature, owing to the magnitude of the velocity anomaly. Instead, we propose that it is due to a carbonatite melt that is produced at depths >400 km. A reasonable estimate of the carbon concentration of the Galapagos mantle is 500 ppm (as CO2), which could yield a ~0.1% carbonatite melt. This melt is likely to extract the noble gases from the rock and transport it vertically to Fernandina's magmatic system. The zone with normal seismic velocity at 100 to 80 km may represent the intersection of the plume with the water-bearing solidus, as the removal of water from olivine is likely to result in an increased seismic velocity. For example, 150 ppm H2O would depress the anhydrous solidus by about 55 km (Hirschmann, 2006). The shallower slow zone is likely caused by more extensive partial melting of the silicate phases in the garnet facies, producing a basaltic melt. Fernadina's high 3He/4He magmas result from mixing of the carbonatite and silicate melts above the plume axis, and trace element models are consistent with this hypothesis. We propose that plume material is carried to the GSC by deep return flow of the asthenosphere toward the GSC (>100 km depth), not along the base of the lithosphere. Flow at this depth will incorporate plume material that is depleted in He and carbon, accounting for the lack of these signals in GSC lavas. Also, the shallow asthenosphere is likely to be flowing with the plate, away from the GSC. Magmas from the northern Galapagos then are created by melting of mantle that has already had melt extracted at the GSC, accounting for their more depleted compositions.

Geist, Dennis

An Evolutionary Model of Galapagos Magma Chambers

Geist, Dennis[1]

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Each of the 7 shield volcanoes of the western Galapagos has a large caldera, direct evidence that a shallow magma chamber exists beneath the volcanoes' summits. Integrative geophysical and petrologic studies have revealed both common and evolutionary aspects of the magmatic plumbing systems. The volcanoes are of 3 petrologic types: 1. Monotonic volcanoes (Sierra Negra, Fernandina, and Wolf) erupt strongly evolved tholeiites. Lavas erupted over thousands of years have exceedingly small differences in composition and eruptive temperature (typically < ±10°). The 3 monotonic volcanoes are very active. 2. Dying volcanoes (Darwin and Alcedo) erupt infrequently and have produced evolved magmas. 3. Diverse volcanoes (Cerro Azul and Ecuador) erupt lavas over a wide range of temperatures and include more primitive, olivine-rich rocks. Deformation measurements indicate that the tops of the magma chambers of the monotonic volcanoes are flat-topped and reside <2 km below the caldera floor. Space for magma is made by both elastic and inelastic uplift of the caldera floor. The active magma body at Cerro Azul, a petrologically diverse volcano, is several km deeper, and there is no evidence of an active shallow body at Volcan Ecuador. Subaerial lavas of the monotonic group are plagioclase-phyric, and olivine is sparse to nonexistent. Submarine lavas include picrites and ankaramites, both with plagioclase phenocrysts. Phenocryst compositions and zoning profiles are interpreted as indicating that virtually none of them crystallized from the matrix that encloses them. Time-series sampling at the 1998 eruption of Cerro Azul and the 1995 and 2005 eruptions of Fernandina indicates that an olivine-rich mush was progressively eroded over the course of the eruption. Sampling during the 2005 eruption of Sierra Negra suggests in-situ crystallization in the shallow magma body. Significant trace element heterogeneity in lavas erupted over the course of a few centuries indicates that there is not a large, homogeneous, largely liquid magma reservoir at the monotonous volcanoes. Estimates made on the basis of trace element compositions are that the liquid reservoir is < 5 km3. These observations and interpretations can be reconciled with an evolutionary, multi-tiered magmatic plumbing system. During the juvenile diverse phase at the leading edge of the hotspot (Cerro Azul and Ecuador volcanoes), magmas are only partly buffered thermally and chemically. They evolve by cooling and crystallization of olivine, pyroxene, and plagioclase, but to different extents and at different depths. The crystals form a growing mush pile, which could be several km thick. Once a volcano becomes mature, as are Fernandina, Wolf, and Sierra Negra volcanoes, all magmas transit through the mush pile before residing in a shallow subcaldera sill, which buffers all magmas thermally and chemically and creates an exceedingly monotonous suite. The mush pile continues to grow by accumulation of buoyant plagioclase at the roof of the system and olivine gabbro mush at the base, and magmas can erode the mush as they are transported from the central axis to the eruptive vent. In the dying phase, which occurs when the volcano is carried away from the hotspot (Darwin and Alcedo volcanoes), the mush begins to solidify and large volumes of silicic magma are generated.

Gibson, Sally A.

Constraints on the transition from active plume upwelling to lateral mantle flow beneath Galápagos: Geochemical evidence from Isla Santiago

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Widespread recent volcanism in the Galápagos archipelago reflects lateral transfer of hot, buoyant mantle from the zone of active plume upwelling towards the Galapagos Spreading Centre (GSC) and east, in the direction of plate motion. Here we examine how the style of mantle flow is reflected in the composition of erupted magmas and focus on Isla Santiago, which is located at the margin between the zones of active plume upwelling and lateral flow. Incompatible-trace-element and isotopic ratios of Santiago basalts are amongst the most diverse of those recently erupted on Galápagos islands. Santiago lava compositions vary gradationally over a distance of ~35km from low-K tholeiites in the northeast to mildly-alkali basalts in the southwest. Isotopic and trace-element ratios insensitive to partial melting processes, such as La/Nb and 143Nd/144Nd, suggest that contribution of the enriched central Galápagos plume component progressively decreases from southwest to northeast across Santiago. Rare-earth-element ratios controlled by depths and degrees of partial melting, such as Sm/Yb and La/Sm, also decrease from southwest to northeast and indicate that the amount of residual garnet (and depth of melting) in the underlying convecting mantle decreases whilst the degree of melting/and or contribution of more depleted peridotite increases from southwest to northeast. Geographical variations in incompatible-trace-element and isotopic ratios correlate with a marked decrease in lithospheric thickness (from ~55 to 45 km) beneath Isla Santiago (Villagomez et al. 2007; Gibson & Geist, 2010). The amount of adiabatic upwelling of the Galápagos plume exerts a strong control on the geochemistry of Santiago basalts but variations in physical processes within the plume itself may impart further influences. There is no evidence of a strong lateral change in temperature of the upper part of the Galápagos plume (Villagomez et al., 2007) but the upwelling rate likely decreases away from the plume axis. Elevated rates of vertical flow and thicker lithosphere beneath southwest Santiago, which is closer to the plume axis, would cause melting of greater amounts of more-enriched mantle at greater depths than beneath the northeast of the island: this is reflected in the larger small-fraction melt tails that are required in numerical models to account for elevated concentrations of strongly-incompatible trace elements. We further suggest that plume material, previously depleted of its most volatile components at great depth (e.g. He, H2O, CO2), is primarily undergoing subsolidus lateral flow (Kokfelt et al., 2005) beneath northeast Santiago as it is transported to the GSC. Upwelling of this mantle to relatively shallow depths enables generation of low-K MORB like melts that contain only a very small contribution of small-fraction volatile-rich melts. At the adjacent GSC, active upwelling together with plate-driven flow cause increased flux of mantle at the base of the melting column and generation of MORB with more enriched-isotopic and incompatible trace element compositions than those erupted in northeast Santiago.

Gonnermann, Helge M.

Modeling the dynamics of magma flow from mantle to surface at Mauna Loa and Kilauea, Hawai'i

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In 2002 Mauna Loa Volcano, Hawai'i, began a period of inflation that lasted for nearly a decade. Almost simultaneously inflation and heightened activity occurred at neighboring Kilauea Volcano. This raises the question if and how both volcanoes are dynamically linked. We present an idealized model for asthenospheric and crustal magma flow that is coupled to kinematic models of volcano deformation. The model is constrainted by continuous global position system (GPS) measurements of deformation at both volcanoes. Model results indicate that summit deformation throughout the past decade at both Kilauea and at Mauna Loa can be explained by coupling of crustal magma flow and storage to a common permeable asthenospheric melt zone located beneath both volcanoes. Each volcano's shallow crustal magma system is connected to the asthenospheric melt zone by a lithospheric magma plumbing system through which changes in magma pressure can be transmitted. Pore pressure diffusion within the porous zone produces a dynamical linkage between both volcanoes. Consequently, increased activity at one volcano may or may not be correlated with activity at its neighbor, depending on the interplay between deep and shallow magmatic processes. A characteristic pore pressure diffusion time between both volcanoes of approximately 1/2 year explains the time-delayed onset of inflation at Mauna Loa relative to Kilauea during 2002. Consistent with geochemical observations, magma flow paths within the asthenospheric melt zone capture compositionally distinct magma from different parts of the asthenospheric melt source over long periods of time. The time for melt flow within the porous layer between both volcanoes is about three orders of magnitude slower than pore pressure diffusion, so that significant redistribution of melt by porous flow requires time scales of 100s to 1,000s of years. Therefore, decadal changes in surface activity are unlikely to affect long-term trends in magma geochemistry.

González, Andrés

A hydro-ecological cross-section of Santa Cruz Island, Galapagos Archipelago

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The unique ecosystems of the Galapagos Islands, renown for their endemism, have evolved in a context of scarce freshwater resources. The volcanic nature of the islands and the atypical "dry" climate (compared to the tropics), have led to little weathering and formation of surface water features. Yet, water is abundant in the highlands during the cool garúa season (June to December), when an inversion phenomenon in the atmosphere forms a dense fog layer from ca. 400 m.a.s.l. to the summit. In these conditions, evaporation and transpiration are reduced and cloud water interception represents an additional input of water. This, combined with the permeable nature of rocks in the highlands potentially leads to high groundwater recharge rates. From January to May the hot invierno season occurs and is characterized by high inter-annual variability of intense precipitations over the island. These seasonal phenomena are understood from a 40-year climatic record, but actual groundwater recharge rates had never been investigated. In the frame of the Galápagos Islands Integrated Water Studies project, we conducted field investigations at several elevations to better quantify the contrasts in hydrological processes along a N-S cross-section on the windward slope of Santa Cruz Island. Two experimental 6x6 m plots have been selected. In addition to usual climatic variables (rainfall, air temperature and humidity, wind speed, solar radiation), we monitored throughfall and stemflow on both sites during both seasons. The first site of investigation, covered by introduced mixed forest of average canopy height of 4-7 m, is located at mid-elevation (ca. 400 m a.s.l). During the garúa season, this site is most of the time at the lower fringe of the fog layer, or below it. At the second site (ca. 650 m a.s.l.), fog occurrence is semi-permanent in the garúa season, and vegetation is

composed by moderately large homogeneous evergreen shrubs. During the invierno season, rainfall is mostly orographic, and individual rainfall events can be monitored. Comparing these two sites with historical climatic data at lower elevation, we finally discuss the influence of seasonal variation and contrasting hydro-ecological conditions over groundwater recharge on Santa Cruz Island.

Grant, Gordon E.

A framework for understanding landscape development of volcanic ocean islands

Grant, Gordon E.[1]

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Archipelagos of volcanic ocean islands, particularly those created by migrating hot spots, represent an unparalleled laboratory for landscape evolution. Where migration rates have resulted in a chain of islands of different and interpretable ages, space can be confidently substituted for time, providing a superb opportunity to examine chronosequences of landscape development. Key landscape properties, including soil development, degree of dissection, drainage network integration and density, and topographic relief can now be systematically arrayed and examined as a function of time. Climatic controls can be explored utilizing both within- and cross-site gradients of wetness and aridity. Volcanic ocean islands are therefore in theory some of the richest and most accessible places on earth to test models and theories of landscape evolution over timescales of millennia to millions of years. Examples of such landscape chronosequences can be observed from volcanic island chains such as the Galapagos, Hawaii, and the Easter and Pitcurin Islands. With the exception of Hawaii, research on landscape development in these islands is rudimentary. Confounding simple interpretations of space for time, however, are other factors that control rates and processes of landscape development. A useful framework for landscape development in volcanic ocean islands must therefore recognize the importance of endogenous features such as differences in styles and products of volcanic eruptions and how these influence subsequent patterns of weathering and drainage development, as well as exogenous controls, such as large-scale sector collapse landsliding, which can instantaneously change local base level and rapidly initiate incision, or glaciation, which can dramatically accelerate erosion rates. Here I develop a hierarchy of controls on landscape development of volcanic islands, and drawing from the literature, present preliminary findings on rates of drainage network development across a set of climatic gradient and exogenous controls.

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Harpp, Karen S.

Plume-Ridge Interaction in the Galápagos I: Lithospheric Control on Volcanic Lineament Generation in the Northern Galápagos Province

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The area between the Galápagos Archipelago and the Galápagos Spreading Center (GSC), the Northern Galápagos Province (NGP), is one of the ideal places in the world to study plume-ridge interaction. Here, the Galápagos hotspot is located slightly off-axis but still has a profound influence on the ridge. In 2010, we carried out a survey across the NGP. The Nazca Plate is densely populated by a wide range of seamount types, from small, flat-topped cones to elongate, polygenetic structures. Most of the Nazca Plate seamounts are arranged in three NW-trending lineaments that intersect the GSC at 20-40 km intervals. Along each lineament, seamounts become larger and increasingly elongate with distance from the GSC. Lineament lavas exhibit variable contributions from the Galápagos plume source in terms of incompatible trace element and radiogenic isotope ratios, yet have $^{3}He/^{4}He$ with primarily MORB-like signatures (~7-8 Ra for most lavas). The only consistent relationship between along-strike positions of the seamounts and their geochemistry is that Sm/Yb increases southward. These observations lead to two important interpretations: a) lithospheric thickness, which increases with distance from the GSC, is likely the dominant control on depth of melt generation at the seamounts; and b) the volcanoes were constructed close to their current locations and not as near-ridge seamounts. Modeling of major element contents from NGP seamounts using MELTS suggests that magmas from most of the study area evolved primarily by olivine and plagioclase crystallization, with little contribution from CPX; crystallization beneath these volcanoes must therefore be limited to pressures <1 kb. Moreover, elevated Al_2O_3 concentrations in NGP lavas lead to plagioclase crystallization at higher temperature than usual and the eruption of plagioclase-ultraphyric lavas, suggesting that high Al_2O_3 is not the result of high-pressure crystallization regionally, but is an attribute of the parental melts and potentially low extents of partial melting. The dominantly shallow crystallization depths across the NGP contrast with the deep crustal crystallization that characterizes magmas from the Galápagos Platform, possibly a reflection of the relatively thin lithosphere immediately south of the GSC. These observations support the model in which plume material experiences initial melting near its focus in the western Galápagos (consistent with recent tomographic studies from the University of Oregon), losing most of its primordial helium signature. Plume material then migrates along lithospheric slope toward the GSC (or is processed through the GSC), contaminating the ambient mantle of the NGP to variable extents on a local scale. Extensional stresses generated by the transform fault at 90°50'W on the GSC cause the NGP to be under tension, resulting in NW-trending lithospheric fractures that initiate melting of a variably plume-contaminated mantle to produce the seamount lineaments.

Hoernle, Kaj

Temporal and Spatial Variations in Galapagos Plume-Ridge Interaction

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The Cocos-Nazca (Galapagos) Spreading Center and ocean crust to the north and south of the ridge axis were sampled during R/V SONNE cruises 158 and 208 between 86.0-92.5°W. At least three distinct components are needed to explain the variation in the chemistry of the on-axis samples: 1) enriched Wolf-Darwin or Northern Domain (as defined by Hoernle et al., 2000; Geology 28) type of component (92.5-91.5°W), 2) enriched Fernandina/Isabella or Central Domain type of component (~91.5-87.5°W) with 206Pb/204Pb >18.7, and 3) depleted component 206Pb/204Pb < 18.7 at the incipient overlapping spreading center (OSC) at 89.2°W and east of the 87.5°W OSC. Preliminary geochemical data from two of the five profiles orthogonal to the ridge axis, along which the ocean crust north of the ridge was sampled, indicate that changes in the flux of plume material to the ridge varied through time. At the western profile between 91.5-92.0°W, ratios of more to less incompatible elements (e.g. Nb/Zr, Ba/Zr and La/Sm) suggest an overall decrease of the northern plume component with increasing age or distance from the spreading axis. At the eastern profile (between 89.0-89.5°W), where depleted material is at present being sampled at the ridge axis, ratios of more to less incompatible elements suggest an increase in the central plume component in the past. These observations indicate variable flux of different Galapagos plume components to the Cocos-Nazca spreading center over the past ~0.5 Ma. Sr-Nd-Pb isotope data is presently being generated in order to test these preliminary interpretations.

Hoernle, Kaj

Petrology/Geochemistry of the Galapagos Hotspot and Hotspot-Ridge Interaction

Hoernle, Kaj[1]

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The petrological/geochemical data from the Galapagos Islands/Seamounts, the adjacent Cocos-Nazca Spreading Center and the Galapagos Hotspot tracks on the Cocos and Nazca Plates (Cocos, Carnegie, Malpelo and Coiba Ridges and associated seamounts) will be reviewed. The talk will focus on long-term compositional variations in the plume and how the plume interacts with the adjacent Cocos-Nazca Spreading center. Since it has been demonstrated that the Galapagos hotspot contains distinct compositional components that dominate in distinct geographical regions of the Galapagos Archipelago and Plateau, the Galapagos plume-ridge system provides a unique place to investigate the interaction between a mantle plume and a nearby spreading center. In particular, the talk will discuss whether the plume material travels to the ridge as a melt or a solid, what path the material takes as it flows to the ridge and the effects of water on melting beneath the ridge. Another goal of the talk will be to elucidate the origin of the different components present in the sampled Galapagos and spreading center volcanic rocks: specifically whether these components are derived from the Galapagos plume, the upper mantle or the oceanic crust. Increasing evidence suggests the presence of multiple depleted components derived from the plume and the surrounding upper mantle. At the end of the talk, several suggestions will be made as to what open questions still need to be addressed and how.

Hooft, Emilie E.

Seismic Constraints on the Formation of the Galápagos and Iceland Platforms

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The Galápagos and Iceland hotspots have formed broad shallow platforms on which sit the oceanic islands. The platforms are typically surrounded by a steep escarpment and a flexural moat. There are competing hypotheses for the formation of the steep escarpments, including faulting, inflation of the platform by lower crustal flow, and volcanic accretion. Recent seafloor surveys along the edge of the Galápagos platform reveal that its escarpment is terraced and sinuous, characteristics that are inconsistent with faulting. The platform is inferred to form by episodic eruption of large lava flows that coalesce to form an escarpment by levee formation. Less is known about the morphology of the edge of the Iceland platform (also known as the insular shelf). It has been proposed that the Iceland platform formed by inflation as a result of lower crustal flow along the ridge away from the plume center. Here we use seismic refraction data to constrain the internal structure and thickness of the edges of the Galápagos and Iceland platforms as well as the process that governs the formation of their escarpments. The Galápagos refraction line is 250 km long and extends from the center of the platform across its leading edge and onto oceanic crust. The data were recorded on four ocean-bottom hydrophones and two broadband three-component land seismometers. The Iceland refraction line is located on the northeastern Iceland shelf at 66.5°N. The profile crosses the Iceland platform and its escarpment; here the platform formed during the initiation of the Kolbeinsey Ridge and is associated with enhanced plume flux. The profile extends onto the adjacent seafloor of the Iceland Plateau and included 20 ocean-bottom seismometers. Arrival times of crustal refractions, mantle head waves, and Moho reflections indicate a striking similarity in the structure of the Galápagos and Iceland platforms and their edges. At the platform edges crustal thickness increases rapidly (the thickness doubles over a distance of ~50 km), and low P-wave velocities are found throughout the crust (mostly <6.5 km/s). These low velocities are consistent with high porosities, which support the formation of the platform edge by repeated stacking of lava flows. In contrast, beneath the interior platform of both hotspots, the thickness of the lower crust is about two-thirds of the total crustal thickness. Under the center of the platform the ratio of intrusive to extrusive lavas, as inferred from seismic velocities, is similar to that of oceanic crust. We conclude that construction of the platform edges is dominated by volcanic accretion, whereas construction of the interior of the platforms is dominated by intrusive magmatism. This interpretation suggests that if platform volcanoes are the source of terraced lava flows, then individual flows have lateral extents of many tens of kilometers.

Ito, Garrett

Dynamics of Plume-Plate Interaction

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The concept of a hot convection plume of mantle rising from the deep mantle and interacting with the lithosphere has been the overriding framework for understanding the origin of the largest and longest-lived intraplate volcano chains, their associated seafloor swells, as well as prominent geophysical and geochemical anomalies at "hotspot-influenced" mid-ocean ridges. Numerical modeling and analog experimental studies have established a basic fluid-dynamical description of plume-lithosphere interaction. The resulting theoretical relationships predict that observables such as the geographic width of seafloor swells and crustal thickness anomalies should increase with increasing plume buoyancy flux, decreasing plume viscosity, and decreasing rate of plate motion. Hence, inferences have been made about the large-scale (10^2-10^3 km) nature of heat and mass transport beneath the largest hotspots, Galapagos included. But many characterizing observations are not readily explained by this first-generation theory. These include punctuated surface volcanism in the form of individual volcanoes and volcanic lineaments, short-wavelength (10^{-2}-10^2 km) variations in magma composition, as well as complex seismic structure of the upper mantle as recently imaged beneath the Hawaiian and Galapagos hotspots. The physical and chemical dynamics of hotspots are rich in processes that have yet to be well explored with theory and adequately tested with combined datasets. For example, convection in the shallow mantle can be more vigorous and smaller in scale than often considered, especially due to changes in viscosity and density with partial melting as well as to variations in the major element composition of the mantle. That mantle convection and partial melting can influence the expression of different source materials in the magmas that are produced leads to questions about which geochemical signatures are caused by these upper-mantle processes and which actually fingerprint the composition of the source material delivered in plumes from the deep mantle. Little is known about the processes of melt migration and the associated chemical transport from the ductile mantle and through the lithosphere, even though these processes critically link what is expressed in magmatism at the surface to the deeper mantle. Filling such gaps in knowledge will require coordinated efforts among geodynamicists, geophysicists, and geochemists. Such efforts are needed to address questions regarding the thermo-chemical evolution of the mantle on a planetary scale, as well as to understand the long-term geologic forcing functions that influence surficial processes on biological and societal time scales.

Jackson, Matthew G.

Ocean Islands and mantle plumes: Outstanding geochemical and petrological questions

Jackson, Matthew G.[1]

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Large quantities of oceanic crust and marine sediment derived from continental crust are injected into the mantle at subduction zones, but their fate in the mantle is not well known. At the surface, geochemists observe that the Earth's mantle, as sampled by oceanic lavas erupted at the surface, is chemically and isotopically heterogeneous, but the origin of the heterogeneity is not well understood and has been long-debated. Nonetheless, a consensus in emerging that the heterogeneity owes to two primary mechanisms: 1.) subduction of geochemically enriched continental and oceanic crust (and associated fluids) into the mantle over geologic time, and 2.) depletion of the mantle by continental crust extraction and continuous melt extraction at mid-ocean ridges. Owing to the lithological differences between mantle peridotite and subducted crust, the Earth's mantle is also likely to accumulate major element heterogeneities, and this lithological variability in the source of hotspots should be apparent in the petrologic diversity of hotspot lavas.

However, the Earth's mantle mixes and stirs chaotically on geologic timescales, and any surviving portions of subducted crust are likely attenuated and their associated geochemical signatures diluted. Furthermore, the "subduction package", including the sediment lithology and the relative proportion of sediment and oceanic crust, is likely to vary at each subduction zone (and within a given subduction zone). The degree to which subducted crust and sediments are processed in a subduction zone, and how these subducted components are processed, is not well known, but is likely to be highly variable in different subduction zone setting. Another important variable, generally neglected, is how the composition of oceanic crust and sediment may have varied throughout geologic time; if hotspots sample Archaean sediments with no modern analogue, it will be difficult to evaluate the origin of the recycled protoliths. Therefore, if oceanic and continental crust are returned to the surface in mantle upwellings, or plumes, and melted beneath hotspots, their geochemical signatures prove difficult to detect and their initial protoliths even more difficult to infer. Perhaps the greatest challenge facing the geochemical community today stems from the recent discovery that modern terrestrial lavas have $^{142}Nd/^{144}Nd$ ratios ~18 ppm higher than chondrites (Boyet and Carlson, Science, 2005). This result implies that all modern terrestrial mantle and crustal reservoirs ultimately were derived from this reservoir with superchondritic Sm/Nd. Today, the $^{143}Nd/^{144}Nd$ of the primitive (albeit non-chondritic) reservoir would be ~0.5130, a ratio that is closer to the depleted MORB mantle than to chondritic. A brand new starting point for the composition of the mantle has enormous implications for our interpretation of the origin of mantle geochemical reservoirs: Reservoirs that were once considered depleted relative to chondritic (e.g., HIMU, with 143Nd/144Nd = 0.51285) are actually enriched relative to the postulated non-chondritic mantle. Another implication is that the size of the depleted MORB mantle must be much large (>50% of the mantle's mass) to accommodate continental crust extraction.

Jefferson, Anne J.

Top down or bottom up? Volcanic history, climate, and the hydrologic evolution of volcanic landscapes

Jefferson, Anne J.[1]

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Volcanic landscapes are well suited for observing changes in hydrologic processes over time, because they can be absolutely dated and island chains segregate surfaces of differing age. The hydrology of mafic volcanic landscapes evolves from recently emplaced lava flows with no surface drainage, toward extensive stream networks and deeply dissected topography. Groundwater, a significant component of the hydrologic system in young landscapes, may become less abundant over time. Drainage density, topography, and stream and groundwater discharge provide readily quantifiable measures of hydrologic and landscape evolution on volcanic chronosequences. In the Oregon Cascades, for example, the surface drainage network is created and becomes deeply incised over the same million-year timescale at which springs disappear from the landscape. But chronosequence studies are of limited value if they are not closely tied to the processes setting the initial conditions and driving hydrologic evolution over time. Landscape dissection occurs primarily by erosion from overland flow, which is absent or limited in young, mafic landscapes. Thus, volcano hydrology requires conceptual models that explain landscape evolution in terms of processes which affect partitioning of water between surface and subsurface flows. Multiple conceptual models have been proposed to explain hydrologic partitioning and evolution of volcanic landscapes, invoking both bottom up (e.g., hydrothermal alteration) and top down processes (e.g., soil development). I suggest that hydrologic characteristics of volcanic islands and arcs are a function of two factors: volcanic history and climate. We have only begun to characterize the relative importance of these two drivers in setting the hydrologic characteristics of volcanic landscapes of varying age and geologic and climatic settings. Detailed studies of individual volcanoes have identified dikes and sills as barriers to groundwater and lava flow contacts as preferential zones of groundwater movement. Erosion between eruptive episodes and deposits from multiple eruptive centers can complicate spatial patterns of groundwater flow, and hydrothermal alteration can reduce permeability, decreasing deep groundwater circulation over time. Size and abundance of tephra may be a major geologic determinant of groundwater/surface water partitioning, while flank collapse can introduce knickpoints that drive landscape dissection. The combination of these volcanic controls will set initial conditions for the hydrology and drive bottom up evolutionary processes. Climatic forcing drives many top down processes, but understanding the relative effectiveness of these processes in propelling hydrologic evolution requires broader cross-site comparisons. The extent of weathering may be a major control on whether water infiltrates vertically or moves laterally, and we know weathering rates increase until precipitation exceeds evapotranspiration. Weathering by plant roots initially increases porosity, but accumulation of weathered materials, such as clays in soils, can reduce near-surface permeability and promote overland flow. Similarly, eolian or glacial inputs may create low permeability covers on volcanic landscapes.

Jellinek, Mark

The Plume-Hotspot Connection, Plate Tectonics and the Remarkable Character of the CMB Region

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The proposed physical link between ocean islands and mantle plumes ascending from the core-mantle boundary

(CMB) region is a powerful one. In particular, the occurrence, distribution, longevity and character of long-lived hotspots, as well as the inferred diversity in the structures and heat transfer properties of their underlying mantle plumes, have specific and restrictive implications for the thermal, chemical and mechanical state of the CMB region, as well as for the mantle convective regime of the planet. Indeed, varied observations and inferences from seismological, geodetic, geomagnetic, geochemical and mineral physics studies, taken together with results from geodynamic models of mantle plumes and plate tectonics, show this region to be one of extraordinary complexity in compositional and thermal structure and in constitution. In this review I will discuss several (improbably persistent) questions: 1) What is a current picture of the thermochemical structure of the CMB region? 2) What are the key mantle dynamics that govern the magnitude and length and time scales of thermal and compositional heterogeneity in this region? 3) How do ocean islands sample the CMB region through melting? (e.g., Is melting heterogeneous?) 4) What are the implications of these mantle dynamics for outer core convection and dynamo action: How are these mantle dynamics ultimately expressed in the radial magnetic field observed at Earth's surface? 5) To what extent is the current compositional complexity of the CMB region related to Early Earth differentiation? Is the Earth simply weird or does it all make sense?

Jellinek, Mark

The influence of diffusive convection on the longevity of hydrothermal plumes

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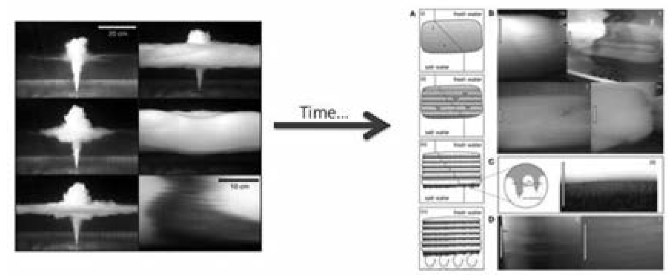
Submarine plumes emitted from hydrothermal vent fields have been widely studied because of their important contribution to the chemistry of the oceans. These highly turbulent mixtures of hot water, micron-sized particles, metal–rich sulfides, sulfates and oxides can rise a few hundreds of meters above the sea floor and spread out laterally up to 20 kilometers. Turbulent entrainment of oceanic water into the plume enhances precipitation of dissolved chemical species and subsequent sedimentation. In theory, the residence time of the suspension is governed by the grain size population and should not exceed a few days. However, deep-water measurements of dissolved chemical species, particulate metals and suspended particles made near mid-ocean ridges reveal that the subsequent cloud can remain stable for several months. This discrepancy motivated a series of laboratory experiments in order to understand the mechanisms responsible for sedimentation of hydrothermal plume particles. To this aim, we inject at a fixed rate a hot mixture of small particles and fresh water in a tank containing stratified salt water. Depending on the conditions imposed at the source and in the environment, large-scale instabilities may develop due to the differential diffusion of heat, salt and small particles (three-components diffusive convection). To understand this new regime, we present a theory suggesting that the occurrence of this phenomenon depends on the population of particles and the depth reached by the hydrothermal plume. The comparison of our results with an exhaustive review of field data on submarine plumes shows that diffusive convection processes can increase the residence time of the suspension up to 5 years, which allows total dissolution of suspended precipitates. Diffusive convection is therefore a good candidate to explain the presence of large amounts of dissolved chemical species far from their source hydrothermal field.



Karlstrom, Leif

Mechanical controls on the longevity and magnitude of large volcanic eruptions

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Magma transport weakens the crust on short spatiotemporal scales through diking, damage accumulation and eruption, but may strengthen or stabilize the crust on longer time and length scales. We propose that maximum magma chamber sizes (and hence maximum volumes of volcanic eruptions) reflect fundamental mechanical limits to the scales of chamber stabilization. The most important of these limits for high melt fraction chambers is the concentration of deviatoric stresses due to Earth's free surface, which become significant as chamber lateral dimension becomes similar to its depth. Hence, maximum size for low viscosity mafic eruptions such as during Flood Basalt emplacement should scale with crustal thickness. Progressive viscoelastic relaxation of stresses generated in rock around Moho-level reservoirs provides a viable mechanism to modulate eruption frequency. We propose that this mechanism controls the duration of main phase flood basalt eruptions and helps to develop topographic anomalies at ocean islands by promoting intrusive magmatism. But viscous relaxation cannot eliminate destabilization of stored melt by free surface stresses. For lower melt-fraction, more crystal rich reservoirs there are additional stabilization mechanisms. Magma with a yield strength will mechanically isolate the fluid reservoir feeding eruptions from locked surrounding magma in which stresses are below the yield stress. Material withdrawal expands the yield surface and effective mobile chamber size as eruption proceeds. This provides a mechanism by which large chambers at shallow depths may be mobilized before premature caldera collapse We explore the eruptive dynamics of large volcanic eruptions with a numerical model that couples conduit flow and magma chamber withdrawal. For both high and low melt fraction magma chambers the mechanical strength of overlying country rocks is the governing parameter for eruption duration before caldera collapse. With this model as a template, we predict the likely range of magma discharge rates, atmospheric volatile loading rate and longevity of the largest volcanic eruptions.

Karson, Jeffrey

Subaerial Seafloor Spreading in Iceland: Manifestations of Ridge-Hot Spot Interactions

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Iceland has long served as a laboratory for seafloor spreading, offering spectacular exposures of spreading-related structures generated in a subaerial environment. Despite the slow spreading rate (<20 mm/yr) across the North American- Eurasian plate boundary, the Iceland hot spot creates an elevated magma budget comparable to intermediate- to fast-spreading ridges. A synthesis of results from previous and recent studies highlights the details of ridge-hot spot interactions. Icelandic crust is much thicker (25-40 km) than typical oceanic crust, but the upper crustal structure (inward-dipping lavas and outward-dipping dikes) is similar to relatively fast-spread crust. Instead of a linear pattern of spreading segments, the 50-km-wide neovolcanic zone of Iceland is composed of an array of overlapping spreading segments (~10 km wide x tens of km long) defining major "rift zones" and creating a much more complex accretionary pattern. Integrating data from the neovolcanic zone and deeply glaciated exposures of Tertiary crust to the east and west reveals the 3-D geometry of crustal accretion. Spreading segment centers are marked by central volcanoes with robust magma production and exposures of felsic to basic intrusive rocks. Focused intrusion of cone sheets and gabbroic intrusions are associated with dramatic subsidence (kilometers) and crustal thickening near segment centers. Along-strike, surficial fissure swarms and underlying dike swarms dominate. The Iceland hot spot, centered beneath the Vatnajökull Glacial Ice Cap offsets the MAR to the east. Oblique spreading systems and transform fault zones link the MAR to the actively spreading rift zones running north-south through east-central Iceland. Rift zones are propagating away from the hot spot both north and south. To the south, the Eastern Rift Zone has propagated southward to the Westman Islands, overstepping the South Iceland Seismic Zone transform and abandoning the Western Rift Zone. To the north, propagation of the Northern Rift Zone has caused transform strands of the Tjornes Fracture Zone to step progressively northward as the Kolbeinsey Ridge recedes. Rift zone propagation and microplate-like rotation in the anisotropic Icelandic crust may account for large-scale, rift-parallel, strike-slip faults and opening of the east-west rift zones. Spreading processes in Iceland have implications for accretionary processes in tectonic environments ranging from magmatic continental rifts to mid-ocean ridges. Ridge-hot spot interactions have created a distinctive style of spreading that may also apply to similar settings worldwide.

Laske, Gabi

The Hawaiian PLUME OBS deployment: Lessons learned and recommendations for a Galapagos deployment

Laske, Gabi[1]

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The Hawaiian PLUME OBS deployment was one of the first deployments of broadband ocean bottom seismometers (OBSs) of the U.S. national OBS instrument pool (OBSIP). The deployment consisted of two 1-year-long phases, one from January 2005 through January 2006 and one from April 2006 through June 2007. Augmented by ten broadband temporary land sites and three seismic observatory sites, the 1000-km-wide network ultimately covered 85 sites to provide continuous seismic records. Seventy-two of these sites were occupied by OBSs featuring a differential pressure gauge (DPG) and a broad-band seismic sensor, either a Guralp CMG-3T, a Nanometrics Trillium 40 or Trillium 240. From the phase 1 deployment, 32 of 35 instruments were recovered and 25 instruments had vertical-component seismic data. One Guralp vertical component did not unlock upon reaching the ocean floor while four instruments reset to recording only the horizontal components. The latter was a programming error of the CPU and does not longer occur. From the phase 2 deployment, 30 of 38 instruments were recovered. Two of these had to be rescued with a remotely operated vehicle (ROV) after they failed to lift from the ocean floor. Of the other lost instruments, we know that one from phase 1 and four from phase 2 experienced catastrophic implosions of the glass balls that are used for floatation and housing of batteries, acoustics and data acquisition. One instrument from phase 1 apparently released early as the ROV visit only found the anchor. The fate of four phase 2 OBSs and one phase 1 OBS remains unknown. Three of the recovered instruments had no vertical-component data. In response to the experience gathered during PLUME and to prevent future losses during deep deployment, the SIO OBS group has been replacing the glass floatation balls with syntactic foam. Despite the instrumental losses, the PLUME deployments provided an extremely rich and high signal-to-noise long-period (T > 10 s) vertical-component dataset. Rayleigh wave dispersion analysis was possible to a degree that any land-based experiment would provide. A strong asymmetry in structure exists in the lithosphere as well as upper asthenosphere which matches the anomalies in the bathymetric swell. Long-period body wave tomography for shear and compressional velocity structure was also successful and our group was able to image a low-velocity anomaly well into the lower mantle. The anomaly is consistent with a thermal plume with an excess temperature of 250 degrees C in the upper and 300 degrees C in the lower mantle. A two-phase deployment of 30 instruments could go a long way to image the Galapagos hotspot. In contrast to PLUME, I would recommend to first occupy a large aperture network with station spacing of 100 - 200 km. Such a network is suitable for capturing the major features of seismic anomalies. A 1-year lag between recovery and deployment would allow an initial data analysis to strategically place a subsequent small-aperture network with station a spacing of 75 km or less. Such a network helps illuminate smaller-scale features in seismic anomalies and also allows to obtain insight into local seismicity.

http://igppweb.ucsd.edu/~gabi/plume.html

Lees, Jonathan M.

Search for Harmonic tremor in the Galapagos

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Harmonic volcano tremor can provide details of conduit physics during magma flow and volcano explosions on numerous volcanoes worldwide. Recent models of tremor [Jellinek and Bercovici, Nature, 2011] suggest that the magma plug oscillates in the conduit. Earlier models imply harmonic tremor originates from internal waves propagating within fluids in the upper parts of the conduit. I present a review of volcano harmonic tremor as observed on numerous volcanoes world wide. These include, Karymsky Volcano, Russia, Tungurahua and Reventador Volcanoes, Ecuador, and Santiaguito Volcano, Guatemala. Examples illustrate that there is a common theme of volcano chugging world wide, independent of volcano size and apparently unrelated to specifics of petrological variations. In many cases the dominant, fundamental period is between 0.7-1.2 Hz. Chugging is defined as tremor that produces an audible sound, typically discrete pulsations similar to the sound of a locomotive. Harmonic tremor has not been reported on Galapagos volcanoes, possibly because seismic and acoustic instrumentation installed previously were not oriented to record these signals. Active volcanoes, such as Sierra Negra and Cerro Azul may have tremor associated with trap door activity. The more silicic Alcedo shows evidence of deep seismicity that may exhibit tremor as yet unobserved. Fumarolic activity at Alcedo indicates shallow fluid activity and the connection between the deeper seismicity and shallow emission is intriguing.

Maclennan, John

Petrological Constraints on Magma Transport and Storage under Iceland

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Iceland is an excellent place to examine the evolution of basaltic melts under oceanic volcanoes. A number of factors contribute to this suitability. First, decades of geological investigation by Icelandic researchers have produced a framework for collection of well-constrained sets of samples. Secondly, access to most of Iceland is straightforward. Thirdly, geophysical surveys provide information about crustal structure and the present distribution of melt in the Icelandic crust. Fourthly, many Icelandic basalts are porphyritic and these phenocrysts and melt inclusions record much of the magmatic evolution. Fifthly, studies of olivine-hosted melt inclusion indicate that the mantle melts which enter the plumbing systems of Icelandic volcanoes are extremely diverse in their trace element and isotopic compositions: such geochemical heterogeneities can be used as passive tracers of the progress of compositional homogenisation by melt mixing in shallow magma bodies. Finally, the large crustal thickness in Iceland allows for thermobarometry, even with significant errors, to distinguish between crystallisation at near-Moho, mid-crustal and shallow-crustal levels. This unique combination of circumstances has allowed for the development of a model of magma evolution under the Icelandic rift zones. Diversity in the Pb-isotopic composition of olivine-hosted melt inclusions from single hand-specimens of high MgO basalts reflects significant short-lengthscale high-amplitude compositional variation in the mantle source regions of individual volcanoes. The end-member compositions of the apparent binary mixing arrays in isotopic/incompatible trace element plots of melt inclusion compositions can be developed by channelised melt flow in the mantle. Extensive mixing of depleted and enriched mantle melts then takes place concurrent with cooling and crystallisation in near-Moho and lower crustal magma chambers. This concurrent mixing and crystallisation is recorded by a drop in the variance of passive chemical tracers, such as La/Yb, in melt inclusions as the forsterite content of the host olivines drops. Quantification of the relative rates of mixing and cooling in lower crustal magma chambers may provide information about the vigour of convection in such chambers. Olivine crystals grow from diverse melts, which then mix and carry the early-formed olivines to the surface. None of the olivines are therefore in equilibrium with their carrier liquids. Barometry based on liquid compositions, clinopyroxene compositions, and the order of appearance of plagioclase and clinopyroxene as liquidus phases, indicates that crystallisation occurs at depths as great as 30 km under Iceland. These depths are recovered from pyroxenes which formed just after the onset of crystallisation of depleted mantle melts. Barometry of less mafic samples provide crystallisation depth estimates of as little as 15 km. The compositions of these samples indicate that they have lost half of their original mass of primary melt as cumulate crystals, and the barometry shows that this crystallisation has occurred in the lower crust. This relationship between depth and extent of crystallisation can be accounted for by a simple model where the solid lower crust forms by crystallisation in a series of stacked sills at lower crustal depths.

Manriquez, Paula M.

A flexure study beneath the Juan Fernandez Hotspot track

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We present two different methods for determining the flexure and the elastic thickness of the lithosphere caused by a three-dimensional, surface load, given the topography and gravity data. We then apply both methods to determine the flexure of the lithosphere caused by the O'Higgins Guyot and O'Higgins Seamount located about 120 km west of the Chilean Trench. The first method is an analitic solution that calculates the flexure of any elastic plate with an applied load. However it does not consider the flexure of the lithosphere caused by the subduction of the Nazca plate under the South American plate, it just calculates the flexure due to the load in an elastic plate far from a subduction zone and gives an interesting analytical solution to a very old problem. The second method solves the fundamental flexure equation using the finite element method. This method is much more adecuate for the study area because it can campute the flexure due to a load distribution near a subduction zone or in the presence of external applied forces. We then forward model the gravity data in order to derive a crustal density model and the crust-mantle interface (Moho). This gravity modeled Moho is compared and used to find the best fitting elastic thickness for the oceanic lithosphere in that region.

Marcillo, Omar E.

Infrasound produced by degassing of shield-volcanos: Hawaii and Galapagos

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Infrasound recorded in a dense network around an active vent in Kilauea volcano illuminates source characteristics and details of near-surface atmospheric conditions. During the summer of 2010, 45-infrasound sensors were deployed for 10 days around the active Halema'uma'u vent to capture the atmospheric response of degassing processes at Kilauea volcano. The activity is characterized by continuous infrasonic tremor. Cross-correlation between the elements of the network, during low-noise hours, provides reliable phase delay times that are inverted for structure and precise location of the vent, and air temperature and wind conditions of the near-surface atmosphere. The results of the inversion show persistent wind speeds up to 15 m/s coming from the northeast, and temperatures oscillating between 10 and 30 °C. The results agree with ground-based weather measurements. However, the inversion is sensitive to the azimuth of the station used as reference for the phase delay calculation. It is suggested that diffraction in the walls of the crater pit and/or refraction at short distances, are responsible for this effect. Further investigation in the influence of topography and the microstructure of the near-surface atmosphere in infrasound propagation at short distances is required to better constrain this inversion. Shield-volcanoes like the ones in Hawaii and Galapagos can remain active for long periods and provide an ideal setting for studies related to degassing processes and the evolution of the source vent. In these studies, infrasound can complement other techniques, such as, seismic, deformation, and gas monitoring by constraining the amount of acoustic energy released in the atmosphere.

McClinton, James T.

Neuro-fuzzy classification of submarine lava flow morphology on the Galapagos Spreading Center, 92°W

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Variations in lava flow morphology along the axis of the Galapagos Spreading Center (GSC) can indicate differences in eruption and emplacement dynamics due to enhanced magma supply from the adjacent Galapagos hotspot. Unfortunately, the ability to discriminate fine-scale lava morphology is usually limited to the small coverage areas of towed camera surveys and submersible operations. This research presents a neuro-fuzzy approach to automated seafloor classification using high-resolution multibeam bathymetry and side-scan backscatter data. The classification method integrates a fuzzy inference system in an adaptive neural network and is capable of rapidly classifying seafloor morphology based on attributes of surface geometry and texture. The system has been applied to a study area on the 92°W segment of the western GSC in order to quantify the abundances and distributions of lava flow morphology types. The classified maps reveal the study area terrain consists of approximately 47% pillow lava flows, 31% lobate lava flows, 12% sheet lava flows, and 10% faulted/fissured areas. An accuracy assessment shows the classification has an overall accuracy of 88.4% with a kappa coefficient of 0.84. Analysis of the distribution and abundance of lava flow types shows that low effusion rate pillow lava eruptions are most abundant at the end of the segment, while high effusion rate sheet lava flows are most

abundant near the middle of the segment. Changes in lava distribution are directly correlated with the depth to a steady-state axial magma chamber below the ridge.

McGovern, Patrick J.

Structure and evolution of Galapagos volcanic edifices: Insights from lithospheric flexure models and comparisons with planetary analogs

McGovern, Patrick J.[1]; Galgana, Gerald A.[1]; Grosfils, Eric B.[2]

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The volcanoes of the western Galapagos islands are known for their distinctive "inverted soup plate" shapes, with a flat upper region (enclosing a caldera) ringed by a steep upper flank zone and gently sloped lower flanks. Fissures that are the sources for lava flows occur on the upper and lower slopes: the former are circumferential and the latter are radial and sometimes arranged in diffuse linear zones aligned toward the centers of adjacent edifices. These edifices are also notable for what is absent: focused linear rift zones and flank failures, as seen at Hawaiian volcanoes. Insights from viscoelastic models of stresses induced by lithospheric flexure can account for several aspects of Galapagos volcano structure. Loading of young, mechanically thin lithosphere leads to high magnitudes of magma ascent-inhibiting horizontal compressive stress in the upper lithosphere. Furthermore, the absence of sediments on the young ocean floor creates a welded basal boundary condition, transmitting compression into the edifice and preventing stress relief from volcanic spreading. These conditions tend to restrict edifice diameter and limit deep-seated flank failure relative to volcanoes on older, stronger lithosphere covered with decollement-favoring clay sediments such as the Hawaiian Islands. Upper lithosphere compression favors the production of oblate or sill-like magma chambers, consistent with geodetic and petrological evidence for shallow magma storage at Galapagos volcanoes. Sustained intrusive activity may ultimately produce upper lithosphere intrusive complexes that contribute to edifice growth and relieve compression in their vicinity, facilitating subsequent eruptions. Central complexes of hot, ductile cumulates or crystal mush, inferred from petrological analysis, could also yield significant flank stress relief, similar to the cumulate cores proposed for Hawaiian rift zones. In the lower lithosphere, magma chambers are likely to be mechanically unstable because they would tend to fail at their lower margins where extensional stress is greatest, sending magma back downward. While flexural stresses tend to inhibit central ascent of magma, conditions on the margins of the edifice, near the flexural arch, will be more favorable. Low differential stress magnitudes and favorable stress gradients (extension increasing upward) can facilitate ascent of magmas in dikes directly from mantle melt zones to the surface. Such a mechanism may account for some lower flank and submarine eruptions. Large basaltic constructs on Venus and Mars offer analogs to Galapagos volcano structures. Dozens of large volcanoes on Venus exhibit prominent annular zones of fractures and associated flows. Radially oriented fractures and flows are often seen beyond these annuli. The Alba Patera and Elysium volcanic rises on Mars exhibit rings of extensional fractures at a prominent slope break separating a flat summit region from the sloping flanks, with linear fault zones radiating beyond. Geophysical evidence and insights from flexure modeling suggest that these edifices are emplaced on thinner lithosphere than average for their respective planets, as at the Galapagos volcanoes.

Mittelstaedt, Eric

Plume-ridge interaction at the Galapagos: Insights provided by new gravity and magnetic observations

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Investigations along the Galapagos Spreading Center (GSC) reveal geophysical and geochemical anomalies that increase in magnitude as the ridge approaches the Galapagos Archipelago (GA); an indication of strengthening plume influence. At the GA and along the GSC these anomalies indicate elevated mantle temperatures, enhanced crustal thickness, and an enriched mantle source. Despite such evidence for communication between an upwelling mantle plume beneath the GA and the nearby GSC, very little is known about the nature of the interaction between the ridge and the hotspot. To explore this question, the FLAMINGO cruise (MV1007) surveyed a region to the west and to the east of the 90° 50'W transform fault. High-resolution EM122 multibeam bathymetry, MR1 sidescan sonar, and gravity and magnetic measurements were collected over a ~42,000 km2 area and exhibit significant variations across the study area. To the west, the Nazca plate is dominated by numerous seamounts aligned along 3 volcanic lineaments. These lineaments extend from the archipelago toward the ridge axis, perhaps following the stress pattern in the lithosphere. To the east, on the Cocos plate, there is very little evidence of constructional volcanism. However, we observe several linear, ridge-parallel, faulted features separating sedimentary basins, and two large bathymetric highs with up to 1km of relief. Gravity anomalies also display significant differences between the Nazca and Cocos plates. Mantle Bouguer Anomaly (MBA) lows closely contour the volcanic lineaments on the Nazca plate with minimums at the centers of the largest volcanoes along the Wolf-Darwin Lineament. On the Cocos plate, the MBA at a given distance from the ridge axis is generally more negative than similar locations on the Nazca plate. In addition, two very negative MBA regions are observed, both of which are slightly elongate in a direction sub-parallel to the Eastern GSC. To better quantify these differences, magnetic anomaly picks are used to create a detailed near-transform kinematic reconstruction. Using this reconstruction as a constraint, we develop an upper mantle thermal model and calculate the Residual Mantle Bouguer Anomaly. We discuss the differences between the Nazca and Cocos plates and plume-ridge interaction at the Galapagos in the context of the gravity anomalies and the magnetic reconstruction, including a discussion of the ridge jump history of the region and variations in crustal thickness.

Perron, Taylor

Origin of morphologic variability among Pleistocene coral reefs

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The mechanisms controlling the development and morphologic diversity of coral reefs surrounding ocean islands have long been the subject of scientific discussion. Reef morphology emerges from a competition between coral growth and the erosion and transport of reef material by waves. Over glacial-interglacial timescales, however, the relative importance of the factors that regulate growth and erosion, particularly subsidence, sea level variations, and dissolution, is unclear. Previous efforts to model coral reef development have related reef morphology to island subsidence, coral growth rate, and changes in eustatic sea level, but none have systematically explored reef evolution over the full range of conditions that different islands are likely to have experienced in the recent geologic past. The mechanisms responsible for the considerable variability in Pleistocene reef morphology are therefore unclear. We hypothesize that interactions among subsidence, sea level cycles, reef growth, and wave erosion are sufficient to explain the observed variability in Pleistocene reefs. As a test of this hypothesis, we present a numerical model of reef profile evolution incorporating island subsidence or uplift, variable sea level, coral growth, and wave erosion. When driven by a simplified sea level record for the last 400 kyr, the model produces eight distinct reef types within the parameter space defined by the two dominant factors of subsidence/uplift rate and coral growth rate. These reef types encompass much of the morphologic variability found in natural reefs. Comparing modeled reef elevation profiles with those of natural reefs on islands spanning a range of subsidence/uplift and coral growth rates, we find good agreement between the observed and modeled reef types. These results provide a framework for understanding the evolution of Pleistocene reefs and could help predict how reefs will respond to changing rates of sea level rise in the future.

Perron, Taylor

Problems in the geomorphology of the Galápagos and other ocean islands

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The variety of ocean islands offers an excellent opportunity to study the influence of time, climate, lithology, biota, and initial topography on landscape evolution. The age range, comparatively dry climate, and minimal erosional dissection of the Galápagos Islands provide an interesting case for comparison with other islands. I provide an overview of the physical geography and geomorphology of the Galápagos, highlighting characteristics of particular interest for their contrasts with other ocean islands. I focus particular attention on comparisons with the Hawaiian Islands, which span a similar range of ages but are considerably wetter. These comparisons raise several unanswered questions about landscape evolution that can be addressed through comparative studies of ocean islands, and for which observations of the Galápagos would be especially useful. First, how does rainfall rate influence the long-term rate of bedrock river incision? Strong climate gradients, both across and among ocean islands, create natural experiments for studying climatic effects on erosion while controlling for factors such as lithology. Second, to what extent do biotic communities steer the course of landscape evolution, and vice versa? Island biogeography and species variability create a unique opportunity to investigate the mutual influence of life and landscapes. Third, how do landscapes evolve during the early stages of drainage network development? Radiometrically dated, incompletely dissected volcanic edifices provide a glimpse of the chronology and topography of these early stages, two factors that are difficult or impossible to reconstruct for most eroding landscapes. Fourth, how does hydrogeology interact with surface evolution on ocean islands? Studies of island hydrology suggest that subsurface structure can strongly influence the location of channelized surface flow, and there are controversial claims that some major landforms are shaped primarily by groundwater. The connection between surface processes and subsurface hydrology may vary with island age, size, and climate. Fifth, how does the coupling of terrestrial and marine processes govern the transition from island to seamount or atoll? Sediment budgets of island interiors are poorly understood, as are the mechanisms linking terrestrial and marine erosion and sediment transport. With these questions in mind, I summarize relevant results from an ongoing study of erosion and landscape evolution on Kaua'i, and offer some suggestions for extending such studies to include comparisons with the Galápagos.

Peterson, Mary E.

Volatile budget of the mantle sources of the Galapagos plume

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The study of volatiles (H2O, CO2, F, S, and Cl) is important because volatiles assert a strong influence on mantle melting and magma crystallization, as well as on the viscosity and rheology of the mantle. Despite this importance, there have been a minimal number of volatile studies done on magmas from the four main mantle sources that define the end member compositions of the Galapagos lavas. For this reason, we present new volatile concentrations from 89 submarine glass chips from dredges collected across the archipelago during the SONNE SO158, PLUM02, AHA-NEMO, and DRIFT04 cruises. Relative enrichment of trace element concentrations allows the glasses to be grouped into three broad groups: enriched, intermediate, and depleted. The intermediate group appears to be the result of mixing between the enriched and depleted groups. We have combined these results with the published volatile data of melt inclusions from Fernandina and Santiago (Koleszar et al, 2009), sites associated with a high 3He/4He and MORB-like mantle source, respectively. The effect of degassing, sulfide saturation, and assimilation of hydrothermally altered material must be understood before using the volatile content of submarine glasses to establish the primary volatile concentration of their mantle sources. For the Galapagos trace element depleted submarine glasses, we find a positive correlation between Sr/Sr*, a positive anomaly created by the assimilation of plagioclase, and all volatile/refractory element ratios (H2O/Ce, CO2/Nb, F/Nd, S/Dy, Cl/K). This suggests significant volatile input from melt-lithosphere interaction. Due to their low trace element concentrations, these samples readily show the alteration signature, thus making the establishment of their primitive volatile content difficult. Despite this, the least modified samples in the depleted group have a S/Dy ratio and F/Nd ratio that fall within the range expected for a depleted source, (Saal et al, 2002). For Cl/K, H2O/Ce, and CO2/Nb ratios, the primitive signature of the depleted group has been overwhelmed by the assimilation input. The enriched group was less affected by the assimilation input, making the volatile concentrations more reliable. Within the enriched group the trace element concentrations are very similar. However, there is a variation within this group in the magnitude of 3He/4He. A high 3He/4He is used to define the mantle end member known as FOZO. This indicates that there are two mantle sources with similar trace element concentrations being sampled by these glasses. This variation in 3He/4He is correlated with the magnitude of a positive Ti and a positive Nb anomaly on a primitive mantle normalized trace element diagram. While there is no distinguishable variation in Cl/K, S/Dy, or CO2/Nb, the ratios of H2O/Ce and F/Nd are both correlated with the anomalies and with the 3He/4He ratio.

Poland, Michael P.

Capitalizing on the Galápagos archipelago as a high-visibility natural laboratory for volcanology

Poland, Michael P.[1]

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During the 20th century, research into Galapagos volcanism mostly consisted of petrologic and geologic mapping studies because logistical challenges precluded geophysical data collection. As the century came to an end, however, application of satellite remote sensing resulted in new insights into volcanic activity, most notably rapid and complex deformation of nearly all the volcanoes in the western Galapagos. These discoveries provided motivation for ground-based geophysical measurements, including GPS and seismic deployments. Models based on these datasets have been used to explain previously noted, but poorly understood, features and processes, for instance, the ubiquitous pattern of radial and circumferential eruptive fissures and the feedback between magmatic intrusion and intracaldera faulting. Such results demonstrate the value of investigations into the dynamics of Galapagos volcanism, and the time is ripe to make even better use of the Galapagos as a high-visibility natural laboratory for volcano science. New research in the Galapagos would benefit fundamental problems in volcanology, including the dynamics of magma supply and storage, the structural evolution of volcanoes, and eruption forecasting. Geophysical studies in the Galapagos are providing new insights into how basaltic magma accumulates and moves beneath the surface. The degassing character of Galapagos volcanoes is largely unknown but could provide essential information on the depth and volume of magma storage and input. Constraints on the structural evolution of basaltic volcanoes have generally been derived from studies of the Hawaiian Islands, yet the Galapagos provide additional, and possibly better, examples of many processes. For instance, basaltic caldera formation and evolution are on display in the archipelago, Galapagos volcanoes generally lack the complications of rift zones and flank instabilities (common on Hawaiian shields), and studies of volcano-volcano interactions can exploit the presence of eight active volcanoes within a few tens of kilometers of one another. Research into eruption forecasting would benefit from the frequent eruptive activity in the Galapagos (in the 50-year period spanning 1961- April 2011, Galapagos volcanoes erupted at least 24 times) and the

fact that many volcanoes in a localized area are at different stages of their eruption cycles. Further, Fernandina is one of very few truly basaltic volcanoes with a historical explosive eruption (in 1968). Research following these themes will also feed into and support ongoing investigations of mantle composition and dynamics. Volcanological work in the Galapagos also has the important intangible aspect of high visibility. The archipelago is a household name due to its place in the history of evolutionary biology, and volcanologists can capitalize on this fame by providing educational and outreach experiences (especially in a virtual sense) that emphasize the volcanic nature of the islands. There are also outstanding opportunities for interdisciplinary research that combine Earth and Life science. Well-publicized research in the Galapagos will provide important visibility for volcanology during an age of shrinking funding for science.

Poland, Michael P.

Magma Supply to Basaltic Shields: An Example from Hawaii and an Opportunity for the Galapagos

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Magma supply rate is one of the most fundamental control on a volcano's eruptive and intrusive activity. At Kilauea Volcano, Hawai`i, magma supply from the mantle can be quantified by tracking the volumes of lava erupted at the surface and magma stored within subsurface reservoirs. For the 50-year period between 1952 and 2002, magma supply averaged about ~0.1 km3/yr. During 2003–2007, however, a surge in magma supply was indicated by increased rates of subsurface magma storage, lava effusion and CO2 emissions. The rate of CO2 emission, which is directly proportional to the amount of magma supplied to Kilauea, more than doubled. Compositional changes in lavas erupted during 2003–2007 indicated flushing of stored, degassed magma as the proportion of high-temperature magma from the hotspot increased within the volcano. The consequences of the magma supply surge included normal faulting along the caldera-bounding faults, an east rift zone intrusion and small eruption, the formation of a new long-term east rift zone eruptive vent, and possibly even the formation of an eruptive vent at the summit of the volcano. Multidisciplinary monitoring data can provide an early indication of changes in magma supply and be used to forecast future volcanic and tectonic activity that may result. The active volcanoes of the western Galapagos archipelago provide numerous opportunities to investigate magma supply from a hotspot, taking advantage of continually improving monitoring and analytical capabilities. Deformation at the volcanoes is well-monitored by InSAR, and eruptions are frequent and relatively easy to characterize. Geodetic and seismic studies could be supplemented by monitoring CO2 and SO2 emissions to provide independent assessments of magma supply and storage and to assess how magma supplied from the hotspot is distributed between the numerous adjacent volcanoes of the Galapagos.

Ramalho, Ricardo

Episodic swell growth inferred from variable uplift of the Cape Verde hotspot islands

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On the Beagle voyage, Charles Darwin first noted the creation and subsidence of ocean islands, establishing in geology's infancy that island freeboard changes with time. Hotspot ocean islands have an obvious mechanism for freeboard change through the growth of the bathymetric anomaly, or swell, on which the islands rest. Models for swell development indicate that flexural, thermal or dynamic pressure contributions, as well as spreading of melt residue from the hotspot, can all contribute to island uplift. Here we test various models for swell development using the uplift histories for the islands of the Cape Verde hotspot, derived from isotopic dating of marine terraces (Laser Ablation U-Th Disequilibrium Geochronology) and subaerial to submarine lava-flow morphologies (Ar-Ar IR Laser Step Heating Geochronology). The island uplift histories, in conjunction with inter-island spacing, uplift rate and timing differences, rule out flexural, thermal or dynamic pressure contributions to swell development. We also find that uplift cannot be reconciled with models that advocate the spreading of melt residue in swell development unless swell growth is episodic. Instead, we infer from the uplift histories that two processes have acted to raise the islands during the past 6 Myr - a local uplift process probably associated with the intrusion of basal laccoliths formed under each island edifice, and a regional process, episodic and acting at the swell's length scale. We conclude that during an initial phase, mantle processes acted to build the swell. Subsequently, magmatic intrusions at the island edifice caused 350 m of local uplift at the scale of individual islands. Finally, swell-wide uplift contributed a further 100 m of surface rise.

Ramalho, Ricardo

Why have the old Cape Verde Islands remained above sea-level? Insights from field data and wave erosion modeling

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The ultimate fate of late stage ocean islands is to be drowned beneath the sea surface and become a guyot. This process is essentially dictated by subsidence in edifices in young lithosphere and/or in fast-moving plates, or by marine erosion that truncates edifices located in old lithosphere and in mid-plate stationary swells like in Cape Verde. Several factors control the transition from island to guyot, chiefly: the size (height and diameter) of the island, subaerial erosion processes, mass wasting, wave energy conditions, amplitude of the eustatic change, coral reef growth, post-erosional volcanic activity, and vertical movements affecting the island edifices. From these, coral reef growth, volcanic resetting and uplift play a crucial role in maintaining ocean island edifices above sea-level. This study reports on how three of the oldest of the Cape Verde islands - Sal, Boa Vista and Maio - have been maintained above sea-level just through an uplift process. These islands, practically devoid of coral reefs or recent volcanic structures, have been increasing in area since the Late Pliocene or early Quaternary, when they were nearly or completely truncated by marine erosion. This study argues, through a combination of field data interpretation and numerical wave erosion modeling, that this increase in area has been almost entirely sustained by a consistent uplift trend during the Quaternary. The study goes on to propose that in the absence of such an uplift trend the islands would probably have been completely eroded by now and turned into guyots. The new term ”razed islands” is also proposed to describe residual islands that are surrounded by extensive shore platforms, without coral reefs, in opposition to the term ”atolls”; razed islands are mainly generated through wave truncation processes whilst atolls are mainly generated by a combination of subsidence and coral growth.

Ramon, Patricio

April 2009 Fernandina volcano eruption, Galápagos Islands, Ecuador: thermal mapping of the lava flows emitted

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Fernandina, the easternmost volcano of the Galapagos Archipelago, erupted in April 2009, satellite data suggested that the eruption began sometime between 22:00Z on 10 April and 00:30Z on 11 April. Based on the information from the seismic station at Santa Cruz island, no earthquakes were associated with this eruption. First eyewitnesses reported an eruptive column on the morning of 11 April. Thermal and SO2 anomalies shown by MODIS and AURA satellites respectively were associated to the onset and the development of the eruption. Officers from the Galapagos National Park Service (GNPS) observed an eruptive fissure during a flight on 13 April which was located very close to the 2005 eruption radial fissure. They observed a fissure that was ~ 200 m long and 10 m wide, and ejected 15 m high lava fountains. A gas-and-ash plume drifted SW and a steam plume was observed as the lava flow poured into the ocean. Three vents discharging lava at ~ 400 m elevation on the SW flank along a radial fissure were active, feeding a lava flow up to 10 m wide according to the observations made by personnel from the GNPS during a new flight on the morning of 15 April, the eruption was still going on however the intensity was lower than in the previous days. During 15-16 April, gas-and-steam plumes from Fernandina drifted up to 555 km W. A field campaign was conducted by members of the Instituto Geofisico-Escuela Politécnica Nacional de Ecuador (IG-EPN) from 27 April to 5 May 2009; the purpose of this campaign was to obtain SO2 and thermal data from field measurements and to compare them to the satellite information. Infrared measurements using a thermal camera FLIR (Forward Looking InfraRed) where carried on during an over flight of the zone affected by the lava flows. These measurements associated with post eruption satellite images allowed an estimation of the area covered by the products of the eruption. Thanks to the strong thermal contrast between the new products and the older lava flows, it was possible to map precisely the limits of April 2009 eruption. The thermal contrast information has been stacked on the satellite images. The area covered by the April 2009 eruption is of about 6.7 km2 which is a value similar to the 1995 eruption (6.5 km2; Rowland et al., 2003). Unfortunately we do not have thickness measurements for the April 2009 lava flows. Nevertheless, considering the similarities between both eruptions, we used the average thickness calculated by Rowland et al. (2003) for the 1995 eruption (14 m), to calculate 2009 eruption volume. It gives an approximate volume of 94*106 m3 of lava emitted. This volume is equivalent to those of 1995 and 1988 but the emission rate is drastically different. This estimation has to be taken carefully as no thickness measurement was done during the fieldwork.

Richards, Mark A.

Petrological Interpretation of Deep Crustal Instrusive Bodies Beneath Oceanic Hotspot Provinces

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Seismic refraction studies of deep-crustal and upper mantle structure beneath some oceanic hotspot provinces have revealed the presence of ultramafic bodies with P-wave velocities of Vp ~7.4-8.0 km/s lying at or above the Moho. Sometimes referred to as "underplating" structures, these intrusive or cumulate bodies have volumes comparable to or larger than those of the basalts erupted at the surface. Well-studied examples include Hawaii, the Marqueses, and La Reunion. However, images from other hotspot provinces such as the Galapagos and Louisville indicate that the lower crust has been intruded by large volumes of gabbroic rocks (Vp ~6.8-7.5 km/s), compositionally similar to or only somewhat more mafic than the erupted basalts. Petrologic modeling of sublithospheric mantle melting due to a hot plume shows that both the seismic velocity and density of crystallized mantle melts increase with melting pressure and temperature. Ultramafic primary melts formed beneath mature oceanic lithosphere at pressures of order ~2-3 GPa (60-90 km depth) can explain the high seismic velocities of the observed ultramafic deep-crustal bodies, and these melts are also predicted to have sufficiently high densities upon crystallization to result in neutral buoyancy at the Moho. By contrast, plume melts formed at depths of ~15-30 km depth beneath thin lithosphere are predicted to have compositions that are more nearly gabbroic, explaining the apparent absence of large ultramafic bodies beneath hotspots formed on relatively young oceanic lithosphere. The velocity and density gradient is particularly strong in the pressure range 0.6-1.3 GPa, suggesting a possible filtering effect whereby plume melts equilibrated at relatively shallow depths beneath very young and thin oceanic lithosphere ($<$15 Ma) may be expected to be of nearly gabbroic composition (~6-10% MgO), whereas ultramafic melts (MgO ~12-20%) formed beneath older, thicker oceanic lithosphere must pond and undergo extensive olivine and clinopyroxene fractionation before evolving residual magmas of basaltic composition sufficiently buoyant to be erupted at the surface. A survey of well-studied hotspot provinces of highly-varying lithospheric age at the time of emplacement shows that deep-crustal and upper mantle seismic refraction data are largely consistent with this hypothesis. These results are also consistent with a recent survey of deep crustal seismic structure beneath large igneous provinces (LIPs). The role of plume temperature, as opposed to the "final" depth of melt equilibration, should also play a role in determining primary melt composition and deep crustal seismic structure, an effect that needs further modeling and analysis in terms of the available seismic, geological, and geochemical data.

Rubin, Kenneth H.

Using Geochronology of Shoreline and Coral Reef Deposits to Study Uplift and Subsidence at Tropical Volcanic Ocean Islands: Examples from Hawaii with Applications to the Galapagos

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Although the details and durations vary widely around the world, volcanic islands experience a well established sequence of events as they form and grow by volcanism, and subsequently or simultaneously cool and erode. This activity loads the lithosphere to varying degrees, influencing the elevation and stress regime within the surrounding oceanic plate via lithospheric flexure. In island groups, age variations between islands and unequal growth histories at neighboring volcanoes have predictable consequences on the uplift and subsidence history of nearby volcanic islands, atolls and guyots, with implications for the long-term ecological history of those edifices. Geological indicators of paleo sea level (e.g., littoral or intertidal deposits, coral reef deposits) provide strong evidence about the vertical histories of such island groups, particularly when they contain dateable material, such as well-preserved fossil marine carbonates. An exceptional fossil coral reef and littoral record in the Hawaiian Islands provides ample evidence for variations in vertical motions in the archipelago in both space and time, as well as relative sea level (RSL) changes in response to global forcing. For instance, our work in this area has shown that the island of Lanai has uplifted more rapidly in the past 200 ka than Oahu and Kauai, despite being closer to the (subsiding) volcanic loading point on the lithosphere, which is centered on the Big Island. Also, we've shown that normal high energy littoral deposits can be distinguished from tsunami deposits by a combination of geological mapping and geochronology. Similar RSL studies have been conducted by others in Hawaii, the Caribbean and the Western Pacific. Despite the potential for unraveling the growth history of the Galapagos archipelago and the strength and elastic thickness of the local lithosphere, to our knowledge there has been no equivalent study of vertical island motion or RSL records in the Galapagos Islands. There are multiple well documented occurrences of modern coral reef building in the islands, as well as one well known uplifted terrace at Bahia Urvina containing several-hundred-year old corals. However, the published literature about them is limited to studies of paleo sea surface temperature and salinity conditions, the recent history of marine upwelling, and changes in species diversity. There are also more than roughly 1000 km of pristine, undeveloped coastline in the Galapagos, providing the potential for an unequaled volcanic island record of paleo-littoral deposits above modern sea level. This presentation will summarize some of the sea level studies we and others have conducted in Hawaii, and discuss how similar studies in the Galapagos would be useful for understanding not only when and how much island shorelines have moved vertically, but also how this reflects volcanic growth history, the history and physical properties of the lithosphere on which the islands sit, and the history of the Galapagos plume flux. Such studies would make an ideal compliment to other efforts to understand the geological and geophysical manifestations of the Galapagos hot spot and the geologic history of the islands.

Ruiz, Mario C.

Seismic Activity and Seismic Monitoring at Galapagos Islands

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Using global seismic networks, more than 80 events are reported at the seismic catalogue of the International Seismic Centre (ISC). The largest magnitude recorded is 5.6 mb. However, Galapagos seismic catalogues (ISC) show a magnitude completeness of 4.5 mb for the 1970-2010 period. It suggests that seismicity at the Galapagos Islands is under-represented due to the scarcity of permanent local stations with the exception of PAYG, a seismic station of the global network installed in 1998 at Santa Cruz island that has been running with a borehole and surface broadband instrumentation. Between 1996 and 2001, the Instituto Geofisico of the Escuela Politecnica Nacional operated a seismic network composed of six short-period vertical stations on Fernandina, Isabela, Bartolome and Santa Cruz. A temporary network was deployed between 1999 and 2003 for a hotspot tomography project using teleseismic events (Hooft et al, 2003, Villagomez et al., 2007).Since July 2009 a network of 16 stations was installed around Sierra Negra and Cerro Azul volcanoes as part of the SIGNET project (Cote at al, 2010). Based on the information collected by these networks, four main seismic zones have been recognized: a) Sierra Negra seismicity is composed by events beneath the caldera with swarms beneath East and South-East flanks, along the ring fault system bounding the caldera, and along the sinuous ridge. b) Fernandina seismic swarm with a SE trend on its southern flank c) A NW-SE trending seismic swarm near Alcedo volcano persisted between 2000 and 2001; activity is high in 2009 and 2010, with clusters within the caldera and the southern flank. d) a seismic swarm located at the western edge of the Galapagos platform about 50 km from Cerro Azul and Fernandina volcanoes with depths down to 40 km beneath sea level. This swarm is active since 2001 and coincides with expected central mantle plume upwelling. In order to properly monitor this activity and to conduct further studies, the Instituto Geofisico of the Escuela Politecnica Nacional with the support of an Ecuadorian Science and Technology Secretariat`s grant will install next year a new permanent seismic network of 6 broad-band stations distributed on Alcedo, Sierra Negra, Cerro Azul and Fernandina volcanoes.

Ruiz Paspuel, Andrés G.

Seismic and ground deformation patterns at Sierra Negra Volcano, Galapagos- Ecuador

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To constrain the ground deformation and seismicity patterns, we analyzed simultaneously the ground deformation data and seismicity form local and global seismic networks. Seismic data was collected using a network of six short-period vertical stations installed by the Instituto Geofisico in 1996 on Fernandina, Isabela, Bartolome and Santa Cruz islands and from PAYG, a broad-band seismic station on Santa Cruz, located more than 100 km away from active volcanoes. The seismicity beneath Sierra Negra volcano as well the seismicity on the Canal Bolivar zone showed shallow, clustered seismicity during 1998 to 1999, coinciding with uplift of the caldera floor of ~0.3 m, whereas deep and stronger widespread earthquakes triggered the trapdoor faulting on 1998 and 2005 (Amelung et al., 2000; Jónsson et al 2005, Chadwick et al., 2006). Although the Canal Bolivar seismic zone is located ~45 km to northwest of Sierra Negra and one event located ~ 30 km to west of the volcano, earthquakes in Feb., 2007 coincided with a brief deflation on the southern of the Sierra Negra caldera (Ruiz et al., 2007). The shallow clustered seismicity under the caldera could be related with a shallow pressurized chamber fed by a deep source. This magma chamber was interpreted as a ~ 2 km deep sill (Amelung et al., 2000; Jónsson et al.,2005, Chadwick et al., 2006, Geist et al., 2006, Geist et al., 2007) that had been inflating for at least 13 years before the 2005 eruption. After the eruption the chamber began to refill and resulted in greater rates of ground deformation of ~212 cm/y. (Ruiz et al 2007). Unfortunately, the seismometers were not functioning during this extremely fast inflation event. Deep seismicity is probably due to deep magma intrusions which also contribute to the ground deformation. In fact, bigger and deep earthquakes triggered the trapdoor faulting at Sierra Negra volcano on 1998 and 2005 (Amelung et al., 2000; Jónsson et al., 2005, Chadwick et al., 2006). The 2007 seismicity at the Canal Bolivar zone, including one event near Cerro Azul volcano, was characterized by several earthquakes with magnitudes between 4.3 and 5.6 mb (NEIC). Although this seismic zone is located ~30 to 45 km to west and northwest, a brief deflation episode was detected on the southern area of Sierra Negra caldera on Feb 2007. This deflation could be driven by depressurization of the underlying geothermal system or by tectonic fault slip and or a combination of both (Ruiz et al., 2007). Southern GPS stations showed greater horizontal movements than the northern stations, suggesting that the magma body could be elongate to the south. Moreover, seismicity from 1997 to 1999 showed a clustered pattern in the southern part of Sierra Negra's caldera. Future investigations could corroborate this hypothesis through to get the local seismicity as well the regional seismicity and combine this information with other methods as ground deformation measurements, microgravity and meteorology.

Schlitzer, William

Plume-Ridge Interaction in the Galápagos III: The Origins of Pinta, Marchena, and Genovesa Islands

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The central Galápagos Archipelago differs from many other ocean island chains in that it is underlain by a 500 x 200 km platform. An appendage of this platform extends ~50 km NW toward the Galápagos Spreading Center (GSC) and underlies Pinta, Marchena, and Genovesa Islands. The flanks of these islands were surveyed using EM122 multibeam and MR1 sidescan sonar and dredged at several locations during the 2010 MV1007 and the 2001 DRIFT04 cruises. The volcanoes that make up the islands are close enough to each other that their submarine bases nearly coalesce. Each volcano has an elongate morphology, with submarine ridges that extend ~30 km north of Pinta toward the 90°50'W GSC transform fault, between Marchena and Genovesa, and ~45 km NE of Genovesa. A flat-topped shoal, which may be a drowned island, extends ~30 km SE from Marchena. An intriguing aspect of this relatively small region is that lavas erupted here exhibit isotopic and trace element signatures that span the entire compositional range observed in the Galápagos Archipelago. Pinta has the lowest ε_{Nd} value in the Galápagos, and lavas from N Pinta Ridge exhibit comparable enrichment. Genovesa volcano, only 150 km to the east, is constituted of lavas that are mostly indistinguishable from MORB with the most depleted signatures in the archipelago (in fact, it is one of the most depleted ocean island volcanoes anywhere on the planet). Marchena, the southern shoal, and submarine lavas from ridges that extend toward Pinta are built of lavas that have trace element compositions intermediate between those of Pinta and Genovesa. Newly measured $^3He/^4He$ values range from 6.5 to 9.5 Ra, with the highest value between Genovesa and Marchena. Despite plume-like trace element and Nd isotopic signatures at Pinta, $^3He/^4He$ values are lower than typical MORB (6.5-6.7 Ra). Just as with the Galápagos Platform, lavas become progressively depleted from W to E, and Sm/Yb ratios decrease across the region from Pinta to Genovesa Ridge. We propose a model in which a heterogeneous plume with enriched and depleted components moving toward the GSC encounters a decrease in lithospheric thickness, which may in part relate to the nearby transform fault on the GSC. The enriched compositions at Pinta may result from limited, deeper melting of enriched compositions owing to a thicker lithospheric cap (e.g., Gibson and Geist, 2010), resulting in magma with elevated Sm/Yb. East of Pinta, the plume melts more extensively and at shallower depths, producing progressively depleted signatures with lower Sm/Yb toward Genovesa. Prior to reaching the northern Galápagos, the plume undergoes an incipient melting phase at the wet solidus near the plume center, losing its volatile components, accounting for the MORB-like $^3He/^4He$ of the northern islands. The degassed material then migrates NE, where increasingly thin lithosphere results in continued decompression melting, yielding lavas with variable plume signatures but lacking the characteristic high $^3He/^4He$ plume signal. The presence of melt here is consistent with the detection by Villagomez et al. of an anomalously slow velocity region at shallow depths underlying the Pinta-Genovesa region.

Segall, Paul

Insights into magmatic processes from deformation and seismicity

Segall, Paul[1]

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As magma moves through the crust it generally deforms the earth's surface in ways that can be measured by GPS, InSAR, tilt and strainmeters. In the upper, brittle crust these strains commonly generate earthquakes. For these reasons, deformation and seismicity are the main geophysical methods for monitoring volcanoes and provide vital constraints on magmatic processes. Eruptions are commonly (but not always) preceded by inflation as magma accumulates in crustal reservoirs, while deflation occurs when magma is withdrawn in eruptions. Some silicic calderas have exhibited decades of episodic uplift and subsidence without intrusion or eruption, suggesting that unrest is hydrothermal rather than magmatic. Volcano deformation has traditionally been analyzed with geometrically simple sources in elastic half-spaces. The data are sensitive to source depth and shape, and to changes in (rather than total) volume of the reservoir; however, some chamber geometries can be difficult to resolve with deformation alone. In contrast, dike intrusions generate characteristic deformation patterns, and are often associated with propagating earthquake swarms, making them relatively easy to identify. Deformation and seismicity accompanying dike emplacement has been observed from 0.5 - 10 hours prior to eruption onset in Hawaii and Iceland.

Hawaiian volcanoes exhibit well-developed rift zones and seaward flank motion. The basal fault beneath Kilauea's south flank has hosted steady creep, transient slow-slip events, and earthquakes as large as M7.6. While such volcanoes present a clear tsunami hazard, we have very limited constraint on premonitory signals that might precede catastrophic flank collapse. The Galapagos volcanoes, perhaps due to absence of a sediment blanket on the pre-volcanic sea-floor, exhibit neither flank instability nor long-lived rift zones. They do experience spectacular intra-caldera "trap-door" faulting, which must interact with the shallow magmatic system in profound ways. Important outstanding questions include: (1) Can we distinguish between deformation and seismicity leading to eruption from that which ends with intrusion? (2) Once an eruption is underway, can we bound its ultimate size and duration (highlighted by air-traffic disruption during the 2010 Iceland eruption)? (3) Can we move beyond kinematic descriptions to relate data to absolute (rather than relative) properties of magma systems, by integrating fluid-dynamical models of volcanic processes into analyses of deformation? Future work should integrate constraints from seismic and electromagnetic imaging, gravimetry, deformation, and seismicity. I will discuss efforts to integrate deformation and seismicity into inversions that yield the space-time evolution of dikes. I will also discuss efforts to model the evolution of magma-chambers coupled to either propagating dikes or cylindrical volcanic pipes. The former show the tendency for a dike to reach earth's surface is favoured by high initial pressure, compressive stress states, as well as large magma reservoirs. The latter have been applied to the 2004-08 eruption of Mt St. Helens, and use both GPS and extrusion rate to constrain the absolute volume of the crustal magma chamber and initial chamber overpressure.

Shearer, Peter M.

Characterizing fault zones at Kilauea and Mauna Loa volcanoes by large-scale mapping of earthquake stress drops and high precision relocations

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Because of ongoing time-dependent variations in volcanism, geodetically observed deformation, and earthquakes, Hawaii's value as a natural laboratory for studying the interactions between magmatic and tectonic processes has long been recognized. We describe initial results of a comprehensive analysis of waveforms from the seismic network operated by the Hawaii Volcano Observatory (HVO) between 1992 and 2009. This includes records from over 100,000 earthquakes at a variety of depths, including shallow seismicity associated with Kilauea volcano and the east rift zone, intermediate depth events along magma conduits, deeper events along a detachment fault zone near 30 km depth, and long-period earthquakes near 40 km depth beneath Mauna Loa. We have converted all the waveform data to a standard format and are now applying both waveform cross-correlation and spectral analysis to the HVO waveforms, using methods similar to those we have successfully applied in southern California. While prior studies have focused on individual regions, our analyses will provide the first comprehensive catalog of relocated earthquakes across the entire Island of Hawaii. The results should give a sharper view of fault (tectonic) and conduit (magmatic) structures, including improved characterization of detachment faults on the south and west flanks of Hawaii. From a systematic analysis of P-wave spectra, it is possible to separate source, path and receiver contributions, and estimate Brune-type earthquake stress drops. Spatial variations in stress drop provide insight regarding the relationship between stress drop and fault geometry. In addition, there have been several large earthquakes, dike intrusions, and slow slip events that provide targets to investigate possible temporal variations in stress drop that may be associated with changes in absolute stress levels. These large-scale waveform analysis methods can be used in other volcanic areas monitored by local seismic stations, including current and proposed experiments on and around the Galapagos.

Shen, Yang

Geophysical constraints on oceanic islands, mantle dynamics and mantle heterogeneity: Part I

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Volcanic islands and seamounts in the deep ocean basins are formed by additional or excess magma production relative to the formation of the oceanic crust at mid-ocean ridges. The cause of this magmatism remains the focus of an intense debate involving several competing hypotheses, which include de-compressional melting of buoyant mantle plumes, small-scale instabilities at the base of the lithosphere, and "leaking" of melts through tensional cracks. In the former two, the amount of excess magma production and the composition of volcanic rocks are controlled by the temperature, composition and upwelling rate of the source mantle, and the thickness of the lithosphere. The primary geophysical constraints come from observations of seismic waves, geoid, gravity, bathymetry, electrical and (paleo)magnetic fields, which measure variations in elastic moduli, anisotropy, density and electrical conductivity of the crust and mantle. These properties in turn reflect properties such as the temperature, composition and fabric of flow in the mantle, and provide critical observations for constraining geodynamic models of mantle flow and melting. Variations in crustal thickness and seismic structure from seismic reflection/refraction, receiver functions, earthquake tomography, gravity and bathymetry provide a key constraint on magma production and thus the mantle temperature and mantle upwelling flux at oceanic islands. The crustal thickness changes substantially from island to island, reaching up to ~46 km beneath Iceland. Estimated excess igneous volume flux along the Hawaii-Emperor chain shows a factor of 2 variation from the maximum to the minimum. Such observations along with petrological evidence suggest an episodic process in the mantle. Combining a melting model with the volume and wave speed of the igneous crust may provide further constraints on the potential temperature, the rate of mantle upwelling and associated geodynamic models. One important question in interpreting excess magma production is whether the thickened crust at oceanic islands and plateaus has been affected by delamination or convective instability of dense lower crust. The lithosphere-asthenosphere boundary defines the upper limit of buoyant mantle upwelling and melt production. Several lines of evidence suggest that the young oceanic lithosphere likely corresponds to a dry, chemically depleted layer over a possibly molten asthenosphere. Beneath old seafloor, the cold thermal boundary layer may extend deeper than and overtake the dehydrated layer as the lithosphere. Reported depths to the lithosphere-asthenosphere boundary at and near oceanic islands are highly variable, ranging from 40 km to 140 km. They do not correlate with plate age, suggesting that the lithosphere beneath ocean islands may have been eroded by hotspot-related processes. The erosion of lithosphere and the rate of mantle upwelling likely strongly depend on the rehydration of the lithosphere and dehydration of upwelling mantle, respectively. (part 1 of 2)

Shen, Yang

Geophysical constraints on oceanic islands, mantle dynamics and mantle heterogeneity: Part II

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Variations in mantle temperature, composition, and melt can be constrained from three-dimensional seismic structure derived by surface and body wave analyses. Regional surface wave studies image structure down to ~200 km depth, and have revealed lower-than-normal asthenospheric velocities as well as variations in lithospheric thickness at several hotspots. Regional body-wave studies constrain mantle structure down to greater depths: the depth of resolution is dependent on the aperture of the seismic network and wavefront healing also affects the size of resolvable anomalies. A strong cylindrical low-velocity anomaly has been mapped in the upper mantle beneath Iceland. At Hawaii, the large aperture provided by an ocean-bottom seismometer experiment allows the imaging of a low velocity anomaly extending down into the topmost lower mantle. The exact size and shape of the low velocity anomaly and estimate of mantle temperature provide constraints on the mass and heat flux and mantle viscosity. Global tomography has shown greater heterogeneities in the upper mantle transition zone compared to the mantle immediate above and below. The transition zone is bounded by major mineral phase transformations. The depth and sharpness of the phase changes and associated seismic discontinuities provide perhaps the strongest geophysical proxies for the temperature and composition in the mantle transition zone. A localized, thin transition zone beneath several hotspots supports the existence of anomalously hot mantle plumes. Interestingly both the width of the low velocity anomaly and the width of the thinned transition zone beneath Hawaii are much wider than what numerical models have suggested. The transition zone may also be a density trap for recycled crust, a reservoir for water, a region of drastic change in redox and carbonatitic melting in upwelling mantle. Processes within the lowermost several hundred kilometers of the Earth's mantle may play a role in hotpot origins. Many but not all hotspots are underlain by an ultra-low velocity zone at the base of the mantle. Perhaps a more striking correlation between the deep mantle and surface volcanism is that the large igneous province eruption sites of the past 300 My lie above the margins of two broad regions with lowered shear-wave speeds and higher than average density in the lowermost mantle beneath Africa and the Pacific. These observations have motivated ideas about a hot and chemically dense layer in the lower mantle and the development of mantle plumes from its surface. There may well be different mechanisms for magmatism at different oceanic islands, plateaus and seamounts. Progress on questions regarding their origins is best achieved with the integration of many types of observational constraints within a consistent petrologic and geodynamic framework. (part 2 of 2)

Shorttle, Oliver C.

Asymmetry of plume-ridge interaction around The Galápagos and Iceland controlled by spreading-ridge geometry

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We present evidence to show that around the Galápagos islands and Iceland, the primary control on the asymmetric pattern of along-ridge geochemical observables is the distribution of spreading-ridges with respect to the plume centre. This finding is in contrast to previous models, in which plume zonation or a non-radially symmetric plume flow have been hypothesised as generating the asymmetric geochemical profiles observed along-ridge. The key observation is that in both the Galápagos and Iceland plume-ridge systems there is a decoupling between the geochemical and geophysical dispersal of the plume head; around each plume centre the axial ridge depth appears symmetric, however the geochemical patterns imply greater plume influence along the Western Galápagos Spreading-Centre and Reykjanes Ridge for the Galápagos and Iceland plumes respectively. The geophysical symmetry in plume head influence, as recorded in the axial ridge depth, constrains the plume to be spreading radially symmetrically.

This implies that the geochemical asymmetry cannot be as a result of the plume preferentially flowing in one direction, nor because of an asymmetry in mixing with ambient mantle. Instead, we propose that partial melting of the enriched component in the plume as it traverses the deep melt region beneath spreading centres, can imprint an asymmetric geochemical signature in the spreading plume head. In a heterogeneous mantle, this partial melting would have the effect of extracting the most incompatible elements from the fusible enriched lithologies in the source, and leaving a progressively depleted residue, which is then transported to the ridge axis. Thus, the main parameter in controlling the spatial distribution of plume signature along-ridge, is the prior melting history of the plume material reaching the ridge axis - itself dependent on the positions of the spreading centres about the plume centre. Simple kinematic models of this depletion of mantle flowing radially in the deepest parts of the melting region are able to match the first order observations from the Galápagos and Iceland.

Sinton, John M.

Magma Migration, Storage and Evolution in the Galápagos Region

Sinton, John M.[1]

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Volcanism in the Galápagos region occurs both along the intermediate-rate Galápagos Spreading Center (GSC) and within the near-ridge Galápagos archipelago. As the GSC approaches the Galápagos hotspot the ridge gets shallower and the crust thickens; the maximum volumetric rate of crustal magma supply (= crustal thickness x spreading rate) occurs 200 km north of the inferred center of the hotspot near 91°W. Magma chamber depth beneath the GSC (and elsewhere) is inversely related to overall magma supply. Magma supply and extent of mantle melting are not correlated, however; rather average extent of mantle melting along the GSC likely decreases, with a volume of deep, low-degree hydrous melts contributing to the excess supply closer to the hotspot. Within the Galápagos archipelago magma supply is harder to quantify and volcanism is considerably more de-focused and widespread. Nevertheless, the trend of continued shoaling (to subaerial island volcanoes) continues, and chemical data suggest that average extent of mantle melting is even lower. Galápagos volcanoes tend to be smaller and less dissected by erosion and mass wasting than Hawaiian ones, and also lack temporal magmatic evolution from early tholeiites to later alkalic magmatism. There are, however, spatial variations in volcanic morphology, eruptive history, geochemistry and geophysical characteristics that generally define northeast-striking patterns away from Fernandina, the inferred center of hotspot upwelling and most active volcano in the archipelago. These patterns are highly oblique to the ESE direction of Nazca plate motion and include the persistance of summit calderas, the frequency and age of recent eruptive activity, variations in isotopic and trace element ratios, inferred mantle potential temperatures, lithospheric seismic velocities and contributions from different mantle source components. Galápagos lava compositions are dominated by transitional basalts that cluster near the tholeiitic-alkalic dividing line in plots of total alkalis versus silica. Highly tholeiitic lavas are rare. The most alkalic Galápagos sample data are from Floreana and Roca Radonda. At least three Galápagos volcanoes (Alcedo, Rabida, Pinzon) clustered near latitude 0° 30'S have erupted lavas with Mg # < 35 and > 56 wt % SiO2. Such silicic lavas are extremely rare in Hawai'i, but moderately common along parts of the GSC and in Iceland. Although crustal melting is commonly inferred for the origin of silicic magmas in some locations, Galápagos andesites and dacites appear to be derived by extensive fractionation in relatively shallow magma reservoirs.

Soule, Adam

Evaluating ridge-hotspot interaction models through crustal stress indicators in the Northern Galápagos Volcanic Province

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The Galápagos Spreading Center (GSC) and Galápagos hotspot have been a focus of ridge-hotspot interaction research over the last three decades. Geochemistry of lavas collected along the ridge provides strong evidence for variable contributions of plume material to the spreading axis. However, the mechanisms by which plume material is transported to the ridge are still actively debated. A key observation used to support geodynamic models of plume-ridge interaction in this region is the presence of several prominent seamount lineaments that span the Northern Galápagos Volcanic Province (NGVP) between the ridge and hotspot. The lineaments appear to radiate from the Galápagos archipelago, and have been attributed alternately to lithospheric channels of warm, fertile mantle; large, lithosphere-scale faults; spreading/transform fault-induced lithospheric stresses; and plume-induced buoyant uplift and asthenospheric shear generated stresses. These volcanic lineaments were previously the only resolvable indicators of crustal-scale interaction between the ridge and hotspot. Here we report results from recent sidescan sonar backscatter and multibeam bathymetry surveys conducted over a >40,000 km2 area centered on the NGVP and lineaments and including the W. and E. GSC and transform and portions of the Galapagos archipelago. The sidescan sonar (10-m/pixel) and bathymetry (50-m/pixel) data allow us to resolve features indicative of the stress state of the crust at orders of magnitude smaller length scales than the lineaments and over a more spatially continuous region. From these data we map the distribution of faults with >15 m throw and seamounts with bases >200 m diameter. We examine the characteristics of the population of faults as a whole and as a function of fault orientation, as well as the distribution of seamounts, their relative size, and elongation direction. We use these observations to investigate the stress distribution in the crust and its relationship to the orientation of the lineaments and plate motions. Our initial results suggest that a broad region of transtension is present around the GSC transform, but that the orientation of those extensional stresses does not coincide with those inferred from the seamount lineament orientations. Observations of seafloor volcanic and tectonic features, along with ongoing work on the geochemistry of lavas from the NGVP and potential field surveys over the same area will be used to discriminate between the multiple models of ridge-hotspot interaction.

Toomey, Douglas R.

Upper mantle structure beneath the Galápagos Archipelago from joint inversion of body and surface waves

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We conducted a joint tomographic study of teleseismic body-wave delay times and Rayleigh-wave phase velocities to constrain the seismic structure of the upper mantle beneath the Galápagos Archipelago. Data are from 10 broadband stations deployed over a period of 3 years and one station of the Global Seismographic Network. The seismic network spanned an area of 200 by 300 km^2, and the station spacing was 50-70 km. We measured 1783 P wave delay times and 1000 S wave delay times from 110 teleseismic events, and we used 12 maps of lateral variation of Rayleigh-wave phase velocity at periods from 20 s to 125 s obtained by us earlier. We invert simultaneously the delay times and phase velocities for three-dimensional variations in P and S wave velocity V_P and V_S, and we allow for variable weighting of body and surface wave data and coupling of P and S wave structures. The inversion solutions contain low-velocity anomalies that extend from the surface to the maximum depth of resolution (~300 km). We interpret the low-velocity volume at depths greater than ~100 km to be the locus of an upwelling mantle plume. Between 300 and 100 km depth the low-velocity anomaly is nearly cylindrical with a radius of ~75 km, and the V_S anomaly reaches a magnitude of -2%. We attribute this reduction to a combination of higher-than-normal temperature and partial melt. The low-velocity anomaly tilts northward as it shoals; at 300 km depth it is centered ~75 km to the south of Isabela, whereas at 100 km depth it is centered beneath that island. We propose that the northward tilt of the plume as it rises is due to background mantle flow toward the Galápagos Spreading Center. At the top of the low-velocity volume is a rapid increase in V_S, which we term the high-velocity lid. We attribute the base of this lid, which is at varying depth across the archipelago and is deepest (~100 km) beneath the southern end of Isabela, to a compositional change produced by the depletion and dehydration resulting from melt extraction. The viscosity increase associated with such dehydration may decrease or stall mantle upwelling, resulting in lateral spreading of the plume. Between 50 and 100 km depth, the low-velocity anomaly is located beneath the northeastern part of the archipelago, a pattern we attribute to melting produced as upwelling mantle spreads toward a region with a thinner lid. There is a pronounced low-velocity anomaly (maximum V_S anomaly of -3%) at depths shallower than 50 km beneath the southwestern part of the archipelago that we attribute to another stage of melting of mantle driven upward by plume flow and residuum buoyancy. This anomaly lies beneath Fernandina and Isabela, sites of the most active volcanoes in the archipelago. Our results support the interpretation that the Galápagos Islands are the product of an upwelling thermal plume that is continuous from at least 300 km depth to the base of a high-velocity lid and also suggest that mantle flow and melting beneath the Galápagos are influenced by the formation of residuum. In support of the last inference, the thickness of the high-velocity lid correlates well with regional variations in lava geochemistry.

Toomey, Douglas R.

Crustal structure beneath the Galápagos Archipelago from ambient noise tomography and its implications for plume-lithosphere interactions

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To constrain the seismic structure of the crust beneath the Galápagos hotspot we conducted a tomography study using high-frequency Rayleigh waves recovered from cross-correlations of ambient noise. Data are from 10 broadband stations deployed over a period of 3 years plus one station of the Global Seismographic Network. The seismic network spanned an area of 200 by 300 km^2 and had a station spacing of 50-70 km. We used cross-correlations of continuous vertical seismic records for 24 time periods that range from 11 to 50 days in duration. We measured Rayleigh-wave group velocities from the stacked cross-correlation signal of all time periods for each of 55 station pairs at frequencies between 0.1 and 0.33 Hz. Such waves, after accounting for the effect of water depth, are sensitive to shear wave velocity V_S structure between 3 and 13 km depth. Crustal V_S is up to 25% lower than that of very young crust at the East Pacific Rise (EPR) and is comparable to that of Hawaii. We attribute the lower-than-normal velocities to heating by increased intrusive activity above the Galápagos plume and the construction of a highly porous volcanic platform emplaced on top of the pre-existing crust. Crustal V_S beneath the western archipelago is up to 15% lower than beneath the eastern archipelago at 3-8 km depth and up to

8% lower at 8-13 km depth. The west-to-east increase in V_S appears to be gradual and correlates with distance downstream from the hotspot. We attribute the velocity increase to cooling of the crust after its passage above the Galápagos plume and to a gradual decrease in porosity in the extrusive layer. On the basis of our results, which constrain the broad-scale thermal and chemical structure of the crust and lithosphere, as well as a synthesis of recent plate reconstructions and gravity data, we suggest that the age of the lithosphere at the time of loading and its thickness and internal structure play major roles in shaping the location of hotspot volcanism and the morphology of volcanic landforms in the Galápagos Archipelago. For instance, variations in the flexural response to loading, which are correlated with volcano size and morphology, cannot be explained by the current thermal state of the lithosphere and thus represent varying elastic strength at the time of loading. In addition, we propose that some of the northwest- and northeast-trending Darwinian lineaments that are found throughout the archipelago are associated with pre-existing variations in lithospheric strength caused by past episodes of ridge jumping and ridge propagation. These zones of weakness are likely reactivated by stresses resulting from plume-lithosphere interactions. Moment tensor solutions for several near-archipelago earthquakes are consistent with reactivation of these lineaments.

Vidito, Christopher A.

Galápagos Plume Source Lithology: Inferences from Olivine Phenocryst Compositions

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Magmas of pyroxenite sources typically crystallize olivine with higher Ni and Fe/Mn and lower Ca and Mn than olivine that crystallizes from a peridotite source (Herzberg, 2011; Sobolev et al., 2007). Source lithology is determined using Fo#, Ni, Mn and Fe/Mn of olivine phenocrysts plotted in diagrams from Herzberg (2011). To characterize the source lithology of the Galápagos plume we conducted high precision EMP analyses of olivine phenocrysts from Cerro Azul, Fernandina, Floreana, Volcan Ecuador, Volcan Darwin, and Roca Redonda. Olivine compositions indicate peridotite source melting for Fernandina (Fig. 1), Cerro Azul and Floreana. This suggests that a peridotite source is present from the middle of the central domain through the southern domain. In contrast, a pyroxenite source is indentified at Volcan Ecuador (Fig. 1), Volcan Darwin and Roca Redonda. This indicates that the northern half of the central domain was formed from a pyroxenite source. Trends of Ni, Mn, Fe/Mn and Ca versus Mg # also reveal the importance of fractional crystallization and possible dissolution of other mineral phases. High 3He/4He (Kurz et al., 2009) correlates with a peridotite source in the south west, while a sharp drop in 3He/4He to the north corresponds to a change to a pyroxenite source. We infer that the Galápagos plume is heterogeneous in terms of source lithological and isotopic structure.

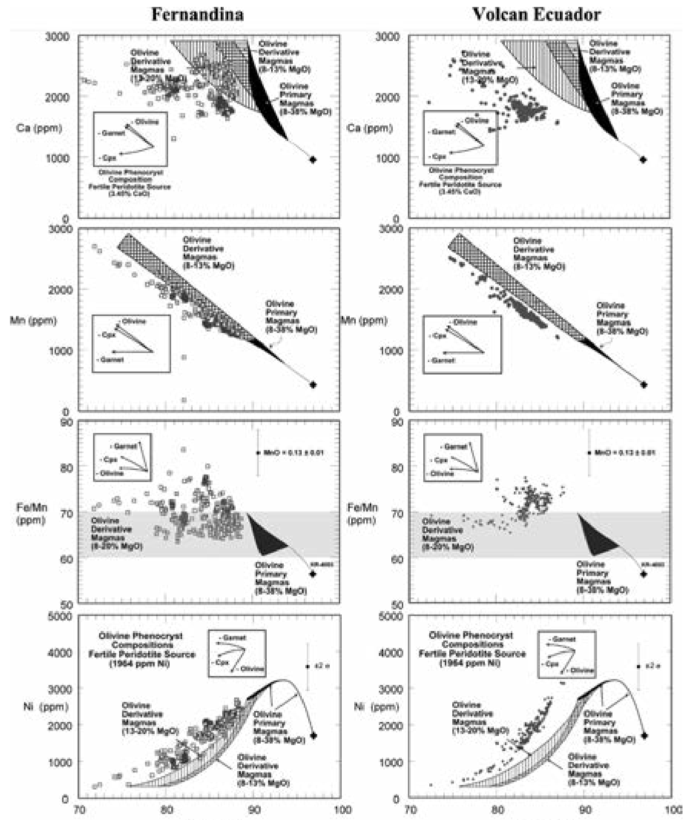

Fig. 1. Ca, Mn, Fe/Mn and Ni plotted against Mg#. Black regions = olivines crystallizing from peridotite- source primary magmas having 8 to 38% MgO. Black filled cross = olivine crystallizing from a total melt of peridotite. Hatched areas = olivines crystallizing from derivative liquids that formed by subtraction of olivine only from primary magmas. Vectors in box show the effects of clinopyroxene and garnet fractionation.

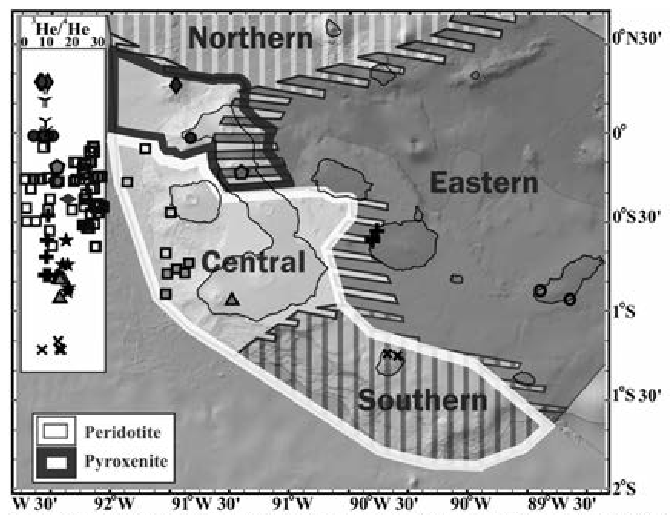

Fig. 2. Isotopic domains (Geldmacher et al., 2003) and areas of peridotite and pyroxenite source magmatism highlighted white and black. Position of the 3He/4He diagram is such that it is adjacent to the related volcanoes (McBirney et al., 1985; Graham et al., 1993; White et al., 1993; Reynolds et al., 2005; Kurz and Geist, 1999; Blichert-Toft and White, 2001; Naumann et al., 2002; Geist et al., 2002; Geist et al., 2005; Teasdale et al., 2005; Geist et al., 2006; Saal et al., 2007; Kurz et al., 2009; Raquin and Moreira, 2009; Kent et al., 2010).

Walters, Rachel L.

Time-dependent geochemical modeling of the rift cycle applied to rift relocations at Iceland

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Rift relocations are a common feature associated with the evolution of hotspot-ridge settings. Iceland provides an excellent natural laboratory to study the changes in volume and composition of mantle melts during a rift relocation. A wealth of published geochemical data already exists for three main active rift zones at Iceland: the Western Volcanic Zone (WVZ) where plate spreading rates are declining as extension is transferred to the Eastern Volcanic Zone (EVZ) and the Northern Volcanic Zone (NVZ) where spreading has been steady since ~5 Ma. These three zones therefore combine to represent a complete rift cycle from initiation (EVZ) through steady-state (NVZ) to extinction (WVZ). During a rift relocation the total extension is partitioned across two parallel active rifts. This process is currently observed in south Iceland as the EVZ propagates southwards and spreading on the WVZ decelerates. During the relocation process the full spreading rate across an individual rift may vary through time from as little as 2 mm/yr up to the total plate separation rate at Iceland, 18 mm/yr. Geochemical observations show that the WVZ and the NVZ produce a similar range of lava compositions; these compositions are significantly depleted in incompatible elements compared to those produced by the EVZ. The EVZ also exhibits a much greater variety of compositions than the WVZ and NVZ. We present new results from time-dependent kinematic modeling of melting beneath a mid-ocean ridge. The spreading rate is allowed to vary in time to represent one complete rift cycle; gradually increasing and decreasing, between 2 and 18 mm/yr, over 5 My for the growth and death of the rift respectively. Melt fraction-depth profiles, taken at 1 My intervals, are used to constrain forward models of melt composition from INVMEL (McKenzie and O'Nions, 1991). The model crustal thickness reaches ~20 km at steady-state, comparable to the observed thickness produced by passive upwelling beneath the NVZ (20.5±2.5 km; Staples et al., 1997). The model results indicate that, for a mantle potential temperature of 1450 °C, the most enriched compositions and the largest range of compositions are produced during the growth stage of the rift cycle. However, the dying rift produces very limited enrichment and variation in the REE compositions because there is insufficient time for conductive cooling to deepen the top of the melting region. The models therefore predict that the WVZ will erupt basalt compositions similar to the NVZ and will maintain high crustal thickness. The REE predictions are consistent with observed geochemical variability from the three main active volcanic zones at Iceland. The model indicates that variation in spreading rate can have a significant impact on the volume and composition of melt during new rift initiation and propagation, but does not hold the same influence during the death of a rift. This is an important result to consider when trying to understand the cause of geochemical variability in a rift system that has been subject to rift relocations, such as the Galápagos Spreading Centre.

Wilson, Emily L.

Plume-Ridge Interaction in the Galápagos II: Volcanic Evolution of the Northern Galápagos Islands

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The Northern Galápagos Province (NGP) is notable for its high density of seamounts, which were recently mapped with EM122 multibeam and MR-1 sidescan sonar in detail during the MV1007 Cruise. The seamounts vary from small, near-axis volcanoes with round bases to anomalously large, composite volcanoes with polygenetic eruptive histories. The five largest volcanic edifices in the region are islands: Darwin, Wolf, Pinta, Marchena, and Genovesa. We have merged detailed observations from fieldwork on Darwin, Wolf, and Genovesa Islands as well as previous fieldwork from Pinta and Marchena (Cullen and McBirney, 1987; Vicenzi et al., 1990) with the recently acquired MV1007 bathymetric data to yield a more thorough perspective on evolution of the NGP volcanoes. These structures share several characteristics that are distinct from the larger volcanoes of the main Galápagos Archipelago. First, even though several of the NGP islands are circular, they are all the emergent tips of elongate ridges ~30 to 60 km in length, which are constructed from series of submarine eruptions. Most of the ridges have en echelon structures, and are polygenetic with multiple eruptive centers concentrated along the ridges. The flanks of the ridges are dominated by lobate flows with highly variable sonar reflectivities, likely the result of a range of weathering, sediment cover, or flow-top morphology. There are also many flat-topped, pancake-like vent features along the bases of the ridges. Wolf, Darwin, and Pinta Islands have each experienced at least one major sector collapse event, depositing debris flows on their submarine flanks. Islands from the main Galápagos Platform have much larger subaerial volumes relative to their submarine bases, have more symmetrical bathymetric footprints, have submarine rift zones, and are surrounded by large volume submarine sheet flows. Petrologically, NGP volcanoes have all erupted significant volumes of plagioclase ultraphyric basalts; megacrysts are consistently larger in the subaerial lavas (to ~3 cm long) but dominate submarine flows as well. In contrast, the western shields of the main archipelago produce submarine lavas rich in olivine phenocrysts and subaerial lavas dominated by small plagioclase grains. The NGP islands exhibit a wide range in radiogenic isotope ratios and incompatible trace element contents. Pinta has signatures similar to those from

Fernandina (which has the strongest plume signal), whereas Genovesa is distinctly MORB-like. Lavas from Wolf, Darwin, and Marchena are intermediate in composition. Despite the regional geochemical heterogeneity in the NGP, submarine and subaerial lavas from each of the volcanic centers are compositionally homogeneous, and the volcanoes exhibit no temporal evolution. The common characteristics of the NGP volcanoes suggest that they did not originate near the Galápagos Spreading Center (GSC) but formed off-axis. Moreover, they must be supplied by magma sources tapping a locally heterogeneous mantle. These observations are consistent with a model in which NGP seamounts and islands are formed in response to regional extensional stresses generated by the intersection of a major transform fault with the GSC.

Yost, Russell

Potential role of soil calcium and phosphorus on Galapagos tortoise growth and well-being

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Russell Yost, University of Hawai`i at Manoa, Rodolfo Martinez, Charles Darwin Foundation, James Gibbs, State University of New York, Stephen Blake, Max Planck Institute. Giant tortoises (Chelonoides nigra) now populate only 6 islands of the Galapagos archipelago. Growth rates have evidently been in a long-term decline. Recent observations suggest tortoise size may differ among the islands. The islands appear to differ in age and degree of soil weathering. Literature on soils of the tropics has documented increased weathering and loss of nutrients with time of soil exposure to tropical climate. Weathering of soils of the tropics usually results in the depletion of bases such as calcium, magnesium and the reduced availability of other nutrients such as phosphorus. Large bones and shell are comprised largely of calcium and phosphorus compounds. Studies of tortoise feeding activity in desert environments suggest they seek out plants with high levels of calcium including cactus. Some studies have documented that gestating female tortoises seek out soils with particularly high levels of calcium and nutrients for direct ingestion. Based on these results from a brief review of literature, we hypothesize that possible differences in tortoise growth among the Galápagos Islands and, indeed, the sustainability and conservation of the giant tortoise may be affected by the availability of the nutrients calcium and phosphorus. We jointly propose this hypothesis and suggest that some measurements of calcium and phosphorus status and nutrition be considered in a comprehensive, interdisciplinary study of tortoise health and growth. To this end we are currently collecting soil for analysis of calcium, phosphorus, and other minerals along the altitudinal gradient of Santa Cruz, which can be expanded to other islands of different ages. It may be that existing data could be analyzed to explore possible relations between tortoise size, growth, and health and the availability of calcium and phosphorus in the foraged vegetation and in the soils upon which it grows. The purpose of this abstract is to stimulate discussion of this hypothesis that may affect tortoise conservation and sustainability in the Galapagos Islands. Suggested actions are discussions with current researchers and an examination of existing data and information necessary to test the proposed hypothesis. With the proposed presentation of this hypothesis to the Chapman Conference of July 2011, we anticipate a thorough examination of this possibility and the first steps in coordination of an effort to test the hypothesis as part of a goal of long term conservation of the giant tortoise in the Galapagos Islands.

Zhong, Shijie

Mantle Plumes, Oceanic Islands and Their Induced Surface Vertical Motions

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It has been suggested that hotspot volcanism and large igneous provinces be caused by decompression melting of mantle upwelling plumes. However, the dynamics of mantle plumes including their relationship with the African and Pacific superplumes have been a subject of intense debate for the last decade. Vertical motion history of lithosphere in response to mantle plume buoyancy and loading of volcanic construct has played an important role in such debates. This presentation will cover three relevant topics that we have studied recently. 1) I will discuss the relationship between the African and Pacific superplumes in the lower mantle and mantle plumes. Our studies show that, although not always, mantle plumes tend to form near the edges of the superplumes that are characterized as chemical piles. This may explain the correlation between the large shear velocity anomalies near the core-mantle boundary and surface hotspot volcanism that was reported by a number of research groups. 2) Our studies show that surface subsidence may occur in a broad area above mantle plumes prior to large igneous province formation as a result of interaction of mantle plumes with the endothermic phase change at 670 km depth and also at the periphery of volcanic construct due to the loading effects. This may reconcile mantle plume models with the long-term surface subsidence and hydromagmatic eruptions that are observed in some large igneous provinces. 3) Detailed modeling of volcanic loading and stress relaxation processes at oceanic islands (e.g., Hawaii) may provide important insights about lithospheric mantle rheology, such as activation energy. Our studies using observed surface topography and deflection at oceanic islands suggest that the lithospheric mantle may be significantly weaker than that deduced from the flow laws based on laboratory studies. A weak lithospheric mantle may help explain a large population of small seamounts in terms of sublithospheric small-scale convection as suggested recently.