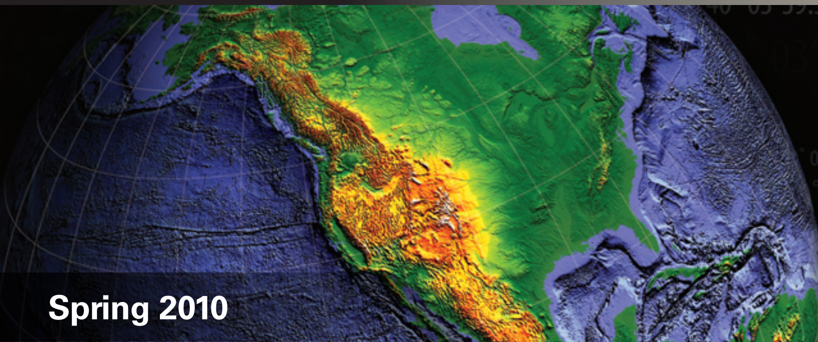

inSights
the EarthScope newsletter
Spring 2010

EarthScope News

Students from the University of Arkansas at Little Rock practice using a GPS unit and modem during the 2009 Student Siting Workshop field trip.

- The **EarthScope Science Plan** for 2010-2020, 'Unlocking the Secrets of the North American Continent,' is available at www.earthscope.org/ESSP. For a printed copy please contact earthscope@coas.oregonstate.edu.
- The **NSF EarthScope program deadline** (www.nsf.gov/funding/pgm_summ.jsp?pims_id=501035) is July 16, 2010.
- The first **EarthScope Institute: The Spectrum of Fault Slip Behaviors** will be held October 11-14, 2010 in Portland, OR. Visit www.earthscope.org for announcement and application. It will be followed (Oct. 15-16) by a workshop to plan research in Cascadia facilitated by the ARRA Cascadia Initiative.
- Steven J. Whitmeyer (James Madison University) recently took over from Jim Davis (Harvard Smithsonian Center) as **Education and Outreach Subcommittee** chair. Thank you, Jim, for your leadership!
- The **EarthScope Steering Committee**, which oversees EarthScope activities, will soon have an opening. Visit www.earthscope.org/program_data/nominations for information.
- The **Transportable Array (TA)** is crossing the Mississippi. Following an introductory workshop at

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U-Pb Thermochronology: 4-Dimensional Imaging of the North American Lithosphere

As the USArray Transportable Array marches eastward, seismic images are providing ever more detailed insight into present day structures of the crust and mantle beneath North America. But how old are these structures and what do they tell us about the geologic history? Precise age constraints are needed for EarthScope to achieve its goal of producing a 4-D (i.e. time-dependent 3-D) picture of the continental evolution.

In some geological settings, thermochronology can establish the age of formation and the subsequent thermal history of structures revealed by seismic tomography. In Montana, for example, portions of two Archean cratons, the Medicine Hat Block (MHB) and the Wyoming Province (WP), are underlain by lithospheric mantle with higher than average wavespeeds (Figure 1), traditionally interpreted as cold and mechanically rigid lithosphere. With U-Pb thermochronology of lower crustal xenoliths that erupted ca. 50 Ma, we can "date" tomographically inferred features and determine the region's thermal history.

Thermochronologic techniques, including U-Pb, $^{40}Ar/^{39}Ar$, and (U-Th)/He systems, allow scientists to constrain the time-temperature (t-T) evolution of rocks. The temperature-dependent diffusive loss of daughter isotopes in the systems can be quantified by volume-diffusion theory to yield reliable, temperature-sensitive dates. The relatively slow diffusive transport of Pb allows U-Pb thermochronology to quantify cooling rates as rocks pass through moderate to high thermal windows (400-700°C) representing cooling histories at 20-50 km depth. At these depths the lower crust contains accessory minerals such as rutile (TiO_2) and titanite ($CaTiSiO_5$), which are amenable to U-Pb dating. Constraints on sample residence depth are derived from geobarometric and sample wavespeed measurements. Lower crustal xenoliths yield thermal histories over tens to hundreds of degrees over hundreds of millions of years. This protracted slow cooling indicates a thick cratonic keel that insulates the deep crust from mantle heating and a crustal cover that insulates the lower crust from rapid cooling. Thermal model calculations that include the xenolith thermal history and residence depth place constraints on the thermal history of the underlying lithosphere (Figure 2). Because seismic velocity of mantle lithosphere is intimately linked to composition and temperature, the age of these anomalies may be best constrained by combining traditional mantle xenolith studies with lower crustal thermochronology.

Outcrops and potential field data delineate the two Archean terranes, the MHB and the WP. An ENE-WSW trending gravity anomaly between the terranes, the Great Falls Tectonic Zone (GFTZ), is interpreted as a suture. Zircon U-Pb geochronology of lower crustal xenoliths reveals a punctuated high-temperature history beginning with craton formation ~2.5-2.7 Ga followed by pervasive magmatic events between ~2.2 and ~1.7 Ga, the later time being consistent with GFTZ formation. U-Pb thermochronology shows no Archean cooling history but instead yields only Proterozoic and younger dates that span up to 800 Ma for a single sample. The youngest measured date in each range corresponds to the smallest rutile crystals

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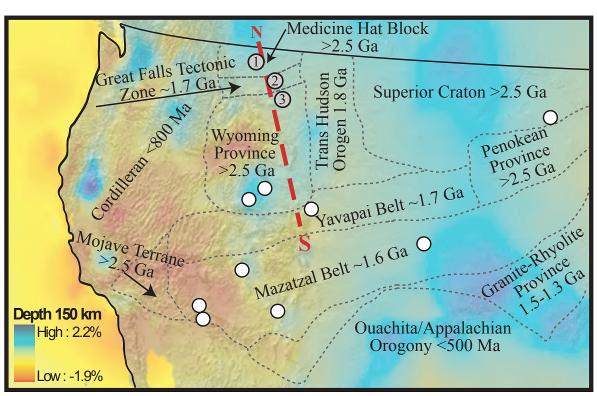

Figure 1: Digital elevation model image with major Proterozoic and Archean boundaries on seismic velocity variations at 150 km depth. Labels indicate terrane name and crystallization age, with Archean terranes labeled >2.5 Ga. In Montana, the Medicine Hat Block and the Wyoming Province (WP) are underlain mostly by higher than average seismic wavespeeds; slow regions in the WP are related to the young Yellowstone thermal anomaly. U-Pb lower crustal thermochronology from xenolith suites (grey circles marked 1-3) across strike of the orogen constrain the thermal evolution of the region's lithosphere. The xenoliths were exhumed ~50 Ma and thus do not record thermotectonicsm associated with Yellowstone. Additional lower crustal xenoliths (white circles) have been collected for future work.

EarthScope News

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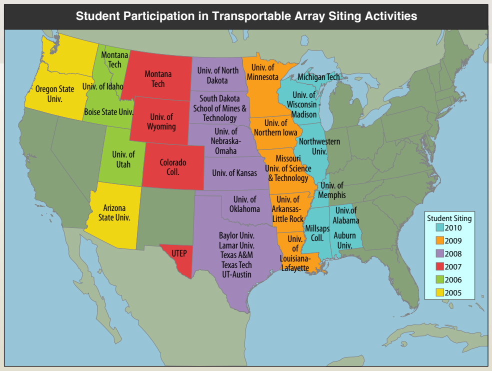
Purdue University (May 24-27), 12 students from Michigan Tech, Millsaps College, Auburn University, Northwestern, University of Wisconsin-Madison, University of Memphis, and University of Alabama, will spend 9 weeks conducting computer-based analyses and field investigations to recommend the best locations for over 130 TA stations east of the Mississippi. Station installation will begin in 2011.



- **Transportable Array (TA)** data from the M 8.8 February 27, 2010 Chile earthquake have been used to image the fault rupture. For a movie of spatial and temporal energy release during the earthquake, see http://seismology.harvard.edu/projects/chile/. The TA also shows multiple surface wave orbits (www.iris.edu/hq/files/Chile_RS_2010_TA.tiff, courtesy R. Aster, New Mexico Tech) and data are featured in the IRIS Teachable Moment presentation (www.iris.edu/hq/retm).

Op Ed*- InSAR: An Essential Component of EarthScope

A major challenge for EarthScope is to monitor Earth surface deformation over a wide range of spatial and temporal scales and to use this information to infer tectonic and volcanic processes at depth. Seismometers and continuous GPS offer high temporal sampling but only at widely spaced positions (10's of km).

Over the past decade, new geodetic imaging techniques such as synthetic aperture radar interferometry (InSAR) and scanning laser altimetry (LiDAR) have emerged for mapping topography and crustal motion at very high spatial resolution. These technologies have routinely imaged rapid surface deformations associated with earthquakes, volcanoes, and glacial flows and are now being extended towards resolving slow interseismic motions.

EarthScope's science goals require a detailed understanding of how crust deforms over time and where stress accumulates due to ongoing geologic processes. For example, deformation observations over volcanic areas, coupled with seismic measurements, yield images of the internal workings of active volcanoes. Similar observations isolating stress accumulation and transfer along and between fault systems are critical to assess earthquake hazards and to gain insight into the physics of faulting. The Plate Boundary Observatory precisely measures position at GPS sites, but the sparse networks lack the spatial resolution to accurately determine strain accumulation rate along fault zones, even for the densely-instrumented San Andreas Fault. InSAR can yield mm- to cm-level deformation maps at 10's of m spatial resolution over 100 km+ swaths to fill this gap.

The initial 2001 Scientific Targets Workshop identified four observatory components: 1) The USArray, 2) the Plate Boundary Observatory, 3) the San Andreas Fault Observatory at Depth, and 4) an InSAR crustal deformation measurement component consisting of existing international radar satellites and platforms to be developed by the US. The 2001 National Research Council review strongly endorsed all four elements. The first three were successfully installed, while InSAR, despite significant cooperative investments from NSF, NASA, and the USGS, has lagged EarthScope needs. To date, the InSAR contribution to EarthScope science has been limited to data purchases and airborne system development. The new EarthScope science plan recognizes the need for more InSAR data: "Radar measurements of fine resolution, spatially continuous crustal deformation are critical to many of the EarthScope science goals, as they reach inaccessible areas with frequent revisit times. A U.S. radar satellite mission is needed to provide these essential data …"

Meeting this need requires several immediate actions. First, development of a US-owned and operated InSAR satellite is necessary to design orbital coverage and to ensure adequate data delivery systems and procedures. Simply purchasing data acquired by foreign systems designed and operated for other purposes has not yielded the temporally dense and spatially contiguous data sets needed for EarthScope science. It is critical that the EarthScope community support NASA's planned DESDynI mission, the quintessential geodetic imaging satellite recommended by the National Research Council decadal survey. DESDynI contains the radar and laser altimetry instruments capable of producing extremely detailed topography. Mission realization requires strengthening the NSF-NASA partnership and embracing collaborative scientific endeavors. The agencies have a clear role to play, but the community needs to strongly support the mission and deliver requirements and scientific arguments for a system that can meet EarthScope goals.

Second, several international radar platforms produce data that can be applied directly to EarthScope science. The foreign data suppliers request scientific collaboration with the US in exchange for significant amounts of satellite data, and NSF and NASA initiatives are crucial to enable and encourage data transfer. Support of community-based data acquisition and delivery organizations, such as WInSAR, must continue to make these data available to researchers.

Finally, airborne systems such as fine-resolution UAVSAR radar should be deployed regularly to provide InSAR data in EarthScope-relevant areas repeatedly and reliably. Campaign airborne missions to acquire fine-scale LiDAR elevation models also are highly valuable and should be coordinated with ongoing EarthScope investigations.

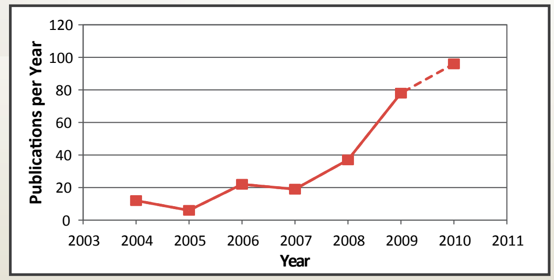
InSAR data greatly extend the scientific foundation for mitigating impacts from earthquakes, volcanoes, and landslides. InSAR observations also help to address subsidence, fluid migration, integrity of levee systems, and carbon sequestration. We hope that the combination of community scientists, affiliated industry, and the US government can collectively provide these important data for the scientific world. ■

By Howard Zebker, Stanford University, Michael Williams, University of Massachusetts, David Sandwell, Scripps Institution of Oceanography, and Andrea Donnellan, Jet Propulsion Laboratory, California Institute of Technology.

*inSights will occasionally include editorial views. Please submit suggestions for topics to the editor.

- **UNAVCO and IRIS** organized rapid responses to the earthquakes in Haiti and Chile. IRIS is leading a community instrument deployment of 60 seismic stations in Chile; for a status of the deployment and updates visit www.iris.edu/hq/chile/. UNAVCO has set up event response web sites for both events to provide and collect information; see www.unavco.org/research_science/science_highlights/2010/M7-Haiti.html and www.unavco.org/research_science/science_highlights/2010/M8.8-Chile.html.

- The **EarthScope web site** (www.earthscope.org) strives to be a meeting place for the EarthScope science community, providing news and highlights, collecting data products and complementary data, assembling an EarthScope publications reference list, and instigating discussion and information exchange at the Thematic Working Groups online forums. We welcome contributions (earthscope@coas.oregonstate.edu) and lively participation.



The number of publications based on EarthScope data (www.earthscope.org/publications) is growing rapidly (2010 projected from 1/10-2/10). Please let us know if your paper is missing or when a new one is published.

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U-Pb Thermochronology: 4-D Imaging of the North American Lithosphere

from the xenolith; the oldest date corresponds to the largest crystals, consistent with the length-scale dependence of diffusion. The large time span indicates prolonged cooling through the Partial Retention Zone (PRZ), a region in t-T space where Pb is partially open to diffusive loss. In general, the slower the lithosphere cools, the longer a mineral phase will reside in the PRZ, resulting in a larger range of radiometric dates between the smallest and largest crystals.

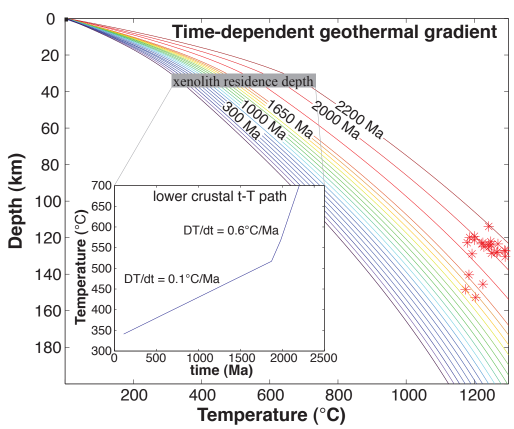

Figure 2: Temperature vs. depth for continental lithosphere in the Northern Wyoming Province, Montana. Time-temperature (t-T) paths from U-Pb thermochronometry (inset) are used to reconstruct the thermal history for an individual xenolith. Geobarometry and sample wavespeeds constrain the t-T history to depth. We can utilize the lower crustal t-T record to thermally model the t-T evolution of mantle lithosphere by extrapolating lower crustal temperatures downward according to lithosphere conductivity while removing contributions of heat-producing elements. Red asterisks mark the previously measured P-T equilibrium of mantle xenoliths from the region. Mantle xenolith P-T data are often used to infer geothermal gradients through the mantle lithosphere. This technique assumes the mantle sample remains in equilibrium even as the geothermal gradient relaxes during cooling. Mantle data from Montana, however, may not have remained in equilibrium during craton cooling and perhaps reflect a hotter and potentially older geothermal gradient than those predicted from the lower crustal xenoliths.

The thermal histories across strike of the orogen are surprisingly uniform (Figure 3). Depending on sample residence depth, lower crustal samples from the Archean and Proterozoic domains record prolonged cooling beginning immediately following collision, ~1.8 Ga, until ~50 Ma when samples were quenched during eruption. The fast seismic anomaly beneath the Archean MHB and WP could, based on upper crust and mantle geochronology, be interpreted as entirely Archean in origin. Lower crustal xenoliths, however, reveal that at 30-50 km depth, the region was heated to 800°C or more during Proterozoic collision. Extrapolating temperatures downward (Figure 2) implies far higher temperatures in the lithospheric mantle and raises the possibility of thermal reactivation and modification by addition of asthenospheric melts. This thermal event was followed by long, slow cooling, suggesting the fast seismic anomalies often associated with stable cratonic regions were not formed until after the Proterozoic collision.

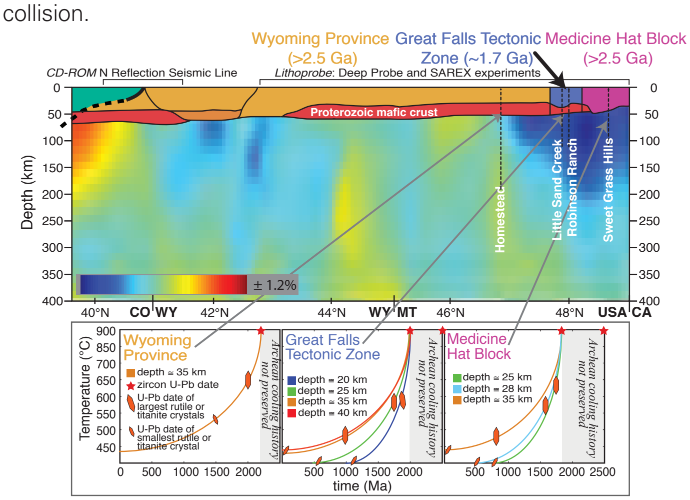

Figure 3: (top) N-S cross-section through the Northern Rocky Mountains along the trend of collected lower crustal suites (heavy red dashes Figure 1). P-wave tomography images the stable regions beneath Montana. A generalized crustal section from the *CD-ROM* and *Lithoprobe* seismic studies caps the cross-section from 0 to 55 km depth. (bottom) t-T paths from samples across the orogen yield similar thermal records with no preserved Archean cooling history due to Proterozoic reheating during craton amalgamation. Following collision, lithosphere cooled rapidly to ~500°C at ~25 km depth within tens of millions of years. The next 1.5 Ga of lithosphere history is recorded by deeper xenoliths, yielding a record of extremely slow cooling towards crustal stabilization and the attainment of low geothermal gradients.

A high-resolution thermochronologic record from the lower crust provides new constraints on the time scales required for the lithosphere to attain the low geothermal gradients measured in cratonic settings today. The near-continuous temperature-time record provided by the lower crustal xenoliths allows us to unravel the tectonic history of cratons, thus connecting the ancient history of lithosphere formation provided by geochronology with observations of the present-day lithosphere produced by geophysics. ■

By Terrence J. Blackburn [a], Samuel A. Bowring [a], Scott Burdick [a], Robert van der Hilst [a], Kevin Mahan [b], Francis Düdas [a], and Katherine R. Barnhart [b], [a]Massachusetts Institute of Technology, [b]University of Colorado Boulder.

See website for expanded version with references.

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the EarthScope newsletter

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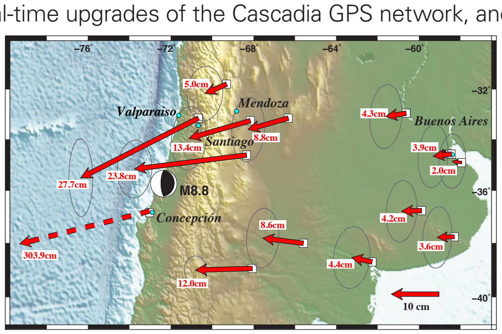
Inside this issue...

EarthScope facilities are funded by the National Science Foundation and are being operated and maintained by UNAVCO Inc. and the Incorporated Research Institutions for Seismology with contributions from the U.S. Geological Survey and several national and international organizations. The newsletter is published by the EarthScope National Office at Oregon State University. The content of the newsletter material represents the views of the author(s) and not necessarily of the National Science Foundation.

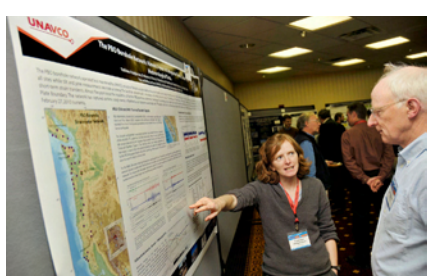
inSights is a quarterly publication showcasing exciting scientific findings, developments, and news relevant to the EarthScope program. Contact earthscope@coas.oregonstate.edu to be added or deleted from the hardcopy mailing list; electronic copies are available at www.earthscope.org/publications/onsite. Editor: Jochen Braunmiller, OSU/EarthScope National Office, jbraunmiller@coas.oregonstate.edu. Production Editor: Charlotte Goddard, OSU/EarthScope National Office, cgoddard@coas.oregonstate.edu

Exciting Year for Geodesy at UNAVCO 2010 Science Workshop

In a year already marked by the fifth largest earthquake on record (M 8.8, Chile, February 27) and the earthquake with the fourth largest death toll since 1900 (230,000 in Haiti, January 12), there was much to be done at UNAVCO's Science Workshop. Over 150 national and international scientists and 15 students convened March 8-11 in Boulder, CO to share results. Attendees were treated to up-to-the-minute observations from both earthquakes, including this map of the coseismic displacement field for the Chile earthquake (courtesy J. Foster and B. Brooks, University of Hawaii). Impressive PBO-related results included presentations about the use of real-time GPS data streams for earthquake early warning, the progress on real-time upgrades of the Cascadia GPS network, and the successful collection of five years of integrated strain, seismic and meteorological data at 78 borehole sites. Several posters highlighted PBO GPS instruments capturing



earthquake events, including a swarm in Yellowstone National Park and a M 6.5 earthquake offshore Eureka, CA that both occurred in January 2010, and a series of explosive eruptions of Mt. Redoubt, AK in early 2009. All abstracts and presentations are posted at www.bit.ly/4KYa32. In addition to plenary and poster sessions, a set of parallel Special Topics Sessions ranging from 'Quantification of earthquake recurrence' to 'LiDAR: shedding light on Earth science' to 'Global science capacity building,' played an important role outlining challenges and opportunities for geodesy that allowed lively discussions among participants. UNAVCO and the National Association of Geoscience Teachers held a pre-meeting workshop on March 8, 'Teaching Geodesy in the 21st Century.' Participants learned how to increase geodetic content in course material and improve teaching using materials that include PBO GPS data. More information at serc.carleton.edu/NAGT Workshops/geophysics/geodesy/index.html. ■



K. Hodgkinson (UNAVCO) discussing the borehole network.