Eos, Vol. 87, No. 23, 6 June 2006

EOS

EOS, TRANSACTIONS, AMERICAN GEOPHYSICAL UNION

VOLUME 87 NUMBER 23

6 JUNE 2006

PAGES 221–232

An Integrated Geologic Framework for EarthScope's USArray

PAGES 221, 224

The GeoFrame initiative is a new geologic venture that focuses on the construction, stabilization, and modification of the North American continent through time. The initiative's goals can be achieved through systematic integration of geologic knowledge—and particularly geologic time—with the unprecedented Earth imaging to be collected under the USArray program of EarthScope (http://www.earthscope.org/usarray). The GeoFrame initiative encourages a cooperative community approach to collecting and sharing data and will take a coast-to-coast perspective of the continent, focusing not only on the major geologic provinces, but also on the boundaries between these provinces. GeoFrame also offers a tangible, 'you can see it and touch it' basis for a national approach to education and outreach in the Earth sciences.

The EarthScope project is a massive undertaking to investigate the structure and evolution of the North American continent. Sponsored by the U.S. National Science Foundation (NSF), EarthScope uses modern observational, analytical, and telecommunications technologies to establish fundamental and applied research in the Earth's dynamics, contributing to natural resource exploration and development, the mitigation of geologic hazards and risk, and a greater public understanding of solid Earth systems. One part of this project is USArray, a moving, continent-scale network of seismic stations designed to provide a foundation for the study of the lithosphere and deep Earth.

Eight Focus Regions for Studying North America

The EarthScope project has the potential to be a transformative activity for the geosciences and to take the solid Earth sciences a step beyond plate tectonics, but only if structural geology, sedimentology, petrology, geochronology, geochemistry, and geophysics are combined in an integrated manner. The goal of the GeoFrame project is to help accomplish this task. This approach requires the contribution of large segments of the U.S. geosciences community, particularly those who provide the crucial information about Earth history across both space and time.

On 3–5 February 2006, a diverse group of about 60 geoscientists attended the GeoFrame workshop in St. Louis, Mo., to discuss an integrated geologic framework for the USArray component of EarthScope. This was the first national workshop that leveraged the results of multiple regional workshops. At the workshop, there was general consensus about the intellectual merit, scientific necessity, and role of GeoFrame in EarthScope science. Further, participants agreed that this type of national planning is necessary for organizing targeted geographic regions across the United States for integrative study.

The task and challenge of the workshop was clear: to integrate the spatial detail and time portrayed by the U.S. geologic map [*Schruben et al.*, 1994] with EarthScope studies of whole Earth and lithospheric processes. Participants agreed that a broad, integrated geologic framework was needed to understand how continents are built, specifically formation and growth of the North American continent through time and its modification by deformation, accretion, magmatism, and rifting.

To give these concepts a more concrete foundation, the workshop participants outlined seven focus regions across the conterminous United States and an eighth focus topic. These areas were identified to address fundamental aspects of the growth, evolution, and modification of the North American continent through time (Figure 1) with further focus on some of the major continent-scale transitions between geological provinces. Recognizing that many interesting areas of the conterminous United States will be overlooked in any selection, the choice of regions reflects a compromise between field areas, research topics, and spatial connections among regions.

The boxes shown in Figure 1 are approximate placeholders that broadly encompass the areas that address many outstanding scientific questions about the fundamental processes that form, stabilize, and modify continental crust. While some geological areas are omitted by this selection, focus areas linked by

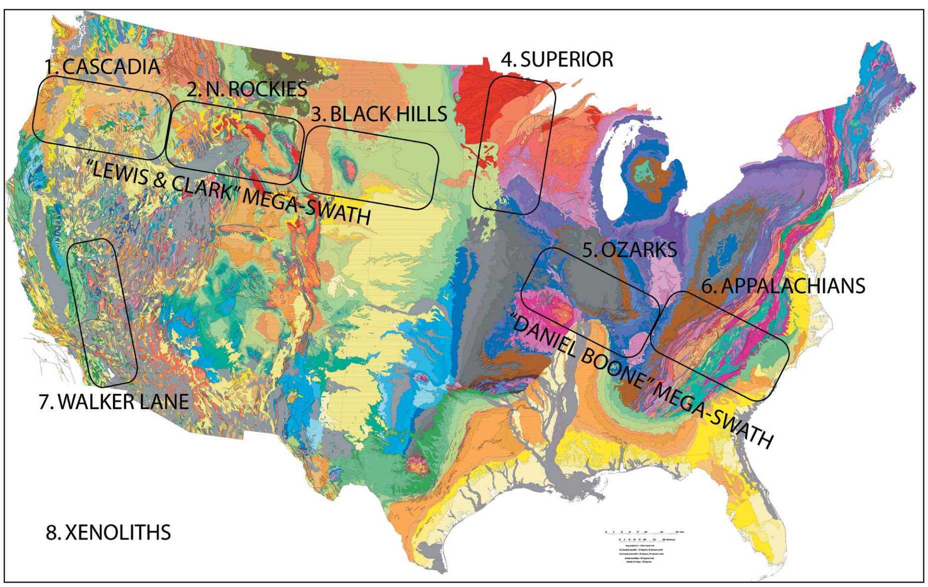

*Fig. 1. Seven of the GeoFrame focus areas placed on the 1974 King and Beikman geological map of the conterminous United States [*Schruben et al., *1994]. The areas collectively constitute a seamless continent-scale experiment, addressing many outstanding scientific questions about the fundamental processes that form, stabilize, and modify continental crust.*

BY B. TIKOFF, B. VAN DER PLUIJM, J. HIBBARD, G. R. KELLER, D. MOGK, J. SELVERSTONE, J. SELVERSTONE, AND D. WALKER

questions posed at the continental scale are compelling at a national scale for both scientific rigor and outreach to a broad community.

Studies within each target area will address fundamental geological questions about the assembly and evolution of the continental lithosphere through time. The areas represent all types of tectonic boundaries (collisional, transpressional, strike-slip, transtensional, extensional) at different times in Earth history (Archean, Proterozoic, Paleozoic, Mesozoic, active). The focus will be on fundamental tectonic processes connected with the building of North America that are best studied within each target area and related to lithospheric and whole Earth plate tectonic processes. The areas collectively constitute a continent-scale experiment.

1. *Cascadia:* The Pacific Northwest offers the best place in the conterminous United States to investigate an active subduction zone, the process of magmatic addition to the continental crust (Cascadia arc, High Lava Plains, Idaho batholith), and the interaction of deformation and magmatism. This is also potentially the best area in the North American Cordillera to study tectonic accretion and subsequent modification of the lithosphere.

2. *Northern Rockies:* The Northern Rockies have a diverse and extensive geologic history that is recorded in rocks that range from ancient (>3.5 billion years old) gneisses of the Wyoming Craton to the modern Yellowstone hot spot/Snake River Plain. The region provides an opportunity to examine two challenging problems in the study of the formation and evolution of continental crust: (1) how newly segregated, low-density crust and lithosphere are integrated into compositionally and structurally mature continents; and (2) how newly formed crust and lithosphere evolve within the continental environment.

3. *Black Hills/Great Plains:* The Black Hills is a type locality of intracratonic deformation, allowing investigation of how displacements/stresses are transferred far into the continental interior. Further, there is a clear indication of crustal- and lithospheric-scale reactivation associated with Laramide uplifts (Black Hills, Bighorn Mountains), although the lithospheric signature of these processes is unknown. It is also possible to investigate large-scale uplift of the entire Great Plains and its possible lithospheric causes.

Together, these first three groups constitute the 'Lewis and Clark' megaswath. The sum of these three areas will allow the examination of modern continental tectonics and the ongoing formation of a mountain belt, and provide a balanced cross section across an entire orogenic belt from hinterland to extended foreland.

4. *Superior:* Located in the Lake Superior Region, this area will allow investigation of the amalgamation of Proterozoic (750 million- to 2.5 billion-year-old) terranes to an Archean (older than 2.5 billion years old) margin and the nature of an Archean tectosphere/Proterozoic lithosphere boundary. The Midcontinent rift cuts both the Archean tectosphere and Proterozoic lithosphere, allowing investigation of how both of these fundamental lithospheric types are altered by superimposed tectonism and magmatism.

5. *Midcontinent:* This area encompasses the Ozark Plateau, the Mississippi Embayment, the New Madrid seismic zone, and the Illinois Basin, which allows scientists to address many questions pertaining to the assembly and behavior of the North American craton. These questions include the location and character of fundamental Proterozoic lithospheric boundaries, the geodynamic role of the approximately 1.4 billion-year-old felsic igneous event, the lithospheric signature of intracratonic uplifts and basins, and the cause of local weakness of the Midcontinent cratonic lithosphere in the New Madrid seismic zone.

6. *Appalachians:* Studies of the Appalachian region allow scientists to investigate the assembly and breakup of supercontinents through two major cycles; specifically, the Proterozoic breakup of the Rodinia supercontinent and the Paleozoic-Mesozoic assembly/breakup of the Pangea supercontinent. The southern Appalachian orogen is the best locale to investigate the response of the lower lithosphere to intense Carboniferous (~360–295 million years ago) crustal shortening during the formation of Pangea. This region also allows investigation of the tectonic nature of a 'passive' continental margin characterized by magmatism and uplift within the last 50 million years and ongoing seismicity.

The Midcontinent and Appalachian segments constitute the 'Daniel Boone' megaswath. As with the 'Lewis and Clark' megaswath, the sum of these areas allows for the investigation of lithospheric architecture and formation of a large mountain belt that spans more than half a billion years, from hinterland to foreland.

7. *Walker Lane:* The Walker Lane Belt, situated in the western Basin and Range province, will seamlessly integrate surface geology, topography, and the history of the continental lithosphere with ongoing processes in the Earth's mantle. Specifically, the area allows study of the present modification of continental lithosphere by the process of transform faulting and rifting. Studies here will leverage the NSF Margins initiative in the Gulf of California by extending the scientific investigations onshore from the Gulf of California to the north into Nevada.

(The first GeoFrame-inspired workshop was held in Reno, Nev., 15–16 May 2006, to address the Walker Lane region. The workshop provided a constructive environment for geologists and geophysicists to learn from each other, mesh expertise, and design investigations to provide the best scientific return.)

8. *Xenoliths:* Collaborative, integrated studies of mantle and crustal xenoliths, or inclusions of other rock types into igneous intrusions, will provide an essential context for both the geologic and geophysical observations throughout USArray. Participants at the February meeting recommended that development of a national xenolith database be considered as an eighth GeoFrame focus area. A 28 May workshop aimed at defining the structure of such a database was sponsored by the EarthChem effort at the 2006 Geochemical Earth Reference Model (GERM) meeting. This workshop was partly inspired by the GeoFrame group.

Future Work

Study of the seven regions should proceed in an intensified fashion, in concert with planned USArray steps such as the 'BigFoot' array, consisting of broadband seismometers spaced every 70 kilometers. Specifically, this stage of investigation would entail map-scale 'densified' arrays of passive source seismic receivers ('LittleFoot' array, a set of ~400 broadband seismometers) and associated active source seismic studies and complementary geophysics, in conjunction with geologically based synthesis and targeted studies.

Workshop participants agreed that detailed planning is now urgently needed to outline studies necessary for each area, and that this planning should be conducted at open workshops where geologists who are familiar with the major questions of the region collaborate with geophysicists cognizant of USArray collection parameters and capabilities, and deeper lithosphere linkages. These integrated working groups would then determine how this data set is best used to address problems related to the evolution of continental crust and underlying mantle.

Moreover, the GeoFrame initiative optimizes public outreach for EarthScope science: Observable geological phenomena uniquely motivate audiences, including educators, scientists, politicians, and the general public. The success of EarthScope requires communication and involvement with and by these groups. GeoFrame can provide a compelling outreach program to the public by a wide range of products and activities that can be conveyed at colleges, K-12 schools, museums, and national and state parks. GeoFrame would provide an enhanced conceptual view of the Earth and the geological processes underfoot. Although the development of an education and outreach component of the GeoFrame initiative is in a nascent phase, it is integral to the concept and presents a unique opportunity for the Earth sciences as a whole.

It is appropriate that 2006 was the year for the formulation of GeoFrame, as it is also the bicentennial of the Lewis and Clark expedition. While only the western extent of GeoFrame roughly follows its path, the more significant similarity is its outlook. GeoFrame is an intellectual successor of that early voyage of discovery; it seeks to understand the 'what is out there,' tangible nature about the place in which we live through collaborations that work together with, build upon, and go beyond EarthScope. The GeoFrame initiative has the potential to transcend regional geologic and geophysical studies by integrating such studies on a national scale to address continent-wide questions. GeoFrame promotes a cultural change in U.S. Earth sciences research, while simultaneously offering broad intellectual and outreach goals.

Acknowledgments

Thanks to all workshop participants for spirited, open-minded interactions, and to the speakers—Casey Moore (University of California, Santa Cruz), Julie Morris (Washington University, St. Louis), Ron Clowes (University of British Columbia, Vancouver), David Simpson (Incorporated Research Institutions for Seismology (IRIS), Washington, D.C.), and Craig Jones (University of Colorado, Boulder)—for providing stimulating and motivating talks. Thanks to John Geissman and Gary Fuis for editorial help. The workshop was supported by the NSF (EAR-060162) and a grant from ExxonMobil for graduate student participation.

References

Schruben, P. G., R. E. Arndt, W. J. Bawiec, and R. A. Ambroziak (1994), Geology of the conterminous United States at 1:2,500,000 scale: A digital representation of the 1974 P. B. King and H. M. Beikman map, *U. S. Geol. Surv. Digital Data Ser., Rep. DDS-0011.*

Author Information

Basil Tikoff, University of Wisconsin-Madison; E-mail: basil@geology.wisc.edu; Ben van der Pluijm, University of Michigan, Ann Arbor; E-mail: vdpluijm@umich.edu; Jim Hibbard, North Carolina State University at Raleigh; George Randy Keller, University of Texas at El Paso; David Mogk, Montana State University, Bozeman; Jane Selverstone, University of New Mexico, Albuquerque; and Doug Walker; University of Kansas, Lawrence.

A Natural Laboratory to Study Arsenic Geobiocomplexity

PAGES 221, 225

Research on seafloor hydrothermal activity has focused primarily on deep-sea black smoker-type locations, which are found along volcanically active portions of the mid-ocean ridges and in deep back-arc basins. Submarine hydrothermal activity, however, is not confined to deepwater environments. Hydrothermal vents have been documented on the tops of seamounts, on the flanks of volcanic islands, and in other near-shore environments characterized by high heat flow. Their easy accessibility, relative to deep-sea hydrothermal systems, makes them excellent natural laboratories to study a wide range of chemical, physical, and biological processes.

Approximately 30 active marine shallow-water hydrothermal systems are currently known. They can introduce toxic elements, such as arsenic (As), antimony (Sb), mercury (Hg), and thallium (Tl) into the coastal ocean, as well as nutrients such as iron (Fe) and carbon (C). Thus, their discharge can have considerable impact on the chemical composition of the biologically important coastal ocean.

One such shallow-water hydrothermal system is in Tutum Bay, Ambitle Island, Papua New Guinea (Figure 1), and it provides an exceptional opportunity to study ecosystem response to elevated temperature, acidity, and As levels. Because of the peculiar chemical nature of the Tutum Bay system, As concentrations are extremely high, while other potentially toxic elements are approximately at background seawater levels [*Pichler et al.*, 1999]. The research presented here links As to microbial, foraminiferal, meiofaunal, and macrofaunal invertebrate diversity and community structure in pore fluids, the water column, and sediments, with high As levels correlating with low species diversity.

The study of As is particularly timely and has become the focus of the scientific community because of epidemic poisoning by As-rich groundwater in Southeast Asia and the enforcement of a new As drinking water standard of 10 micrograms per liter (down from 50 micrograms per liter) by the U.S. Environmental Protection Agency since January 2006.

By T. Pichler, J. P. Amend, J. Garey, P. Hallock, N. P. Hsia, D. J. Karlen, D. R. Meyer-Dombard, B. J. McCloskey, and R. E. Price

Arsenic, pH, and Temperature in Tutum Bay

The submarine hydrothermal springs in Tutum Bay are located approximately 150 meters offshore at 5–10 meter water depth. Venting occurs as focused discharge of a clear hydrothermal fluid at discrete ports, 5–15 centimeters in diameter (Figure 2a), and as diffuse discharge of gas bubbles (94–98% carbon dioxide; Figure 2b). The hydrothermal waters are slightly acidic (pH ~6) and of predominantly meteoric origin. The concentration of As in the hydrothermal fluid is approximately 1000 micrograms per liter, and the combined As release into Tutum Bay is as much as 1.5 kilograms per day.

The sediments in Tutum Bay are mostly weathering products of volcanic rocks, and are heavily coated with hydrous ferric oxides (HFOs) near the vents, gradually decreasing with distance. Starting at approximately 200 meters away from the area of hydrothermal venting, the sediment composition is carbonate-dominated. At a reference site beyond the influence of hydrothermal venting (Figure 1), the sediments consisted entirely of calcium carbonate, thus providing a suitable 'non-hydrothermal' material for comparison with the Tutum Bay sediments.

Fieldwork was carried out in November 2003 and May 2005, the ends of the dry and wet seasons, respectively. To study the transition from hydrothermal to 'normal' marine conditions, a sampling transect was established that started at Vent Four in the northern portion of the hydrothermal area [*Pichler et al.*, 1999] and continued to the west for approximately 300 meters. A multitude of chemical, physical, and biological data were collected along the transect at a sediment depth of 10 centimeters, with emphasis on As in the sediment, and As, pH, and temperature in the pore water (Figure 3). Great care was taken to assure that measurements were made at exactly the same location where samples were collected, and that all team members worked on subsets of the same samples. With few exceptions, As concentration and temperature decreased with distance from the

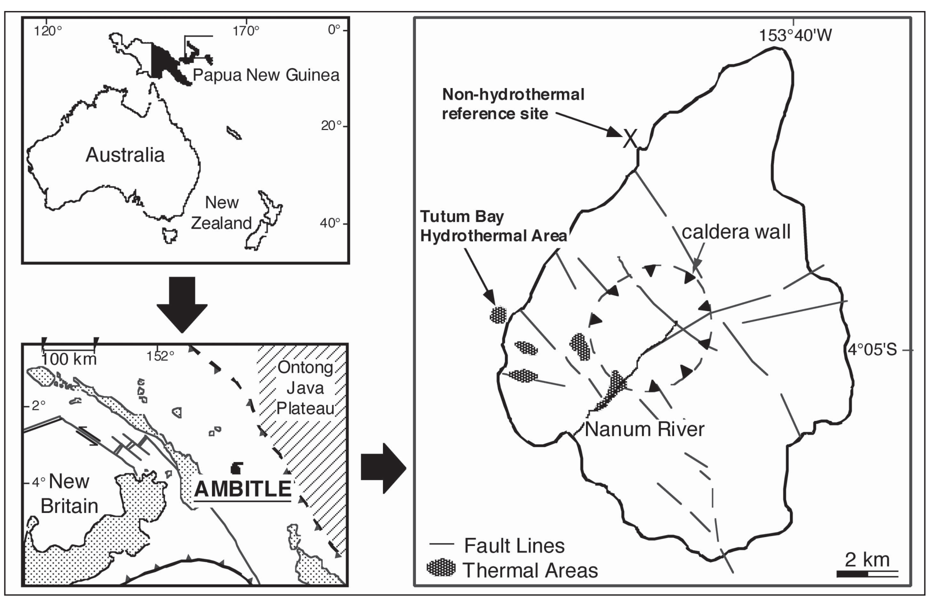

Fig. 1. Location of Ambitle Island and the shallow-water hydrothermal vents studied. Tutum Bay hydrothermal area and the control site are indicated [from Pichler et al., *1999].*