Maximum **scope**

A distinctive group of researchers on the EarthScope Bighorn Project are using innovative approaches in seismology and structural geology to study the formation of the Laramide Rocky Mountains. **Dr Christine Siddoway,** one of four female investigators in the team, explains their work

DR CHRISTINE SIDDOWAY

Could you begin by introducing the Earthscope Bighorn project and highlighting the reasons for its establishment?

The EarthScope Bighorn Project is an integrated geological and geophysical investigation of the Bighorn Mountains in Wyoming. The aim of the multi-institution interdisciplinary investigation, led by University of Wyoming investigator Eric Erslev, is to identify the process of formation for some of the 'signature' mountain ranges of the North American West: the Laramide Rocky Mountains. Unlike many active mountain belts (orogens) of the world such as the Andes, Himalayas, New Zealand Alps or St Elias ranges that developed upon plate tectonic boundaries, the vast mountains of the Laramide Rockies formed well within the continental portion of the North American tectonic plate, far from a zone of plate convergence.

What is the significance of using geology and geophysics to study the Rocky Mountains in particular?

The Bighorn Mountains have a structural architecture that is so well known to geologists worldwide that it serves as an archetype for within-plate, intracratonic deformation. One thing that geologists perceive but that it is perhaps difficult for the casual traveller to appreciate is the phenomenal scale of the structure: there is a difference in elevation of 10,000 m from the 'basement'-cover contact beneath the adjoining Bighorn Basin to its restored position over the top of the mountain range.

Are you able to provide a brief background on the Laramide orogeny of the Bighorn Mountains? Have your studies provided any further insight into this phenomenon?

The Laramide Orogeny occurred during plate convergence between the Farallon and North American tectonic plates during the time period 75-45 million years ago. Distinctive aspects of the orogeny are: the involvement of crystalline basement in the near-surface faulting ('thick-skinned' deformation); the migration of diffuse magmatism and distributed deformation into the continental foreland, distant from the plate boundary zone; and the formation of large asymmetric sedimentary basins between basement-involved uplifts. In the Rocky Mountains, deformation produced an anastomosing array of basement-cored arches separated by lens-shaped foreland basins. Estimates of the amount of shortening necessary to form the Bighorn arch ranges from 8-13 per cent. Rather than fold-thrust style deformation, the Laramide features large-scale anticlinal structures that are either asymmetrical and bounded by thrust faults, or symmetrical, with smaller reverse faults on both limbs.

Are there unanswered questions that the Bighorn project seeks to address?

Paradoxically – in light of the scale of the Bighorn range and the large number of geology visitors – there is not a consensus about which of the multiple hypotheses proposed for the formation of the prodigious arch best explains its form. The mechanism for shortening of strong Archean lithosphere has long been unresolved due to lack of geophysical imaging. The Bighorn Project seeks to obtain a 3D seismic image of the integral structures that form the architecture of the range, and thereby to test the four principal hypotheses that have been proposed to explain the Bighorn Mountains intracratonic arch.

How important has collaboration been to the project?

There is extraordinary harmony and cooperation among the collaborative group, with strong communication and collaboration between the graduate and postdoctoral researchers at the various institutions. This makes for the strongest possible interpretations of the 3D/4D architecture of the Bighorn arch that are derived from multiple independent methods

Is it significant that the project is led by – and involves a high proportion of – women participants?

I believe this is a really distinctive and unusual aspect of the Bighorn Project. Considering the demographics of the Earth sciences community in the US, the rich collaboration among women researchers who have a leadership role as Principle Investigators (PIs), and the number of women students who are contributing to the research is notable. Four of the six PIs and both postdoctoral researchers on the project are women. In addition, the project has supported two MSc and four undergraduate women researchers. For us participants, the experience has been exemplary as an affirmation that capable and innovative female researchers are attaining leadership stature in Earth sciences, a field that has historically been dominated by men at the top levels. We feel a great optimism about the future prospects for influential future contributions by female researchers who received academic training and advanced their professional standing through participating in the Bighorn Project.

Big discoveries in the **Bighorns**

A group of **EarthScope** researchers are making important discoveries about the formation of intracratonic mountains, in an integrated geoscience project that has wide-reaching impacts

THE STRIKING APPEARANCE of the Bighorn Mountains has long fascinated geologists and tourists alike. The crystalline rocks and the layered sedimentary rocks that cover them form an elongated, doubly-plunging arch, which visitors can actually see when they observe that the sedimentary layers on the east side of the range slope down to the east, and those on the west dip to the west. On the outer flanks of the range, geological faults cut through the rock creating abrupt changes in the angle of the layers, as Dr Christine Siddoway, a Principal Investigator for the EarthScope Bighorn Project, explains: "The high, interior parts of the Bighorn Mountains are underlain by crystalline-textured granite and gneiss that have properties of great strength and resistance to erosion. The granites and gneisses – often referred to as 'basement' rocks – have these characteristics partly because they are of great age, but also because they formed at depth in the Earth's crust during the Archean Eon, more than 2.5 billion years ago".

MECHANISMS OF FORMATION

The process of formation of the basement arch is the focus of the EarthScope Bighorn Project, which addresses not solely the Bighorns but also seeks to increase understanding of the structures responsible for within-continent deformation, as Siddoway outlines: "Our findings apply to an array of global problems, ranging from lithosphere-scale linkage of foreland arches to plate tectonics and regional fracture patterns in basement-involved orogens that commonly control oil and gas production". The team of Bighorn Project investigators hope to determine the mechanisms that drive the formation of basement-involved arches, like the Bighorns, which will greatly advance knowledge of intra-continental deformation worldwide. In doing so, this research deepens the understanding of continental lithospheric rheology, one of the fundamental problems in plate tectonics.

AN INTEGRATED PROJECT

As an integrated Geoscience initiative, the EarthScope Bighorn Project brings together an innovative combination of approaches to its study of the range. Notably, these are:

- The use of a hybrid active/passive high-resolution seismic studies
- The use of iterative retrodeformation techniques that balance surface areas and 3D volumes to develop GIS-based geometric/kinematic models of the upper crust over time-integrated steps
- The involvement of student participants who undertake individual research, through internship training and as academic theses that are part of the Bighorn Project

SEISMIC SOLUTIONS

The first of these encompasses the Bighorns Arch Seismic Experiment (BASE), which in 2010 was successful in imaging the crust and mantle below the Bighorn Arch by carrying out an active-source wide-angle reflection and refraction survey led by Kate Miller and Steve Harder. This allowed project researchers to measure crustal velocity and thickness, and identify large-scale structures: "Extraordinarily high-resolution images were obtained through use of 21 seismic shots recorded on 1,800 'Texan' dataloggers, with 4.5 Hz vertical component geophones," Siddoway explains. The visionary experiment produced 15,000 total travel times for inversion, obtaining the first high-resolution P-wave velocity models of the crust and upper mantle of the Bighorn region.

The project employs passive seismic data, recorded principally from broadband

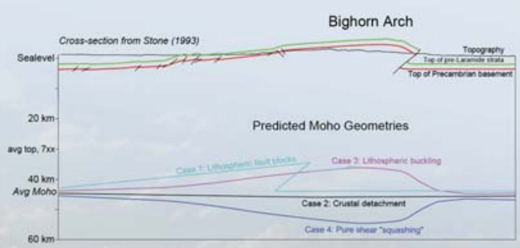

FIGURE 1. Simplified cross section of the Bighorns Arch, showing four contrasting Moho geometries for the four lithospheric models being tested. Scenarios one and four have been ruled out.

DOCTORAL STUDENT WILL YECK AND INTERN AUSTIN ANDRUS AT WORK INSTALLING A BROADBAND SEISMOMETER instruments, such as the EarthScope USArray and BASE's EarthScope FlexArray. Investigator Anne Sheehan conceived the innovative use of 850 of the Texan instruments as recorders for naturally occurring distant (teleseismic) earthquakes. Siddoway elaborates: "Traditionally, the 'Texan' instruments are used solely as active sensors, so it is an innovation in our experiment to extend their use to the passive realm as a means of enhancing the continuity of the seismic imaging". Meanwhile, Dr Megan Anderson at Colorado College uses the broadband seismic data to refine the team's understanding of the structure of the deeper lithosphere, by examining the frequency dependence of splitting for teleseismic shear waves (shear wave splitting analysis). Anderson's work tests whether the asthenospheric mantle 'fabric' that is delineated by shear wave transmission behaviour is due to shearing in response to current North American absolute plate motion or whether the anisotropy is a residual product of Archean tectonism.

INTERPRETING AND CORRELATING

Dr Eric Erslev at the University of Wyoming and Siddoway at Colorado College have been correlating the seismic interpretations with structural geology datasets obtained from fault arrays in the field by graduate and undergradute students. "The faults provide geometrical, kinematic and temporal control on the lithospheric scale structures from seismology," details Siddoway. Through procedures designed to test the viability of competing models for arch formation, a grand scale 4D model is being developed, tested and refined by Erslev, using innovative methods of 3D structural balancing.

STRIKING DISCOVERIES

The project findings indicate that the Bighorn arch was formed upon a pre-existing (probably Precambrian) fault, which acted as a nucleation point for a ramp that broke upwards from a sub-horizontal detachment at a depth of around 30 km. The researchers have discovered a prevalence of strike-slip faulting that accompanied the 'characteristic' Laramide contractional deformation: "We document distributed strike slip in wide zones of pervasive fracturing and shear that correspond with pronounced topographic lineaments within the crystalline rocks of the arch core, and within a zone along the northern limit of the Bighorn arch". The project is testing whether relative displacements across these zones are responsible for the development of the vast basement arch with its overarching anticline observed in the sedimentary cover rocks. Excitingly, the 4D Earth model of the Bighorns is nearing completion. Based on key seismic constraints provided by the 3D configuration of the Moho and mid-crustal interfaces imaged by BASE, it will enable the fuller visualisation of the temporal dimension of formation process.

COLLABORATION ACROSS THE BOARD

Central to the goals of the Bighorn Project is not only the strong collaborative ethos between PIs and institutions, but the involvement of student participants. The Bighorn Project included contributions from studies undertaken by more than 10 Masters, doctoral and postdoctoral researchers, and helped to facilitate an industry internship that allowed one student to gain proficiency with the use of ELFEN software. Individual research was conducted by more than 20 undergraduate students, through the Keck Geology Consortium programme, Integrated Research Institutions for Seismology (IRIS) internships, and thesis-research opportunities from the project's participating institutions. Proving its commitment and impact across all levels of study and research, further education and training opportunities were provided to over 40 volunteers from schools around the country.

FIGURE 2. Shaded relief digital elevation model of the Bighorn Mountains, Wyoming. The white area corresponds to the elevated terrain that approximately corresponds to the crest of the elongate NW-SE-orientated structural arch.

WIDE-RANGING OUTREACH

Dissemination is a key component of the EarthScope Bighorn Project's objectives. It aims to give access to its 4D models to education and training programmes and enable participation from geologists across academia and industry. As well as this, the project's PIs will continue to disseminate in peer-reviewed publications, at conferences and through online resources: "The valuable seismic datasets from passive and active source instruments will be available after the proprietary period via the IRIS PASSCAL data repository and archive," Siddoway outlines. Other data recorded during EarthScope's USArray Transportable Array (TA) field campaign have already been disseminated within the USArray community. Whilst the delimitation of the lithospheric-scale structures is notable, continued work is needed to resolve the crustal-scale faults within the crystalline core of the Bighorn arch and their influence upon seismic wave transmission. This will not only impact on our knowledge of the Bighorns, but will help accomplish the aim of the national EarthScope programme to characterise the lithosphere in the mid-continent and cratonic regions of North America.

INTELLIGENCE

BIGHORN PROJECT

FORMATION OF BASEMENT-INVOLVED FORELAND ARCHES: AN INTEGRATED EARTHSCOPE EXPERIMENT

OBJECTIVES

The EarthScope Bighorn Project is an integrated geological and geophysical investigation of the enigmatic basement-involved foreland arches that formed the Bighorn Mountains of Wyoming. The project employs innovative integration of geological and seismological research.

KEY COLLABORATORS

Eric Erslev, University of Wyoming

Kate Miller and **Lindsay Worthington**, Texas A&M University

Anne Sheehan, **Ziaohui Yang**, **Colin O'Rourke**, and **Will Yeck**, University of Colorado – Boulder

Steve Harder, University of Texas – El Paso

Christine Siddoway and **Megan Anderson**, Colorado College

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CONTACT

Dr Christine Smith Siddoway
Professor of Geology

Geology Department
Colorado College
Colorado Springs
CO 80903
USA

T +1 719 389 6717
E csiddoway@coloradocollege.edu

www.bighorns.org

www.coloradocollege.edu/dept/GY/faculty_christine_siddoway.asp

DR CHRISTINE SMITH SIDDOWAY

graduated with a BA from Carleton College in 1984, before studying for an MSc at the University of Arizona in 1987 and attaining her PhD from the University of California – Santa Barbara in 1995. She is currently Professor of Geology at Colorado College, where her research interests include structural and metamorphic geology, Gondwana tectonics and tectonic evolution of the Rocky Mountain foreland.

COLORADO COLLEGE