

EarthScope Synthesis Workshop

Life and Death of a Craton: A 4D EarthScope perspective on the role of the Wyoming Craton in the evolution of North America

Montana State University

January 10-13, 2019

Workshop Goals

1. Synthesize what we have learned about the evolution of the Wyoming Craton, integrating EarthScope-derived data with other extant scholarly research since the 2005 EarthScope in the Northern Rocky Mountain workshop;
2. Identify major research questions within the overall 4-D evolution of the Wyoming Craton and its place in the assembly of Laurentia/North America, based on integration of all components of EarthScope science (geology, geophysics, geochemistry, geochronology....), and the scientific evidence available (or needed) to address these questions.
3. Outcomes: a) Workshop report summarizing the central questions, findings/interpretations, and vision for future research; b) a writing plan for follow-on synthesis articles (possibly as a themed volume) with writing groups, topics, and timelines identified; and
4. Education and outreach plan to translate EarthScope science to formal and informal educational venues.

January 10 (Thursday)

Travel day; **Check in at Lewis and Clark Hotel; Dinner 7:00 PM** (meet in hotel lobby at 6:45 for shuttle to restaurant, Open Range (Main Street)); Introductions; Overview; Logistics; Goals and Outcomes

January 11 (Friday) Montana State University Student Union Building Room 233

Daily Theme: What do we know? What have we learned about the composition, architecture and evolution of the crust/mantle system as a result of EarthScope science in (under) the Wyoming Craton?

[12 minute talks, 5-6 slides/presentation; 3 minute discussion: What “big” questions are addressed? What are the key findings and their significance? Next steps towards an integrated understanding of the North American continent?]

8:00 Breakfast service SUB 233 (Student Union); Network, make a new friend!

Overview and Context

8:30 Dave Mogk; welcome, logistics; Context and Overview (review of 2005 EarthScope in Northern Rockies workshop); workshop goals and anticipated outcomes

8:45 Suzan van der Lee, Gene Humphreys, Heather Ford: Results of the EarthScope 4-D Evolution of North America workshop: The challenges of connecting surface geology to EarthScope-resolved features

Crustal Genesis (Archean petrogenesis, tectonics [plate or not]....)

9:00 Paul Mueller—The Wyoming Province: A Unique Archean Craton

9:15 Dave Mogk—TTGs We Have Known and Loved: 1.5 Ga of Growth and Recycling of Archean Continental Crust in the Northern Wyoming Craton (NWC)

9:30 Carol Frost—The Archean geologic history of the southern Wyoming Province: a focus on the extent of ancient crust and time of cratonization

9:45 Darrell Henry—Archean Metamorphic history of the northern Wyoming Province (NWP); implications for Precambrian plate tectonics, level of exposure across the NWP vs. metamorphic grade.

10:00 David Bowen— The View from (of) the Top: Considerations of the Phanerozoic Stratigraphic Cover on the Wyoming Craton

10:15 BREAK

Precambrian Crustal Evolution (assembly, reassembly, reworking, mobilization of the Wyoming Craton; Late Archean through Paleoproterozoic)

- 10:30 **Kevin Chamberlain**—Some Key Observations Pertinent to the Formation and Stabilization of the Wyoming Province
- 10:45 **Jen Gifford**— Lessons Learned from the Great Falls Tectonic Zone, Medicine Hat-Wyoming Suture: Crustal xenoliths and the Little Rocky Mountains
- 11:00 **Julie Baldwin**— Paleoproterozoic metasupracrustal suites on the NW flank of the Wyoming Province: insights into an evolving continent
- 11:15 **Jeff Vervoort**— Neoproterozoic and Paleoproterozoic crystalline basement rocks of the Clearwater and Priest River complexes: Constraints on the formation of western Laurentia
- 11:30 **Ryan Wilhelmi**—Nothing Quiet on the Western Front: Late Archean to Neoproterozoic Evolution of West-Central Laurentia
- 11:45 **Kevin Mahan** – Deep crustal structure, processes, and properties from xenoliths, basement exposures, and seismic observations in the northern Rocky Mountain region
- 12:00 **Lunch**—Catered, Room 230 SUB

Post-Cratonization Geologic History/Contemporary Structure

- 1:00 **Dave Mogk/Paul Mueller/Carol Frost**: Some Reflections on the Mesoproterozoic Belt-Purcell Basin
- 1:15 **Tom Kalakay**—From Contraction to Extension: Tectonomagmatic Architecture of the Sevier Orogenic Wedge of Western Montana

What's Up With the Mantle?

- 1:30 **General Discussion**: What can we learn from magnetotellurics about deep crustal structure, shear zones, hydration of the crust and controls on crustal strength?

1:45 **David Snyder:** Weakening Cratons by Metasomatism: Conductivity Maps the Alteration

2:00 **Heather Bedle:** Synthesis of regional-scale geophysical, geochemical, and thermal models of the crust and upper mantle beneath the Wyoming craton

2:15 **Katie Cooper:** The Making and Breaking of Cratons

2:30 **Break**

2:45 **Suzan Van Der Lee:** The Wyoming Craton is no Longer a Craton

3:00 **Gene Humphreys:** Laramide-age growth of the Wyoming Craton by ocean plateau under-accretion

3:15 **Vera Schulte-Pelkum:** Deformation and Structural Evolution of the Deep Crust and Lithosphere from EarthScope Seismic Data and Geological Ground Truth

3:30 **Heather Ford:** Imaging the mantle structure of cratons: Implications for the formation and modification of the Wyoming lithosphere

3:45 **Ray Russo:** TBD

4:00 **Bob Detrick--** The Transportable Array—A Unique capability for the Earth Sciences Community

4:15 - 5:30 **General Discussion and Reflections**

Suggested Discussion Questions: [We will not have time to address all these questions. But, they can be possible topics for focused writing in the rest of the workshop and beyond. These questions derive from earlier workshop reports, EarthScope Science plans, and other communications.]

- When and how are cratons formed? What are the chemical and physical properties of cratons? How are craton-keel systems established and what are the geodynamic implications of their survival?
- What are the geochemical/geochronological/geophysical components that are unique (or intrinsic) to the Wyoming Craton, and how do these compare with cratons of the world (Superior, Slave, Kaapvaal, Pilbara...)?
- Some cratons have Hadean roots and others not. Wyoming does—is there any effect on subsequent history?
- When and how has the Wyoming craton been modified/reactivated chemically and physically?
- What is the role of the Wyoming Craton in the assembly of Laurentia? Why do some Archean cratons resist Proterozoic reactivation, and some don't? What does it mean if

the GFTZ and THO are the same age? How does Wyoming fit in the overall evolution of the “United Plates of America”?

- Is the Wyoming Craton being destroyed—tectonic erosion, foundering, delamination? What is the impact of the Yellowstone “hot spot” and “who” will win the battle between the craton and the hot spot?
- The Belt Basin--what is the implication of the non-Laurentian zircons in the belt? Where did all the sediment come from that fills the belt basin? How did the craton survive such large-scale extension (20 km of sediment)?
- Phanerozoic events: how has the margin of the Wyoming Craton been modified by the Mesozoic accreted terranes? Why did Laramide-style deformation penetrate the craton, while Sevier-style deformation was relatively limited? What about Eocene, Miocene, and Quaternary (Basin and Range) extension?
- Significance of Eocene alkalic volcanism in the Montana alkali province/GFTZ.

6:00 **Dinner Downtown** (TBD); continued discussion; networking...

January 12 (Saturday) Montana State University Student Union Building Room 230

Daily Theme: The “work” day of the workshop. Addressing the “big questions” of integrated EarthScope Science and Education

[Small group discussions in break out groups; report out to whole group.

Outcome: detailed outline of a) Big questions, b) Evidence from EarthScope science [maps, figures, graphs, datasets, data-products such as tomograms....], c) Key findings and interpretations. Group work will be recorded in Google Docs for future development.

8:00 **Breakfast service SUB 230; Networking**

8:30-9:30 **Whole group discussion**

- a) Big ideas from yesterday’s presentations to be added to the list of discussion topics from the end of Friday’s session.
- b) Big questions identified in EarthScope Science Plan AND from 2005 EarthScope in the Northern Rockies workshop (how well did we do in the past decade in identifying and addressing these questions)?
- c) Charge to working/writing groups

Suggested Working Groups I—Disciplinary approaches

[Outcomes: Record discussion topics in the Google Drive as a detailed outline of a) Highest priority research topics; b) Major contributions; c) Major results and interpretations; and d) References. Note: at 10:30 some participants may want to migrate to another session, or emissaries may be sent from one group to another to integrate information]

1. Archean/Paleoproterozoic crustal evolution (geochemistry, geochronology, isotopic emphasis) [Mueller, Frost, Mogk, Vervoort, Gifford]
2. Precambrian to Phanerozoic geology, petrology, tectonics, structural geology, basin formation, magmatism [Baldwin, Chamberlain, Henry, Karlstrom, Kalakay, Mahan, Bowen]
3. Lithospheric/mantle structure [Bedle, Cooper, Russo, Van der Lee, Schulte-Pelkum, Ford, Humphreys, Detrick, Bedrosian]

9:30-11:30 Small Group Discussions: a) Geochemistry/geochronology/isotopic tracers; b) structural geology/tectonics/petrology; c) Geophysics. (Record key discussion points on Google Docs); Take a break as needed. (Rooms 232, 230 available for break outs).

11:30-12:15 Report Outs from Discussion Groups (15 minute overviews)

12:15-1:15 LUNCH

1:15-1:45 Whole Group Discussion—Cross-cutting and Integrative Science
Suggested topics from earlier workshops/literature. **Group will help refine these topics and self-select for participation.** [Refine or add to topics below. Then form small working/writing groups to explore topics of highest importance and interest].

What does EarthScope science tell us about these suggested topics:

- a. Archean tectonics/geodynamics; processes, pathways, rates, heat production, crust formation/extraction, global geochemical recycling back to the mantle, magmatism.....
- b. Paleoproterozoic mobile belts—what is the nature/relationship of GFTZ, THO, southern accreted terranes, supercontinent cycles.....
- c. Cratonization and geodynamics—when and how did the tectosphere form? How does mantle structure/dynamics impact crustal structures, epeirogeny vs. orogeny, basin formation (how continental lithosphere accommodated the immense thickness of Belt basin sedimentation), modern Laramide, Sevier, Basin and Range structures...?
- d. The nature of the boundary between the western edge of Precambrian North America and the Phanerozoic accreted terranes, along with the structural and chemical modifications of the lithosphere associated with the Sevier and Laramide orogenies; batholiths associated with Phanerozoic magmatic arcs and the related orogenic belts; how did this magmatism impact the ancient lithosphere of North America more so in the Northern Rockies than perhaps anywhere along the Cordilleran margin. This basement involvement in Cordilleran deformation may have been controlled by the unique

ancestral structure of the lithosphere (e.g., structures like the Lewis and Clark line) or the dynamics of terrane collision and accretion along the Idaho suture zone, Cheyenne belt, Black Hills/THO, etc.

- e. Structure AND composition of the lithospheric mantle—what is its composition, when and how did it form, nature of the 7X layer, physical and chemical properties it implies.
- f. Interaction of the ancient lithosphere of the Wyoming craton with the Yellowstone hot spot and associated Snake River Plain volcanism and the shallow subduction regime of the Farallon plate.
- g. Fate and impacts of slabs, drips, plumes, windows, delamination,Consequences for structures, magmatism.
- h. Additional Questions Suggested by Gene Humphreys:
 - a. What is the timing and are the processes for early craton mobility and then stabilization (changes in forces or strength, and due to what)?
 - b. How prominent is post-Archean craton destruction, and what are the processes involved in its destruction? How do we know?
 - c. What is the global importance of cratons: e.g., on protecting and stabilizing continents, and on influencing patterns of tectonics & mantle flow?
 - d. By what means did the Al-Fe rich complement to depletion get removed from cratons?
 - e. What controls the depth extent of cratons?
 - f. The creation of shields seems to roughly involve Archean craton creation and Proterozoic shield assembly. What tectonic insight is gained by understanding this transition?
 - g. Is the evolution from Hadean *stagnate lid* to Phanerozoic *plate tectonics* progressive, or does it involve fundamental transitions in state?
 - h. By what processes does metasomatism occur, and what are its effects on composition, strength and density?
 - i. How much variety is there in the processes of craton creation? Is south Africa fundamentally different than North America? E.g., the role of mantle plumes verses tectonic-like processes?

1:45-4:00 **Small Working/Writing Groups** (Break as needed). [Small group discussions in break out groups; report out to whole group. Outcome: detailed outline of a) Big questions, b) Evidence from EarthScope science (maps, figures, graphs, datasets, data-products such as tomograms....), c) Key findings and interpretations, d) References. Group work will be recorded in Google Docs for future development].

4:00-5:00 **Report Out of Writing Groups**. General Discussion and input from whole group.

Dinner Downtown (TBD)

January 13 (Sunday) Montana State University Student Union Building Room 230

8:00 **Breakfast service SUB 233; Networking**

Outcomes Day

8:30-9:30 **Whole group Discussion I—Education and Outreach Opportunities, Led by Elisabeth Nadin, ESNO**

Whole group brainstorming about how to translate EarthScope science to broader audiences: a) K-12 teachers (curriculum, partnering with established groups like IRIS, UNAVCO, NESTA....); b) Undergraduate studies (SERC,) including minority institutions (e.g. tribal colleges); c) Graduate studies (COMPRES, CIG...), d) Informal education for general public.

9:30-10:00 **Break Out Groups II**

Finalize outlines; confirm writing assignments; timelines

10:00-11:00 Whole Group Discussion II—Writing Plan

- a. Report out of status of each writing group
- b. Workshop report (Conveners; input about key points of report).
- c. Themed Journal Volume (Geosphere, other????); Identify outlet.
 - a. Article title/topic; writing team
 - b. Data available
 - c. Recruitment of other authors?
- d. Follow on theme sessions at GSA, AGU (who takes responsibility for organizing)?
- e. Timeline
- f. What's Missing? Conspicuously absent is any input using geodetics, lidar, neotectonics, etc.

11:00 **Wrap up:** Reflections on progress made; next steps needed

End of workshop evaluation?

Distribute box lunches for travel.

Depart for airport as needed to catch flights.

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the Wyoming Craton in the evolution of North America**

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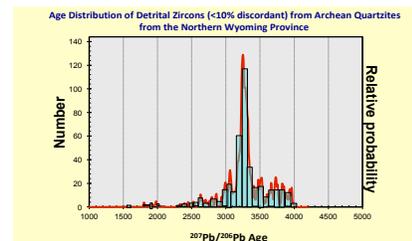
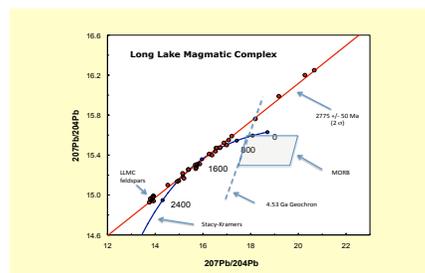
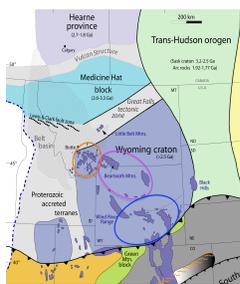
ABSTRACTS

The Wyoming Province: A Unique Archean Craton

P. Mueller, U. Florida; D. Mogk, Montana State Univ.; D. Henry, Louisiana State Univ.; J. Wooden, USGDS (retired)

The spatial extent of the Wyoming Province (WP) we know today has not changed much since Kent Condie first proposed the name at the 1972 IGC (Fig. 1). Over subsequent years we have developed a greater understanding of the Province, largely through geochemistry. Over the past ~20 years with the availability of ion microprobes (e.g., SHRIMP) and multi-collector LA-ICP-MS we have generated an improved chronology of the craton via U-Pb analyses of both magmatic and detrital zircons. This geochemical and geochronologic database has allowed us to recognize useful subdivisions: Southern accreted terranes (SAT), the Beartooth-Bighorn magmatic zone (BBMZ), and the Montana metasedimentary terrane (MMT). The BBMZ and MMT are strongly linked in their evolution by the common Pb isotopic compositions of Mesoarchean rocks. Secondary Pb isochrons show that the BBMZ and MMT share a unique Pb isotope signature (crustal Pb paradox) reflecting crustal evolution that included an early stage with U/Pb ratios greater than average crust (Fig. 2). The uniqueness lies in the fact that only the Slave Province of Canada among all recognized Archean cratons shows evidence of an early, high U/Pb episode(s) of crust formation. We have also developed substantial Sm-Nd and Lu-Hf databases with model ages to 4.1 Ga that add to our understanding of the complexity the craton's development and the enriched nature of the early stages of growth.

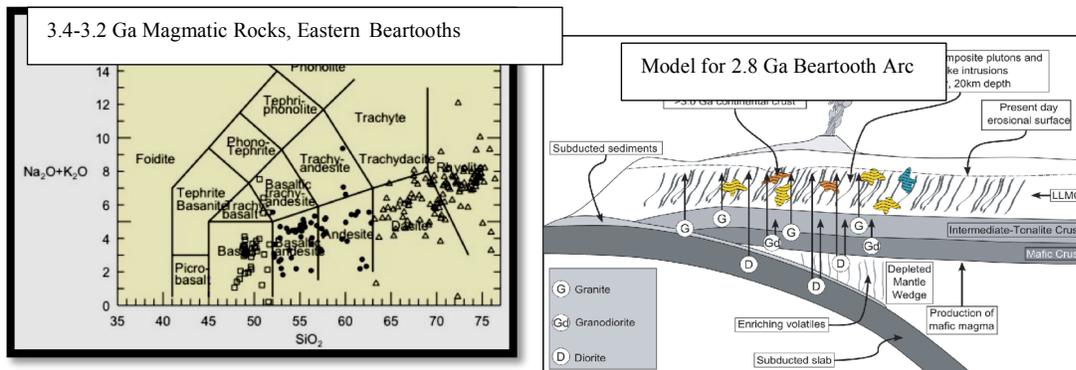
The earliest evidence of crust formation in the WP comes from detrital zircons in Archean quartz-rich meta-sedimentary rocks (to 4.0 Ga) and xenocrysts (to 3.8 Ga). Hf isotopic values suggest that this crust evolved in a plume-like environment and then transitioned to a subduction-driven crust production around 3.4 Ga, culminating in a widespread ~3.2 Ga event (Fig. 3). The 3.2 event was followed by an equally widespread 2.8 Ga event in the BBMZ and MMT (Fig. 2). These rocks show similar geochemical signatures to modern arc magmas (enriched LIL and depleted HFSE). In the southern Beartooth Mtns., we have documented a cross section from the middle to upper crust of a 2.8 Ga continental arc, including greenschist facies metasedimentary rocks. Around the borders of the WP, Neoproterozoic magmatism is well documented (e.g., in the Wind River, Wasatch and Tendoy Ranges) and Neoproterozoic metamorphism has been recorded in these and other areas (e.g., Tobacco Root and Granite Mtns., and Gallatin and Ruby Ranges). Accepting the detrital zircon record as a fair sampling of the Archean crustal growth episodes that entailed felsic magmatism, we see several prominent episodes: 3.5 to 4.0 Ga, 3.2 to 3.4 Ga, 2.8 to 2.9 Ga, and 2.5 to 2.6 Ga. Crustal growth was not continuous, but included distinct episodes of quiescence. Paleoproterozoic (1.7-1.9 Ga) mobile belts now surround the WP along its margins (e.g., Trans-Hudson orogen, Great Falls tectonic zone, Cheyenne Belt, Farmington zone, Hartville uplift), but Proterozoic magmatism other than mafic dikes is extremely rare and confined to the outer margins of the craton, documenting the robustness of the craton's Archean keel.



TTGs We Have Known and Loved: 1.5 Ga of Growth and Recycling of Archean Continental Crust in the Northern Wyoming Province (NWP)

D. Mogk, Montana State Univ., P. Mueller, Univ. Florida, D. Henry, Louisiana State Univ., J. Wooden, USGS (retired)

The NWP has evolved through episodic pulses of magmatism over a 1.5 Ga period from ~4.0-2.5 Ga. The oldest record of magmatogenesis is in detrital zircons with ages of 4.0-3.6 Ga preserved in high-grade metasedimentary rocks across the province. Initial ϵ_{Hf} values for these zircons systematically decrease with time suggesting extensive recycling of older crust. The oldest rocks exposed in the NWP are 3.5-3.6 Ga TTG, that are likely derived from garnet-bearing mafic lower crust. A major crust-forming event occurred across the NWP over the protracted interval 3.4-3.2 Ga, producing rocks of the TTG suite, monzodiorites and granites. Detrital zircons from these rocks are dominant in younger metasupracrustal rocks. Geochemical signatures of these rocks include LIL enrichment, negative Eu anomalies and HFSE depletion, indicating derivation in a subduction setting involving older crust (4.0-3.5 Ga inherited zircons) as well as juvenile material (based on ϵ_{Hf} values). After a 400 Ma hiatus, a second major subduction event began at ~2.8-2.9 Ga and produced the voluminous (>400,000 sq. km) magmatic rocks that comprise the Beartooth-Bighorn Magmatic Province. This suite of rocks includes diorites, tonalites, granodiorites and granites, with trace element signatures and enriched initial isotopic values (U-Pb, Rb-Sr, Sm-Nd, and Lu-Hf) that suggest they were also produced in an environment similar to a modern continental arc. This range of compositions was generated over a restricted time interval (<50 Ma), suggesting coeval melting of multiple mantle and crustal sources. Intracrustal decompression melting produced local leucogranites in shear zones during Late Archean (2.55 Ga) tectonic adjustments. Magmatic evolution of the NWP 1) began 4.0-3.5 Ga by melting of primitive mantle and derivative mafic crust in a plume setting (i.e. stagnant lid model), 2) produced thick sialic crust through protracted, episodic magmatism from depleted and enriched sources in the interval 3.4-3.2 Ga by 'sag' or subduction processes, 3) developed a modern-style continental arc on older, thick and stable crust in the Mesoproterozoic (2.8 Ga); and 4) generated ~2.55 Ga partial melts along shear zones during a Neoproterozoic period of tectonic juxtaposition or rifting associated with a "break-out" of Wyoming from a larger craton that may have included the Slave craton.



The Archean geologic history of the southern Wyoming Province: a focus on the extent of ancient crust and time of cratonization

Carol D. Frost, Department of Geology and Geophysics, University of Wyoming

The Wyoming province is one of around a half-dozen Archean cratons with histories going back to the Eoarchean and Hadean. The ancient origin of Wyoming province continental crust was first recognized from the northern part of the craton (Wooden and Mueller, 1988). This abstract focuses on evidence that this old core of the province extends as far south as the Granite Mountains. U-Pb zircon dates of 3.45-3.33 Ga for layered gneisses in the Granite Mountains are interpreted as igneous crystallization ages (Frost et al., 2017). To date, no other Paleoproterozoic intrusions have been documented from Laramide uplifts within the state of Wyoming. However, Archean rocks in these uplifts preserve three kinds of evidence for the presence of ancient crust: Eoarchean inherited and detrital zircon, common Pb evidence for an early crustal precursor with high $^{238}\text{U}/^{204}\text{Pb}$ (“high μ ” signature), and Nd and Hf evidence for Eoarchean to Hadean crustal sources.

- Eoarchean zircon has been documented from central Wind River Range migmatite (Aleinikoff et al., 1989), and as inherited zircon in Granite Mountains orthogneiss (Frost et al., 2017). Eoarchean detrital zircon is also present in quartzite from South Pass, southern Wind River Range.
- Feldspar and initial Pb compositions of whole rocks with high μ first documented from the eastern Beartooth and Bighorn mountains have also been identified in the Wind River and Teton Ranges, and in the Owl Creek and Granite Mountains (see compilation in Frost et al., 2006; Cornia, 2003; Fischer and Stacey, 1986).
- Initial Hf isotopic compositions of 3.82 Ga zircon require Hadean precursors, and unradiogenic initial Nd isotopic compositions of Paleoproterozoic and Mesoproterozoic orthogneisses in the Bighorn and Granite Mountains likewise indicate Eoarchean antecedents (Frost et al., 2017).

These results suggest that the old core of the Wyoming province extends south to include the Teton and Wind River Ranges, Owl Creek, Granite, and Bighorn Mountains. This area is underlain by high velocity lower crust imaged by the DeepProbe and Sarex experiments. The southern accreted terranes were added to the province by 2.62 Ga; this part of the craton apparently lacks high velocity lower crust.

The Wyoming province was intruded by voluminous felsic orthogneisses at ~2.85, 2.80, 2.67, and 2.63-2.62 Ga and the Stillwater intrusion and mafic dikes at 2.71-2.72 and 2.69-2.68 Ga (Chamberlain et al., 2003). Subsequent deformation, metamorphism, magmatism, and alteration affected the western and southern craton margins between 2.60 Ga and 2.43 Ga (Frost et al., 2018), suggesting that cratonization coincides with the Archean-Proterozoic transition.

Aleinikoff et al., 1989, *Contributions to Mineralogy and Petrology* 101, 198-206

Chamberlain et al., 2003, *Canadian Journal of Earth Sciences* 40, 1357-1374

Cornia, 2003, M.S. Thesis, University of Wyoming

Fischer and Stacey, 1986, *U.S. Geological Survey Bulletin* 1622, 13-24.

Frost et al., 2006, *Canadian Journal of Earth Sciences* 43, 1419-1444.

Frost et al., 2017, *Geological Society of American Bulletin* 129, 259-280.

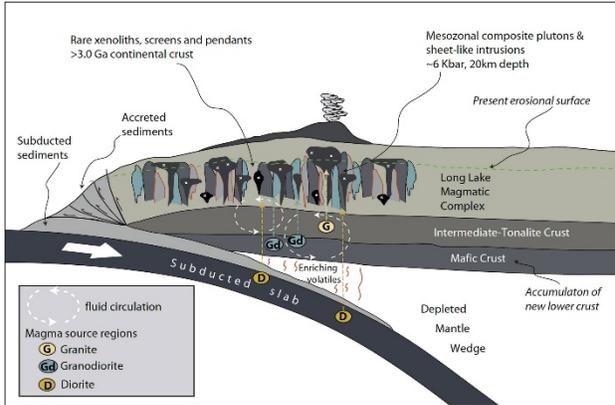
Frost et al., 2018, AGU abstracts, Fall meeting, Washington DC.

Wooden and Mueller, 1988, *Earth and Planetary Science Letters* 87, 59-72.

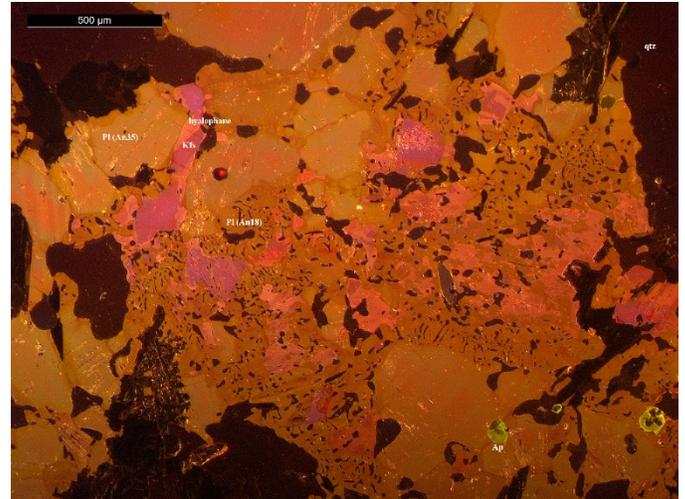
ARCHEAN METAMORPHIC HISTORY OF THE NORTHERN WYOMING PROVINCE (NWP): IMPLICATIONS FOR PRECAMBRIAN PLATE TECTONICS, LEVEL OF EXPOSURE ACROSS THE NWP VS. METAMORPHIC GRADE

Darrell J. Henry; Dept. of Geology and Geophysics, Louisiana State Univ., Baton Rouge, LA

Much of what is interpreted at depth in the Wyoming Province should be informed by what is observed in Laramide-uplifted basement rocks, and this is particularly informative in the various blocks of the Beartooth Mountains (MT/WY). In the western margin of the Beartooth Mountains there is a fundamental discontinuity in the Archean basement between the Beartooth-Bighorn Magmatic Zone (BBMZ) to the east and the Montana Metasedimentary Province (MMP) to the west. The North Snowy block and parts of the South Snowy block have been interpreted as zones of tectonic mixing of allochthonous units being emplaced into their current tectonic setting at ~2.55 Ga. Within the eastern portion of the South Snowy Block and Beartooth Plateau Block, 2.8 Ga plutonic and metamorphic rocks represent a continuum of crustal levels (~10-25 km) within a Mesoarchean continent. Although these rocks contain a diverse record of crustal evolution extending before 2.8 Ga (as early as ~4.0 Ga), it is the 2.8 Ga magmatic rocks (tonalite-trondhjemite-granodiorite i.e. TTG suite) that volumetrically dominate the region from the South Snowy Block (partially in Yellowstone National Park) to the Beartooth Plateau Block (~110 km distance). Magmatic rocks in the westernmost area are dominated by undeformed bulbous, peraluminous, epizonal, quartz-monzonitic plutons that cut metasedimentary rocks with low-P assemblages e.g. andalusite-staurolite (~580°C, ~3.5 kbar). The rocks cut by the plutons include metamorphosed turbiditic rocks with detrital zircon populations with a range of 2.9-3.6 Ga with a significant population at 3.0-3.1 Ga. The protolithic sediments exhibit lithologic and compositional similarities more akin to active continental margin settings. In contrast, in the eastern part of the area 2.8 Ga magmatism in the Long Lake magmatic complex includes a diverse series of meta-dioritic rocks to metaluminous TTG suite rocks. Each of the igneous rock types do not exhibit consistent sequential field, geochemical or geochronologic relationships i.e. they are essentially coeval, but independent, magmatic units that are mixed in a ductile environment. In the easternmost area there are numerous enclaves/pendants including aluminous migmatites with peak metamorphic conditions of 750-800°C and 7-8 kbar. The protolithic sediments exhibit lithologic and compositional similarities more akin to passive margin settings. The detrital zircon in the metaclastic rocks in the east do not contain the younger 2.9-3.1 Ga, but have abundant 3.2-3.3 Ga (and older) detrital zircons. Between the west-east PT extremes, the transition is not continuous – there is a shear zone along the Yellowstone River that exhibits a P change of 3 kbar. These plutonic and metamorphic rocks are interpreted as belonging to a section of 2.8 Ga continental crust developed in response to subduction-zone processes and ultimately exposed at varying depths. Later fluid interactions include partial hydration of anhydrous mineral assemblages (e.g. granulites and anhydrous igneous rocks), local dehydration and second generation of granulites from hydrous metamorphic rocks and/or introduction of K- and Ba-rich fluids to significantly metasomatize pre-existing rocks. Each of these interactions strongly influences the textural and chemical characteristics and their resultant interpretation.



Schematic depiction of tectono-magmatic framework for 2.8 Ga magmatism emphasizing the presence of older crust, multiple sources for the magmas and possible fluid influx sources.



Optical cathodoluminescence image illustrating metasomatic influx of K, Ba fluids to generate new minerals (albitic plagioclase and Ba-rich hyalophane).

A few key references:

- Mogk, D. W., Mueller, P. A., and Wooden, J. L., 1988, Archean Tectonics of the North-Snowy-Block, Beartooth Mountains, Montana: *Journal of Geology*, v. 96, no. 2, p. 125-141.
- Mogk, D. W., Mueller, P. A., and Wooden, J. L., 1992a, The Nature of Archean Terrane Boundaries - an Example from the Northern Wyoming Province: *Precambrian Research*, v. 55, no. 1-4, p. 155-168.
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The View from (of) the Top: Considerations of the Phanerozoic Stratigraphic Cover on the Wyoming Craton

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Phanerozoic accommodation above the Wyoming Craton was created and destroyed as its tectonic setting evolved. Beginning as a passive margin during the early Paleozoic, it was influenced by a series of orogenic events as it transitioned from a passive margin to a retroarc foreland to a retroarc foreland segmented by basement uplifts (Antler Orogeny, mid-Paleozoic; Ancestral Rockies Orogeny, late-Paleozoic; Nevadan Orogeny, early-Mesozoic; Sevier Orogeny, mid-Mesozoic; and, Laramide Orogeny, late-Mesozoic to early-Cenozoic). The western margin of the Wyoming Craton was next extended by Basin and Range faulting (mid-Cenozoic to present) and finally impinged upon by the Yellowstone “hotspot” on its western boundary causing regional uplift. Superposed on these tectonic events, sea level changes caused inundation and withdrawal of marine waters from the craton. These interactions, along with global climate changes and plate migration across latitudinal climate zones, resulted in a stratigraphy first dominated by carbonates, then mixed siliciclastics and carbonates, and finally siliciclastics. The strata deposited were punctuated by numerous unconformities of variable duration and origin. This stratigraphy overlying the Wyoming Craton is well-documented from many decades of observation and description. Less well-understood are the causal mechanisms of stratal thickness patterns, distribution and duration of unconformities through space and time, and the linkage between geodynamic and stratigraphic processes — especially those of durations of 3 to 8 million years that appear to be synchronous over large areas of the Earth.

		Stratigraphy	DZ Samples	Tectonic Setting and Orogenic Events	Tectonostratigraphic Assemblage	
Cenozoic	Tertiary	Pliocene		Convergent Margin	Laramide Orogeny	TSA4 Retroarc foreland segmented by basement uplifts; non-marine
		Miocene				
Oligocene						
Eocene	Willwood Fm.	● (2)				
Mesozoic	Cretaceous	Paleocene	Fort Union Fm.	● (2)	Sevier Orogeny	TSA3 Retroarc foreland; shallow marine to fluvial siliciclastic sediments
		Upper	Lance Formation	●		
			Meeteetse Fm.	● (4)		
			Mesaverde Fm.	●		
		Cody Shale	●			
		Frontier Fm.	● (13)			
	Mowry Formation	● (2)				
	Lower	Muddy Formation	● (2)			
		Thermopis Shale	●			
		Sykes Mtn. Fm.	●			
	Jurassic	Upper	Cloverly Fm.	● (6)	Nevadan Orogeny	TSA2 Transitional to retroarc foreland; shallow marine & non-marine clastic sediments
			Morrison Fm.	● (3)		
		Sundance Fm.	● (3)			
		Gypsum Spring Fm.	●			
	Triassic	Chugwater Group	●	Passive Margin	Antler Orogeny	TSA1 Proximal miogeoclinal strata; mixed carbonate & siliciclastic sediment; dominated by shallow marine & marginal marine facies
		Permian	Dinwoody Fm.			
Phosphoria Fm.	● (2)					
Pennsylvanian	Goose Egg Fm.	●				
	Tensleep Sandstone	● (3)				
Mississippian	Amsden Fm.	●				
	Madison Limestone	●				
Devonian	Darby Fm.	●				
	Beartooth Butte Fm.	●				
Ordovician	Bighorn Dolomite	●				
	Gallatin Group	●				
Cambrian	Upper	Gros Ventre Fm.	● (2)			
	Middle	Flathead Ss.	●			
	Lower		●			
Precambrian		●			Archean crystalline basement	

From May et al., 2013

SOME KEY OBSERVATIONS PERTINENT TO THE FORMATION AND STABILIZATION OF THE WYOMING PROVINCE

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The Wyoming Province displays a rich geologic history with implications for continental growth mechanisms, Archean tectonics, the advent of plate tectonics, and cratonic formation and stability. For the purposes of the 4-d synthesis Earthscope workshop on the Wyoming craton, there are at least 4 key observations that need to be considered:

1) The Wyoming Province comprises 2 major lithospheric blocks that formed at different times, in different places, from different mantle reservoirs, by different mechanisms. The ancient core in the north, denoted as the Beartooth-Bighorn Magmatic zone (BBMZ, Mogk et al., 1992) and the Bighorn and Sweetwater subprovinces (Chamberlain et al., 2003), is characterized by broadly distributed, possibly plume-style magmatism, ca. 2.95-2.75 Ga; derivation from a Hadean-aged, high- μ ($^{238}\text{U}/^{204}\text{Pb}$) mantle reservoir; intrusion by Archean mafic dike swarms, ca. 2.72, 2.69 and 2.67 Ga with attendant plume heads; thick crust (Moho \geq 60 km, DeepProbe); 10 km-thick fast lower crustal layer; and thermal and tectonic quiescence since 2.6 Ga. In contrast, the Southern Accreted Terranes (SAT, Mogk et al., 1992; Chamberlain et al., 2003; Frost et al., 2006) contain abundant greenstone fragments, ca. 2.85 to 2.65 Ga; appear to have formed by subduction and accretionary processes; are derived from an isotopically juvenile mantle; has relatively thinner crust (45 km Moho); lacks a fast, thick, lower crustal layer; are intruded by only Proterozoic mafic dikes, no Archean dikes; and was thermally reactivated and unroofed in the MesoProterozoic (ca. 1.5 Ga, south of the Geochronologic Front of Peterman and Hildreth, 1978).

The two lithospheric blocks accreted along the Oregon Trail Structural Belt (OTSB, in Sweetwater subprovince, north of the Granite Mountains) during several discrete events from 2.66 to 2.62 Ga based on direct dates on deformation (Grace et al., 2006, Frost et al., 2006; Parker et al., 2015; McLaughlin 2016). The collision resulted from convergence between the Wyoming and Superior provinces, based on paleomagnetic data (Kilian, 2015). It is likely that the SAT formed as part of the Superior Province and was left behind during Proterozoic rifting, ca. 2.1 Ga, of Wyoming and Superior (Kilian et al, 2016).

2) The ancient core of the Wyoming province may have formed by 3.3 Ga, but evidence for an earlier craton is much less certain. The two terranes with the highest abundance of ca. 3.3 Ga and older rocks, the Montana Metasedimentary Province (MMP, Mogk et al, 1992) and Sacawee block (Granite Mountains) are welded to the ancient core by late Archean shear zones, the North Snowy Block and Oregon Trail Structural Belt, respectively, so it is unclear whether they are representative of the ancient core, or accreted later. Pb isotopic data from the ancient core reflects a Hadean-aged, high- μ mantle reservoir rather than melting of older crust. Nd isotopic data from the BBMZ range from near mantle compositions at 2.9 Ga to source components with mantle separation ages of 3.8 Ga. This Nd isotopic range could be satisfied by formation of the

Wyoming province proximal to an older craton such as the Slave, from a shared high- μ mantle, with Acasta-aged continental detritus reaching the BBMZ source regions.

3) The rocks exposed in the BBMZ/Bighorn and Sweetwater subprovinces (Bighorn, Beartooth, Owl Creek and Granite Mountains) have remained shallower than ~10 km depth since the Archean. Rocks exposed at the surface of the southern Bighorn and Beartooth Mountains cooled through 450 °C (U-Pb closure temperature for apatite) ca. 2.60 Ga; the northern Bighorn batholith cooled through 450 °C by 2.82 Ga, ~30 Ma after crystallization; Rb-Sr biotite dates (300 °C) immediately north of the Granite Mountains are Archean (Peterman and Hildreth, 1978). The plutons may have formed at greater depths, but were at least partially unroofed during the Archean. Subsequent tectonism and burial has kept them within ~10 km of the surface based on typical regional thermal gradients.

4) The eastern margin of the Wyoming Province (Archean-Proterozoic boundary) lies immediately east of the Bighorn and Laramie Mountains. Results from the Earthscope-funded BASE geophysical and geologic experiment across the Bighorn Mountains revealed distinct contrasts in lithospheric architecture beneath the Bighorn Mountains and Bighorn basin to the west compared to the lithosphere beneath the Powder River basin to the east of the Bighorn Mountains (Worthington et al., 2016; Yeck 2015). The variations in geophysical properties and the presence of a steep reflector at depth east of the Bighorn Mountains have been interpreted as a complex Proterozoic orogen that includes small, Archean microcontinents analogous to the Trans-Hudson orogen to the north (Worthington et al., 2016). This orogen (Black Hills/Dakotan/Central Plains) includes rocks exposed in the Black Hills and Hartville Uplift. Final closure of Wyoming and Superior provinces occurred ca. 1.72 Ga based on direct dates on deformation and paleomagnetic data (Kilian et al., 2016).

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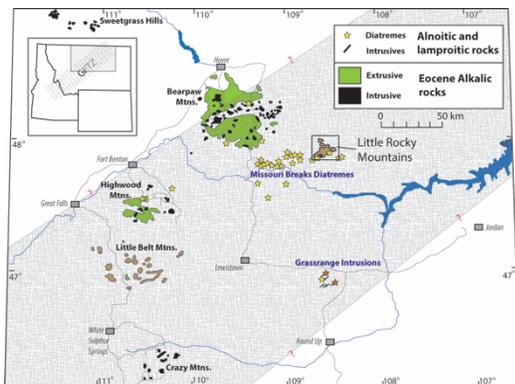
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LESSONS LEARNED FROM THE GREAT FALLS TECTONIC ZONE, MEDICINE HAT-WYOMING SUTURE: CRUSTAL XENOLITHS AND THE LITTLE ROCKY MOUNTAINS

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Thorough studies of the Wyoming Province (WP) require understanding the role it played in the assembly of Laurentia. We concentrated on the two prominent features separating the Archean Wyoming and Hearne cratons: the Paleoproterozoic Great Falls tectonic zone (GFTZ) and the Medicine Hat block (MHB). Both are poorly defined spatially because of sedimentary cover. The GFTZ was recognized on the basis of differences in geophysical patterns, isopachs of Paleozoic sedimentary sections, and lineaments; however, juvenile arc rocks in the Little Belt Mountains (LBM; U-Pb zircon and Nd isotopic data from the LBM suggest that the GFTZ formed at ~1.86 to 1.80 Ga due to ocean subduction and collision between the WP and MHB¹) and strongly overprinted Archean rocks in southwestern Montana show it to be a dominantly Paleoproterozoic feature. To better define the GFTZ, geochronological and geochemical analysis of crustal xenoliths collected from Montana Alkali Province volcanics² and exposed basement rock in the Little Rocky Mountains³ (LRM) were analyzed. U-Pb geochronology of zircon separated from xenoliths from the Montana Alkali Province (MAP) yield igneous crystallization ages from ~1.7 to 1.9 Ga and 2.4 to 2.7 Ga, as well as metamorphic ages from ~1.7 to 1.8 Ga. Zircon Lu-Hf and whole-rock Sm-Nd data indicate that the xenoliths originated from reworked older continental crust mixed with mantle-derived components in all cases. Whole-rock trace element patterns show fluid mobile element enrichments and fluid immobile element depletions suggestive of a subduction origin. The Little Rocky Mountains (LRM) of Montana provide access to exposures of Precambrian crust in the WP-GFTZ-MHB suture region. U-Pb ages of zircons from Precambrian rocks of the LRM range from 2.4 to 3.3 Ga. Whole-rock analyses yield Sm-Nd T_{DM} from 3.1 to 4.0 Ga and initial $\epsilon Nd(T)$ values calculated at U-Pb zircon crystallization ages range from -0.9 to -10.5, indicating significant contributions from older Archean crust. The age and isotopic composition of the LRM gneisses are similar to crust in the northern WP (2.8 to 2.9 Ga), but Paleoproterozoic K-Ar cooling ages suggest crust in the LRM experienced Paleoproterozoic metamorphism and deformation that characterizes the GFTZ. Consequently, its history differs from the adjacent Beartooth-Bighorn magmatic zone of the



Generalized depiction of Cenozoic alkaline rock occurrences in the MAP; LBM and LRM locations. The limits of the GFTZ (shown as cross-hatch pattern) are not well defined.

northern WP, which does not record Paleoproterozoic tectonism, but has a strong correlation with the Montana metasedimentary terrane that was strongly overprinted during the Paleoproterozoic Great Falls orogeny⁴ that defines the GFTZ.

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Paleoproterozoic metasedimentary suites on the NW flank of the Wyoming Province: insights into an evolving continent

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The Ruby Range in southwest Montana is within the Montana Metasedimentary Terrane (MMT) at the northwestern margin of the Wyoming Province. Once thought to be dominantly Archean in age, this range is now known to have experienced a profound tectonothermal event termed the Big Sky orogeny (1.79 -1.72 Ga). A transect along Stone and Cottonwood Creeks was selected for U-Pb zircon, LASS monazite, and Lu-Hf garnet dating. The section includes three major lithotectonic units: the Christensen Ranch Metasedimentary Suite (CRMS), the Dillon gneiss, and the Pre-Cherry Creek Suite. Three detrital zircon samples from quartzites within the CRMS record distinct depositional signatures. Two samples record atypical MMT signatures with peaks at 2.6-2.7 Ga and grains as young as 2.5 Ga. The presence of late Archean and earliest Paleoproterozoic ages requires both a younger depositional age for these rocks than was previously inferred as well as heterogeneity in source regions. Pelitic gneisses interlayered with the quartzites record monazite ages of 1.76-1.79 Ga. The exception is in one sequence north of the Stone Creek fault where garnet leucogneiss is intrusive with respect to the CRMS pelites. Here, monazite ages from the pelite and leucogneiss are 2.43 Ga and 2.48 Ga respectively. Garnet from the leucogneiss has been dated by Lu-Hf and is 2.43 Ga. A pelitic gneiss that occurs as a screen in the Dillon unit yields mixed ages of 1.78 and 2.44 Ga. The younger population occurs almost entirely as inclusions in garnet. Garnet leucogneiss from the Dillon unit records an identical 2.48 Ga age as that of the CRMS sample. Two samples of migmatitic Pre-Cherry Creek gneiss record ages of 1.76-1.77 Ga with scarce 2.4 Ga cores. A sample of garnet leucosome from the migmatitic gneiss contains a dominant population 1.77 Ga grains. In contrast, zircon from the leucosome yields 2.43 Ga ages, but REE patterns indicate that zircon grew prior to garnet so could be inherited. Phase equilibria modeling suggests that all of the rocks were metamorphosed to upper amphibolite facies conditions during the Big Sky orogeny. Pelitic schists from the CRMS all reached suprasolidus conditions with temperatures and pressures exceeding 7 kbar and 750 °C. Retrograde decompression and re-equilibration is preserved as cordierite-bearing corona textures in some samples at 4-6 kbar and 630-680 °C.

These results indicate that the Big Sky orogeny occurred at 1.79-1.76 Ga in the Ruby Range and profoundly affected all of the lithotectonic units. However, ages from the garnet leucogneiss place constraints on an earlier period of widespread crustal melting at 2.43-2.48 Ga, a period that may reflect the penultimate stage of crustal assembly that was subsequently followed by rifting and collision during the Big Sky orogeny.

Neoproterozoic and Paleoproterozoic crystalline basement rocks of the Clearwater and Priest River complexes: Constraints on the formation of western Laurentia

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The geology of north-central Idaho, broadly known as the Clearwater country, has long been enigmatic. While there have been suggestions of older crystalline basement rocks in the region (e.g., Reid et al., 1973) this basement has been largely obscured by later events: covered by thick strata in the Meso- and Neoproterozoic, subjected to metamorphic events in the Mesoproterozoic and Cretaceous, intruded by the Idaho batholith in the Cretaceous, and finally extended and intruded by magmas in Eocene. In total, this complex geologic history—and the rugged nature of and difficult access to much of this terrain—has made this region the terra incognita of Northwest U.S. geology. Recent U-Pb zircon dating and Hf and Nd isotope geochemistry of rocks in this region, however, have now documented the existence of Neoproterozoic and Paleoproterozoic rocks, which extend along a 115-km stretch of north central Idaho. Together with new data from the Priest River complex, this represents the largest belt of Neoproterozoic and Paleoproterozoic crust exposed in the Northwest U.S. outside of the Wyoming Province.

To better understand the origins of these basement rocks—and their role in the formation of North American continent—we have determined zircon U-Pb ages, Hf isotopes in zircon, and Hf-Nd isotopes in whole-rocks from 20 magmatic rocks throughout the Clearwater and Priest River complexes. A small subset of these samples yield a narrow range of Neoproterozoic ages from 2.66 to 2.65 Ga; the remaining 16 samples have Paleoproterozoic ages, also within a narrow range (1.87 to 1.84 Ga). In total all analyzed units from the Clearwater and Priest River complexes define a bimodal age distribution at ~2.65 Ga and ~1.86 Ga.

Zircon Hf analyses of samples from both complexes yield a rather narrow range of positive $\epsilon_{\text{Hf}(t)}$ values (+1.2 to +3.3) for the Archean samples (2.66 Ga – 2.65 Ga) and a much wider range of $\epsilon_{\text{Hf}(t)}$ for the Paleoproterozoic samples (1.87 Ga – 1.84 Ga) from ~ -6.5 to +5.7. Whole-rock Hf and Nd isotope signatures are consistent with the zircon Hf isotopes. These results indicate that the ca. 2.65 Ga Archean samples were derived from a relatively homogenous chondritic to slightly depleted mantle source and the ca. 1.86 Ga Paleoproterozoic orthogneisses formed from the mixing of varying amounts of depleted mantle and evolved continental crust. The earliest Paleoproterozoic rocks have the largest contribution from older crust with an increasing depleted mantle contribution through time.

Based on the strong similarity of age and isotopic signatures between the Clearwater and Priest River complexes, it is likely that these represent different exposed parts of same basement province. In comparison with other basement terranes in northwestern Laurentia, the crystalline basement in the Priest River and Clearwater complexes appear to be distinct from the Wyoming province and the Medicine Hat block, although the composition of the latter is still poorly documented. If so, the Priest River and Clearwater complexes may represent a distinct Archean-Paleoproterozoic crustal block—which we call the Clearwater block.

NOTHING QUIET ON THE WESTERN FRONT: LATE ARCHEAN TO NEOPROTEROZOIC EVOLUTION OF WEST-CENTRAL LAURENTIA

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The spatial, temporal, and geochemical evolution of much of west-central Laurentia (i.e. nw Wyoming Craton, Grouse Creek Block and Selway Terrane) remains poorly characterized, primarily because basement rocks west of the exposed northwestern margin of the Wyoming Craton (i.e. Laramide uplifts in the Dillon Block and Tobacco Root mountains) are intruded by younger plutonic rocks and covered by voluminous Belt Basin sediments as well as younger volcanism. However, defining the nature and age of this part of Laurentia is key to understanding the Precambrian history of North America, including its role in Precambrian supercontinent cycles. Here we present recent U-Pb and Lu-Hf isotopic analysis of zircons from two less well characterized exposures of Precambrian basement rocks in west-central Laurentia at the northwestern edge of the Wyoming Craton near Dillion, Mt (Blacktails Mountains) and southwest in the Grouse Creek block near Ketchum, Id (Wildhorse Gneiss).

Initial results from the first single grain U-Pb and Lu-Hf isotopic analyses of zircons from basement rocks in the Blacktails indicate a history dating back to at least the Mesoproterozoic, with reworking of older crust in the Neoproterozoic. Neoproterozoic magmatism occurred at 2.77-2.74 Ga, a unique age in this part of the Wyoming Craton that predates 2.67 Ga rocks to the south (e.g. Wind River, Teton Range) and postdates rocks to the east in the Beartooth Range. Basin formation and sedimentation occurred after ~2.7 Ga followed by high-grade metamorphism, including anatexis at (2.55-2.45 Ga), a previously documented, regionally extensive event. In the Grouse Creek Block two age clusters of Archean basement from the Wildhorse Gneiss are : 1) 2.67 Ga tonalitic banded grey gneiss with an initial ϵ_{Nd} value of -3, and 2) 2.47 Ga quartz monzonite with initial ϵ_{Hf} values ranging from -7 to -14 (average of -10) and initial ϵ_{Nd} of -6. Mesoproterozoic (Belt Basin) age quartzites and paragneiss overlying this basement yielded zircon U-Pb ages of 1410-1910 Ma that document increased crustal recycling from the Paleoproterozoic to early Mesoproterozoic in this part of Laurentia. Moreover, these metasedimentary rocks contain a significant proportion of North American Magmatic Gap (NAMG) zircons (1490-1610 Ma), suggesting derivation from non-Laurentian sources. Neoproterozoic (670-690 Ma U-Pb ages) meta-igneous rocks (with intermediate to mafic composition) intruding these units show chemical signatures indicative of formation in a rift environment and a range of initial ϵ_{Hf} values -6 to +5 with an average of +2 and provide evidence of protracted rifting during the breakup of Rodinia that partially remobilized older (Mesoproterozoic?) crust. These results along with other recent studies of Precambrian basement in west-central Laurentia demonstrate the importance of further work in this area for the following reasons: 1. Archean rocks west of the exposed Wyoming Craton boundary are likely more widespread and older than previously reported 2. A late Archean early Paleoproterozoic thermal event documented in multiple parts of the nw Wyoming Craton appears to extend southwest to the Grouse Creek Block and may help elucidate the early Paleoproterozoic history of the Wyoming Craton prior to amalgamation to Laurentia 3. Combined U-Pb and Lu-Hf

isotopic analysis of detrital zircons from Belt Basin rocks and Neoproterozoic igneous rocks in west-central Laurentia will help provide better paleogeographic constraints for Proterozoic supercontinents.

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Deep crustal structure, processes, and properties from xenoliths, basement exposures, and seismic observations in the northern Rocky Mountain region

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Geophysical studies, xenoliths, rare exposures of once deep rocks, and magmatic records all provide different perspectives with which to investigate the structure, composition, and properties of lower continental crust. Each has its own inherent biases and/or limitations, making integrated approaches particularly valuable in advancing our understanding of lithospheric evolution. Our studies of the Wyoming Craton include structural, metamorphic, geochronological, and petrophysical analyses of xenoliths and comparison to the observed seismic velocity structure of the deep crust from EarthScope's USArray and other regional experiments, and similar investigations of exposed basement along the northern margin of the craton in southwestern Montana. The big questions include the following with example key finds below:

- 1) What is the nature of the modern deep crust of the Wyoming Craton and how did it evolve?
- 2) What were the roles of tectonic processes along the northern margin of the Wyoming Craton during amalgamation with Laurentia?
- 3) How can we use deep exposures of basement in southwestern Montana to discover new insight into deformation processes in general?

Diverse petrologic and geochronologic signatures of deep crustal xenoliths from central Montana and variations in calculated bulk seismic velocities support a composite origin for the high-velocity lower-crustal layer ("7.x layer") that is present in parts of the Wyoming Craton and southern Medicine Hat block. Heterogeneity of physical properties within the layer (e.g., velocity steps) and a locally reduced contrast in properties across the crust/mantle boundary owing to upper mantle metasomatism may help explain contrasting seismic interpretations of crustal thickness in the region. In conjunction with xenolith studies in the southern Rockies, insight is also gained into how subsequent modification of deep crust during younger tectonic events may influence lithospheric properties and mountain-building processes. For example, Late Cretaceous (ca. 70 Ma) deep crustal hydration is documented from the central Colorado Plateau, with the fluid possibly sourced from dehydration of shallowly subducted oceanic lithosphere. The influence of garnet-consuming hydration reactions on the density and rheological structure of lower continental crust has potentially important geodynamic consequences for regions that may have once had higher density and higher velocity properties like the northern Wyoming Craton.

New and compiled geochronological and petrological data from southwestern Montana that bear on the Big Sky Orogen show that the age of high-grade tectonism progressively youngs southeastward away from the presumed core of the orogen towards the margin of the undisturbed craton, from ca. 1800 Ma to ca. 1720 Ma. These spatial and temporal patterns of lateral growth and propagation of the orogen are similar to those observed in other collisional orogenic systems, and they may reflect multiple collision phases, protracted collision, and/or postcollisional collapse.

Several deeply exhumed ductile shear zones crop out in the Madison Range, observations from which inform on general deformation processes and their potential seismic signature. For example, studies of outcrop-scale shear zones in meta-gabbro-dike dikes suggest that shear zone evolution involved (1)

initial strain localization by nucleation from pre-existing fractures that focused fluid infiltration, (2) grain-size reduction by microfracturing, dislocation creep, and synkinematic metamorphic reaction, and (3) a switch to grain-size sensitive granular flow accommodated by fluid-assisted diffusion in ultramylonite. From a seismic perspective, this evolution is interesting because it suggests that marginal strain gradients where dislocation creep microstructures dominate may contribute as much or more to the bulk seismic anisotropy of the shear zone compared to the higher strained cores where crystallographic alignment due to deformation is weaker.

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Some Reflections on the Mesoproterozoic Belt-Purcell Basin

David Mogk, Montana State Univ., Paul Mueller, Univ. Florida, Carol Frost, Univ. Wyoming

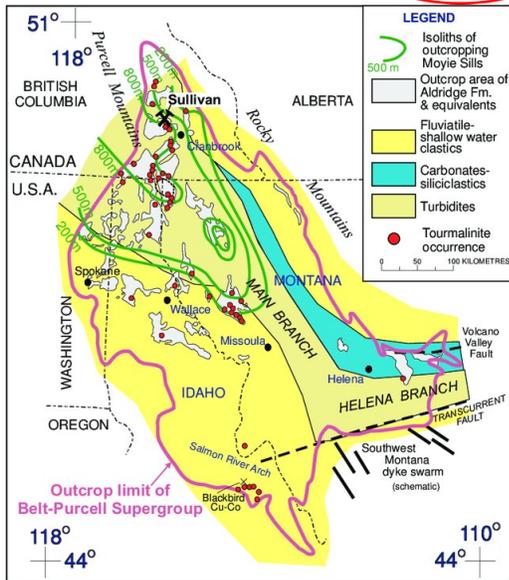
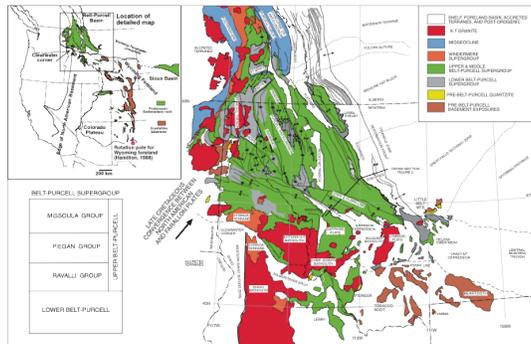
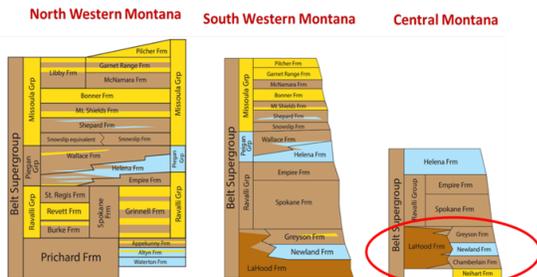
The Mesoproterozoic Belt Basin is a fault-bounded rift basin comprised of a northern half graben, central horst, and southern graben (Sears, 2007). It is one of the largest sedimentary basins over all geologic time, covering an area of over 200,000 km² in Montana, Idaho and SE British Columbia with stratigraphic thicknesses on the order of 20 km. The depositional environment has been interpreted as an intercontinental rift system, and includes both marine and fluvial sedimentary units. Sedimentary sequences include basal units of conglomerates and 10-12 km of marine turbidites (LaHood and Pritchard Formation), carbonates, and deep water silt and mudstones (Newland Formation); subaerially deposited, fluvial sands and muds of the Ravalli Group; carbonate and clastic muds of the Piegan Group; and, fluvial sands and muds of the Missoula Group. Deposition of the most voluminous units occurred ~1500-1320 Ma ago (Lydon, 2004); the oldest detrital zircons (3.8 Ga) are in the LaHood sandstones and conglomerates, but ~1700 Ma in younger units. The unique setting in space and time of the Belt-Purcell Basin raises important questions about its tectonic and depositional environment(s), provenance of its sediments, and role in global tectonic reconstructions:

- What is the provenance of the sediments in the Belt-Purcell Basin? Early geochemical and isotopic studies by Frost and Winston (1987) demonstrate that most of the sediments were not derived from the Archean of North America but came from a western source. Detrital zircon (and Ar-Ar detrital muscovite) studies by Ross and Villeneuve (2013) also interpreted the sediments to have been at least partially derived from a non-Laurentian, western craton based on zircons with ages in the N.A. magmatic gap, with only subordinate input from Laurentian sources. Mueller et al. (2016) have shown that within the LaHood Formation there must have been compartmentalized, time transgressive sub-basins that received sediment from multiple, disparate sources.
- Are “lower Belt” units (e.g., Neihart Quartzite) actually pre-Belt (prior to rifting); and is it more appropriate to think of these rocks as post-Great Falls orogeny due to post-orogenic extension and collapse, i.e., <1700 Ma)?
- The western conjugate to the Wyoming Craton is a matter of speculation, and has been interpreted as the Siberian Platform (Sears and Price, 2002) or alternatively Australia (Gawler craton) and/or East Antarctica (Moore, 1991, Ross and Villeneuve, 2013). The Belt Supergroup provides an important reference point for understanding the break-up of Laurentia.
- The extent to which pre-existing crustal and mantle structures led to formation and evolution of the Belt Basin is unknown. The Basin overlies parts of the Wyoming Craton, the Great Falls Tectonic Zone, and accreted terranes to the west. Did the presence of the Wyoming craton to the south influence the location and development of the Belt rift basin? How has the geometry of the Basin affected a) Phanerozoic depositional systems, and b) the geometry of younger structural events (e.g., the Sevier style thrusting in the easternmost Helena Embayment)?
- How did the Belt Basin maintain relative tectonic quiescence during deposition over such a long period of time, and how could the crust in this area have accommodated ~20 km of

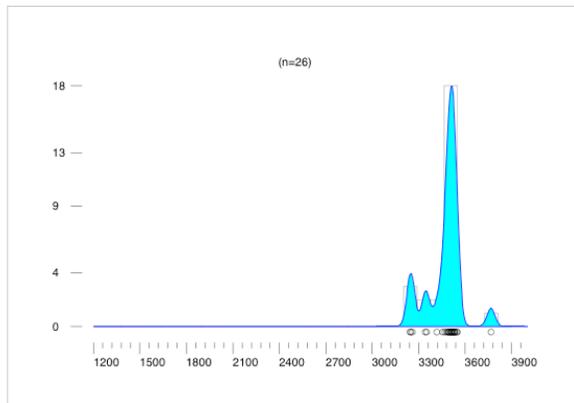
deposition? How did subsidence and extension occur with only limited magmatism, (e.g., Moyie sills in the western basin but none in the eastern Helena embayment?)

- What controls metallogenesis in the Belt-Purcell Basin, which is host to world class deposits such as the Sullivan Zn-Pb-Ag SEDEX deposit of British Columbia, the Coeur d'Alene Ag-Pb district of Idaho, Montanore and Black Butte Deposits of Montana and what did it have to do with Phanerozoic deposits, e.g., do they represent remobilized Belt deposits? Zartman showed that Pb in some of the Pb deposits had an Archean source, but most deposits were of Paleoproterozoic derivation; what are the implications for source area and mobilization of metals in these deposits?

From Vuke et al., 2009



from Sears et al., 2007



From Lydon, 2007

LaHood Formation
Conglomerate Matrix, Jefferson Canyon

FROM CONTRACTION TO EXTENSION: TECTONOMAGMATIC ARCHITECTURE OF THE SEVIER OROGENIC WEDGE OF WESTERN MONTANA

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The Cordilleran orogen was built upon a passive margin sequence of Middle Proterozoic and Paleozoic sediments underlain by a complex foundation of Paleoproterozoic and Archean crust. In the northern Rocky Mountain region, the first major disruption of that sequence began during the late Mesozoic with terrane accretion and continental arc magmatism near the western margin of North America. During that time, the back-arc region underwent eastward thrusting of Middle Proterozoic, Paleozoic and Mesozoic sedimentary sequences. From ~79 to 75 Ma the Sevier orogenic wedge developed large basement culminations along a hingeline, formed in the north by the tapered edge of the Middle Proterozoic Belt Basin and to the south by the tapered Paleozoic miogeocline (DeCelles and Mitra, 1995). In SW Montana, at ~75 Ma, basement-dominated and Belt-dominated culminations were replaced by silicic plutons, including the large volume Boulder batholith, that invaded the fold and thrust belt at all crustal levels. Late Cretaceous plutons are dominantly laccolithic and particularly localized along thrust ramps. Most intruded along major or local thrust systems and thus inflated the hanging wall sections. The resultant thick (16–17 km) igneous culmination evolved over a relatively short interval, thickening the orogenic wedge to the point of supercritical taper and facilitating motion within the Helena salient thrust system (Lageson et al, 2001, Kalakay, 2001). South of this magmatic zone, taper of the Sevier orogenic wedge was kept in steady state by development of basement culminations. To the north, wedge dynamics were controlled by a thick, relatively strong wedge of Belt sediments (Fuentes et al, 2012). Shortening on the Lewis thrust system (northern sector), and thrusts in the Helena Salient occurred roughly between 75 Ma and 52 Ma (Fuentes et al, 2012; Harlan et al, 1988). Major hinterland extension, in the form of core complexes, began around 54–53 Ma (Foster et al., 2001, 2007) and overlapped with ongoing contractile deformation in the foreland.

The Eocene Anaconda detachment, which translated the Boulder batholith tens of kilometers eastward, exposes a footwall showing high-temperature deformation, metamorphism, crustal anatexis, and plutonism in the middle crust of the Montana hinterland (Foster et al, 2007). Eocene extensional structures and fabrics are superimposed on hinterland structures that developed much earlier, during Late Cretaceous contraction and metamorphism. Late Cretaceous, high temperature strain is heterogeneously distributed within the footwall of the Anaconda core complex, but extreme tectonic attenuation of Middle Proterozoic Belt stratigraphy dominates. The age of this attenuation is estimated to be ~74.5 +/- 0.4 Ma (Foster, unpublished data) as constrained by the syn-kinematic Storm Lake pluton. Eocene detachment faults, which exhumed metamorphic core complexes in the northern Cordillera, are kinematically linked to large strike-slip faults such as the Lewis and Clark fault zone. The Lewis and Clark fault system separates ENE-directed extension in the Priest River complex from ESE-directed extension in the Bitterroot and Anaconda complexes. This is part of a regional extensional geometry (from BC, Canada to northern Nevada), where stretching lineations in core complex mylonites are oriented 100°–110° and coincide with the general trend of the transcurrent faults. Extension and exhumation of middle crustal rocks within this region was concentrated in areas that also experienced voluminous Eocene midcrustal magmatism. Most are also underlain by thick sequences of undeformed and un-metamorphosed (i.e., “orogenically fertile”) sedimentary packages. Such widespread extension was probably initiated by a change in plate boundary conditions combined with the rapid influx of heat from beneath the western Cordillera, but the driving forces remain unclear.

Major questions regarding the tectonic evolution of the Cordillera are as follows:

- 1) How much does orogenic wedge or crustal rheologic profile vary in space and time?

- a. Must consider variations in composition/lithology
 - b. Must also consider changes in thermal regime (e.g., magmatic input)
- 2) How much do variations in crustal rheology control variations in thrusting, hinterland thinning, and the transition to extension?
- 3) Are mantle kinematics coupled with kinematics in deforming continental crust? If so, how?
 - a. What large-scale phenomenon is responsible for Eocene extension with such consistent kinematics?
- 4) Do field studies test or help refine the dimensions of plate-scale models (e.g., flat slab subduction, slab break-off, slab windows, etc.)?

Magnetotellurics and Related Geophysical Methods: Open Discussion

What can be revealed by regional magnetotellurics surveys regarding the structure and role of fluids in the crust?

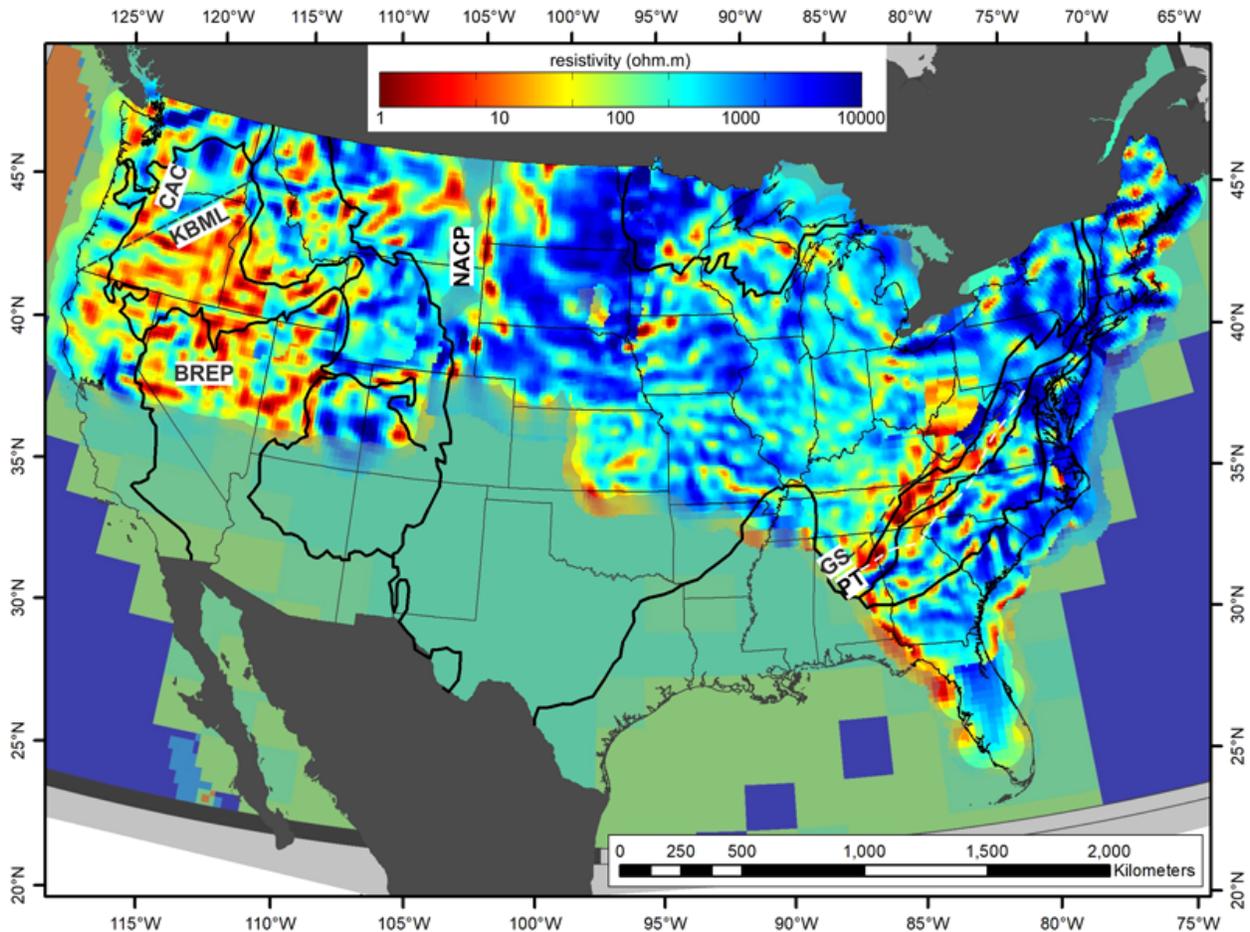


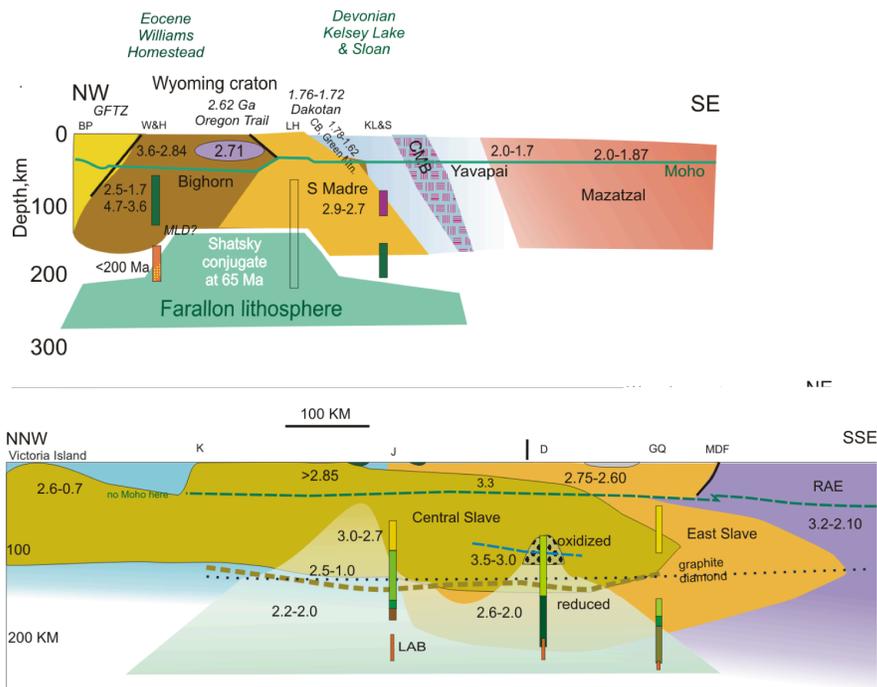
Image from: Kelbert, A., S. Erofeeva, C. Trabant, R. Karstens, and M. Van Fossen (2018), Taking magnetotelluric data out of the drawer, *Eos*, 99, <https://doi.org/10.1029/2018EO112859>. Published on 27 December 2018.

Weakening Cratons by Metasomatism: Conductivity Maps the Alteration

David Snyder, Laurentian University

Metasomatism is increasingly recognized to have a major effect on the strength and durability of cratons embedded within continental lithosphere, especially by those in the mineral and diamond exploration industries. Conductivity variations mapped by 3-D magnetotelluric surveys appears to partly map the extent of the metasomatism. This can be correlated in to places with decreased S-wave speeds or seismic discontinuities. Because large temperature variations are deemed improbable with in cratonic lithosphere today, both of these geophysical anomalies must instead be attributed to compositional variations, probably increased amounts of graphite, sulfides, or hydrous minerals. Robust 3D surveys and modelling is now available from the Slave, Rae, Superior, Gawler, and Wyoming cratons. All of these cratons appear extensively affected by metasomatism at depths greater than 80-100 km with local effects projecting upward into the crust. The Wyoming craton is exceptional in that it is largely resistive and that its lower lithosphere, presumably pre-conditioned by metasomatism, is interpreted to have been replaced by the arrival of the Farallon oceanic plate lithosphere. Below are cross sections of the Wyoming and Slave cratons.

Snyder, D. B., Humphreys, E., and Pearson, D. G. (2017) Construction and destruction of some North American cratons. *Tectonophysics*, 694, 464-485.



Synthesis of regional-scale geophysical, geochemical, and thermal models of the crust and upper mantle beneath the Wyoming craton

Heather Bedle, The University of Oklahoma

Recently, datasets have been gathered with the intention of synthesizing them in a single software that will allow manipulation and quantitative analyses. The goal of this is to collect a variety of datasets that include geophysics (active and passive seismic, crustal and mantle regional tomographic models, gravity, magnetic), geochemical datasets (xenolith), thermal models, and geologic maps. Data can consist of discrete data points, 1D, 2D, and 3D datasets (volumes or surfaces). The hope is that the range of data can be directly analyzed and co-rendered to allow for additional insights concerning the Wyoming craton. Deep, 2D seismic reflection datasets are currently being analyzed (Figure 1) and loaded into Petrel for modern analysis. An example of this legacy data is the COCORP seismic lines from the late 1970s, that have not gone through modern processing and analysis workflows. Acquisition of additional 2D crustal seismic results (Deep Probe, CDROM, BASE) will be attempted. A quick analysis using recently results by Worthington et al. (2016) suggest that resolution of continental scale tomographic models such as NA07 (Bedle and van der Lee, 2009), may not provide adequate resolution for new insights at this scale (Figure 2). Regional- to local-scale tomographic models need to be acquired. This synthesis is in very early stages of development.

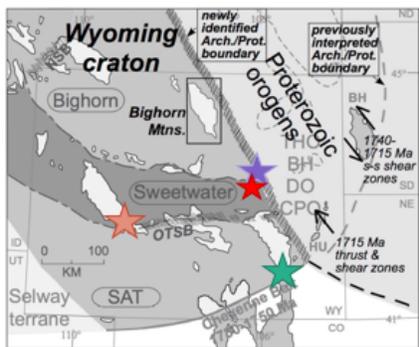
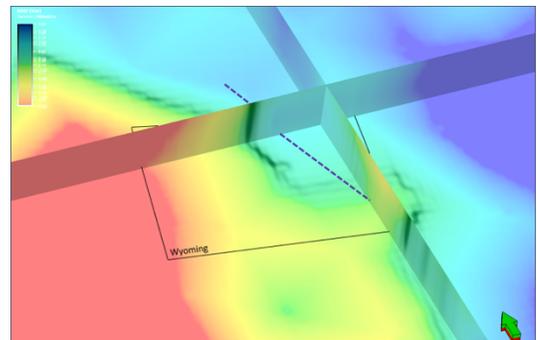


Figure 1: Location of acquired data on tectonic map after Worthington (2016). COCORP 2D seismic data (orange and green stars), Powder River Basin 2D Seismic reflection data (purple star), and Teapot Dome 2D and 3D seismic reflection data (red stars). These datasets occur near cratonic transitions.

S-velocity model NA07 amplitudes (rainbow colorscale) and coherence attribute (greyscale) to identify sharper transitions in the upper mantle velocity structure. Outline of Wyoming (black), and proposed Archean-Proterozoic transition by Worthington et al., 2016 (purple dashed) are annotated for reference.

Figure 2: 3D view of the co-rendering of



THE MAKING AND BREAKING OF CRATONS

C.M. Cooper, Washington State University

The first order observation of cratonic lithosphere is that it is there. While this might seem a bit of a flippant statement, the persistence of (most) cratonic lithosphere to survive and witness the majority of Earth's history requires either possessing intrinsic properties that inhibit deformation (Lenardic & Moresi, 1999; Lenardic et al., 2003; Cooper et al., 2006), proximity to regions that preferentially experience more deformation (Lenardic et al., 2000; Cooper & Conrad, 2009), or a combination of the two. If we point to intrinsic properties providing craton stability, this can then winnow down the processes that led to the formation of thick, stable, cratonic lithosphere (Cooper et al., 2006; Cooper & Miller, 2014 and see Lee et al., 2011 for an in-depth review). However, just making stable lithosphere isn't sufficient to meet that first order observation of being observable present day – (most) cratonic lithosphere is also long-lived, meaning that it must remain stable in changing dynamics. Making long-lived lithosphere (that can survive for billions of years) is more complicated than making thick lithosphere that is stable during past conditions. Often the conditions that allow for building cratonic lithosphere do not provide longevity, and, more problematic, the conditions required to make long-lived, thick cratonic lithosphere are not provided by the past dynamics (Cooper et al., 2006; Cooper et al., 2017; Beall et al., 2018). Thus, there is the potential for some cratons to not survive until present day. They, perhaps, weren't built to last or their material properties modified postformation, no longer ensuring stability. Regardless, understanding stability, longevity, and instability requires exploring the interplay between the intrinsic lithospheric properties and mantle dynamics to determine when you make and you break cratons.

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THE WYOMING CRATON IS NO LONGER A CRATON

Suzan Van der Lee, Northwestern University

I: Pre-Earthscope S-velocity models for the old, cold, and stiff mantle lithosphere of the North American Craton show surprisingly little of it beneath Wyoming. This has typically been interpreted as being the result of extensive alteration – via metasomatism – of the Wyoming Craton’s mantle lithosphere.

II: Early tomographic results from Earthscope/USArray data supported this image and interpretation of the Wyoming Craton.

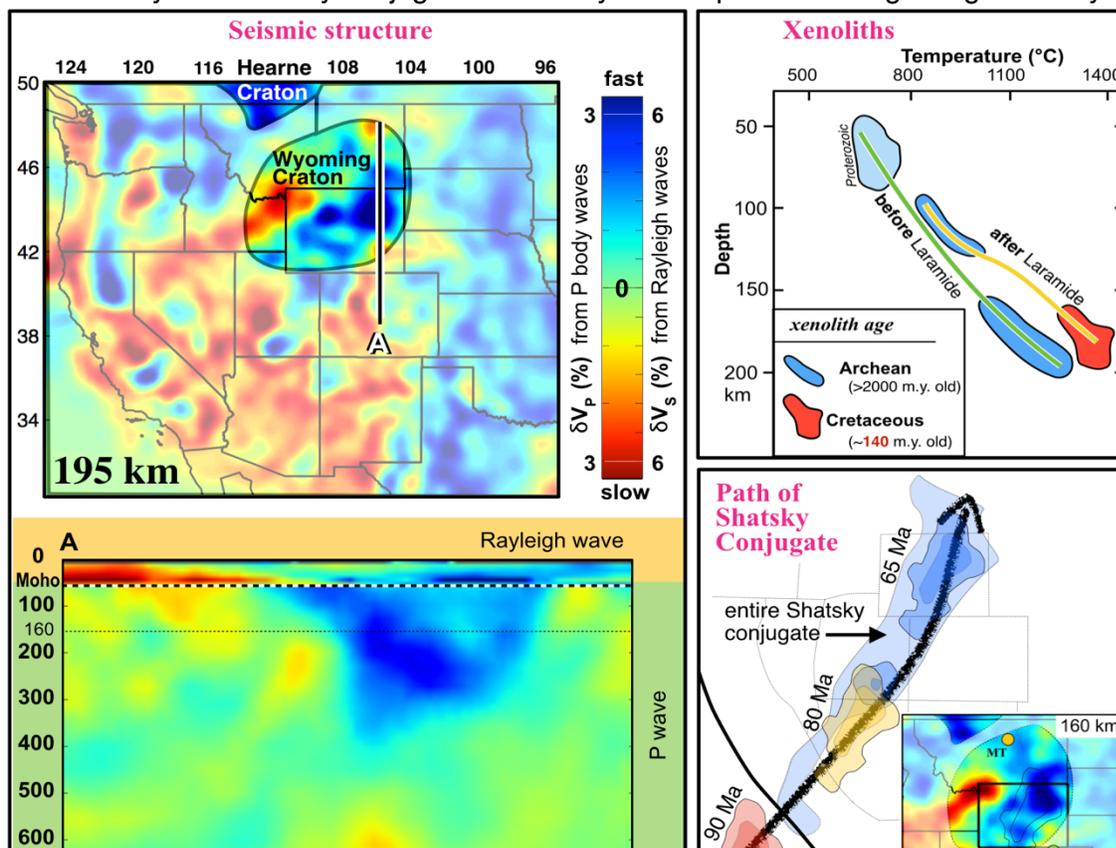
III: But was the Craton really metasomatized or was it supplanted by the lithosphere of a subducted intra-oceanic plateau? We use subsidence and sedimentation data from the western interior basin and tectonic-plate reconstructions, to track particular slab fragments over geological time. The results suggest that the Western Interior Basin was underlain by a flat slab for most of its formation, which presents a ready source for metasomatism of the overlying Wyoming Craton lithosphere.

Laramide-age growth of the Wyoming Craton by ocean plateau under-accretion

Gene Humphreys, University of Oregon

High-velocity mantle (blue areas in left-side figures) extends to ~300 km beneath Wyoming. If this mantle is craton, what could increase its buoyancy since ~80 Ma, after the area sat near sea level for 100s of m.y.? Devonian xenoliths (green line, upper right figure) indicate a typical craton: ancient rocks to ~200 km and a low heat-flow gradient. However, post-Laramide xenoliths (gold line in figure) indicate that 20-60 km of basal craton was replaced with young mantle of ~140 Ma age. Also notice that the high-velocity mantle structure is elongated NE-SW, which is not like the Wyoming craton.

It seems impossible to account for (a) 1-2 km of uplift of cool mantle, (b) replacement of the lower craton with young mantle, and (c) the oddly shape and very deep volume of high-velocity mantle; and all this, deep within the continental interior. But just when and where it is needed, a buoyant ocean plateau – the Shatsky conjugate – arrives on the flat-subducting Farallon Plate. The 140 m.y. old Shatsky conjugate has nearly the shape of the imaged high-velocity structure.



Left side. Seismic tomography, using Rayleigh waves for the crust and P body waves for the mantle. Section crosses the high-velocity structure at its deepest (and conjugate of Tamu, Earth's largest volcano).

Top right. Xenolith profiles from a pre- and a post-Laramide site (sites shown in figure bottom right).

Bottom right. Inferred path of Shatsky conjugate, showing its main body and entire conjugate at 65

Ma.

DEFORMATION AND STRUCTURAL EVOLUTION OF THE DEEP CRUST AND LITHOSPHERE FROM EARTHSCOPE SEISMIC DATA AND GEOLOGICAL GROUND TRUTH

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1 University of Colorado Boulder, 2 Stony Brook University, 3 Lehigh University

The continent-spanning EarthScope Transportable Array and densified FlexArrays allowed seismologists to develop many new techniques for array-based earthquake source and deep Earth imaging. New surface wave gradiometry using ambient noise and advances in receiver function methods enable detailed imaging within the lithosphere. Two developments of close relevance to investigating the evolution of the continent and of the Wyoming Province in particular are imaging of seismic velocities in the lower crust and imaging of deformation-related rock fabric preserved in the deep crust and lithospheric mantle. Parts of the continental U.S., including parts of the Wyoming province, show higher-than-average seismic velocities in the lower crust. The thickness of this layer is shown in Fig. 1 from a joint inversion of surface waves and receiver functions. Its distribution does not correlate well with Precambrian boundaries and instead follows the Laramide front, suggesting recent reworking of lower crustal material, which is also borne out in xenolith studies (see Mahan talk).

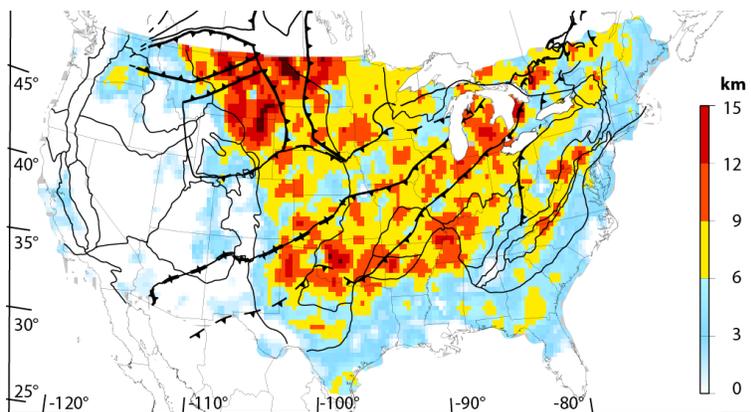


Fig. 1: Thickness of high-velocity ($V_s > 4.0$ km/s) lower crust from joint inversion of surface waves and receiver functions. Thick back lines are Precambrian boundaries, thin black lines physiographic boundaries. Thick layer largely ends at the Rocky Mountain-/Laramide Front. Modified from Schulte-Pelkum et al., 2017, *Tectonics*.

An important caveat is our continued difficulty in resolving lower crustal and Moho structure accurately in common settings. Near-surface effects under sedimentary basins in receiver functions and tradeoff in surface wave resolution between uppermost mantle and lower crust continue to lead to artifacts in seismic results. A related issue is the possible discrepancy between seismic and petrological Moho depths. The largest velocity increase may not coincide with the crust-mantle boundary, for example in the northern Wyoming province.

Deformation of the continental crust is recorded in structural rock fabric. P receiver functions show characteristic variations with event azimuth that can show shear zones with contrast in such fabric down to 2-3 km thickness and resolve their depths, an approach better suited to conducting structural geology at depth than other methods targeting anisotropy. Fig. 2 shows the continent-wide signal strength from dipping foliation and dipping interfaces integrated through the crust into the uppermost mantle, with higher signal strength in orogens. Other panels in Fig. 2 show the strike of individual dipping contrasts or foliation at depth across the Wyoming Craton in comparison with mapped shear zones and bulk structural fabric. This method opens the possibility of extending structural mapping to depth.

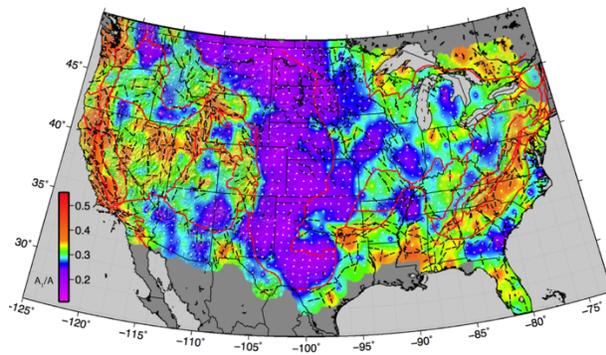
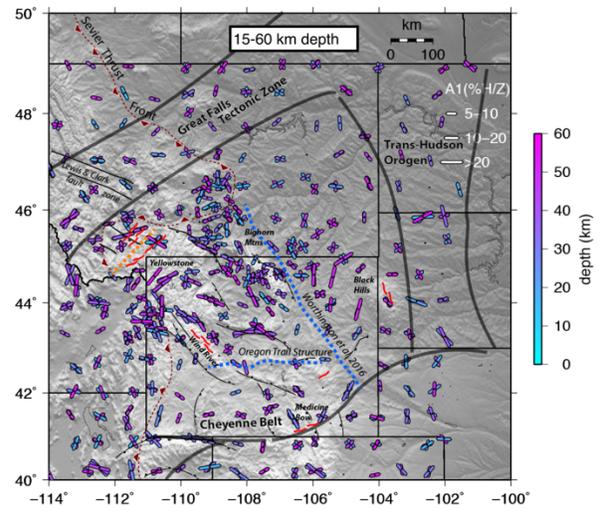
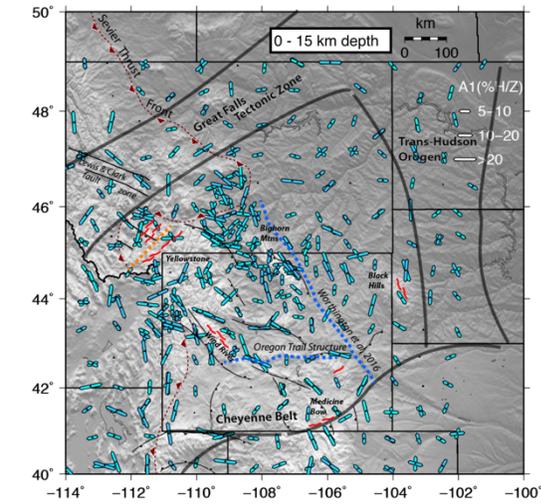


Fig. 2. (top left) Receiver function strikes (bars) of dipping interfaces or contrasts in dipping foliation in upper crust (bar color=depth) show alignment with Laramide structures. (top right) Same for lower crust into mantle; some alignment with Precambrian NE-SW oriented structures. (bottom left) Signal strength from dipping interfaces or foliation across continental TA; orange = strong deformation signal. Bars show strike of individual contrasts as above.

IMAGING THE MANTLE STRUCTURE OF THE WYOMING CRATON: IMPLICATIONS FOR THE FORMATION AND MODIFICATION OF CRATONIC LITHOSPHERE

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To seismologists interested in characterizing mantle structure, the word craton is often used to describe continental regions of fast seismic wave speeds that extend to depths of ~150-200 km. The high velocities are thought to be indicative of a cold, depleted mantle. Despite the cold temperatures, which would reduce buoyancy, the cratonic lithosphere appears to be convectively stable, indicative of a rheology capable of withstanding the tectonic demolition that occurs elsewhere. Two questions that arise from the conclusion that cratonic mantle is old and stable are 1) What process (or processes) produced the mantle material found within cratons and 2) under what circumstances can cratonic lithosphere be modified or destroyed.

Lithospheric mantle discontinuities within the Wyoming craton (and elsewhere).

In a 2010 paper by Abt et al., the term “mid-lithospheric discontinuity” (MLD) was coined in order to describe a pervasively observed seismic discontinuity within the lithospheric mantle of the stable North American interior, typically observed at depths of ~80-120 km. Similar observations were made in other cratonic settings (e.g., Ford et al., 2010; Fisher et al., 2010) and discussions of what these discontinuities might imply for the formation and evolution of the cratons at the global scale quickly advanced (e.g., Selway et al., 2014). The presence of Earthscope’s Transportable Array (TA), and improvements to USArray, generated additional data and allowed for a more detailed understanding of the properties of the MLDs beneath stable North America. For example, a Ps receiver function study of the Grenville region of North America suggested that MLDs may have resulted from lithospheric deformation. However, a subsequent study of several permanent seismic stations within the Wyoming and Superior cratons found that while significant evidence for fossilized deformation (i.e., seismic anisotropy) exists, it does not typically coincide with the observed MLDs within the Wyoming and Superior

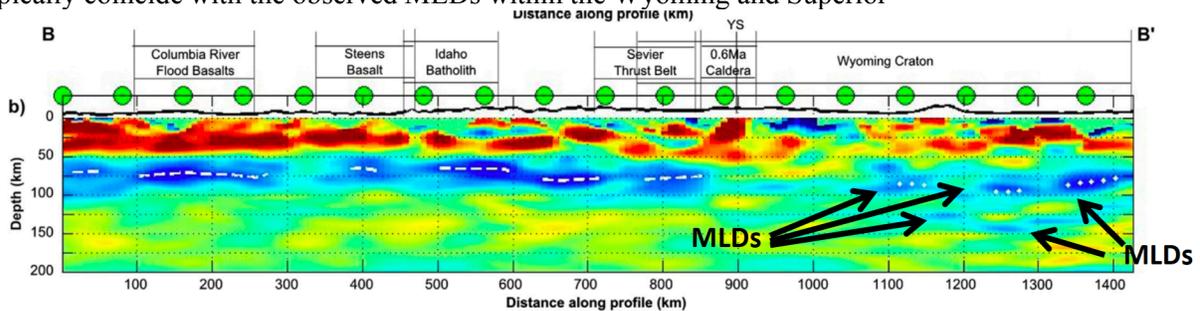


Figure 1. Modified from Figure 3 of Hopper et al. (2014). CCP stacked S_p receiver functions. Red color indicates positive velocity contrast, typically associated with the Moho. Blue indicates a negative velocity contrast. This is often associated with the lithosphere-asthenosphere boundary (e.g., distances 0-900 km along profile) but is also associated with MLDs beneath the Wyoming craton (i.e., distances ~1000-1400 km along profile)

cratons (Ford et al., 2016). Analysis of TA data has led to some of the most significant advances in our understanding of MLDs. Hopper et al. (2014) generated high resolution images of the lithospheric mantle beneath the Wyoming craton MLDs (Figure 1) and demonstrated that MLDs are not a single step-like discontinuity, but rather a series of smaller discontinuities, which are hypothesized to be the result of subduction processes related to craton building.

Addressing Laramide-associated structural changes to the Wyoming craton (co-PI: Maximiliano J. Bezada, University of Minnesota)

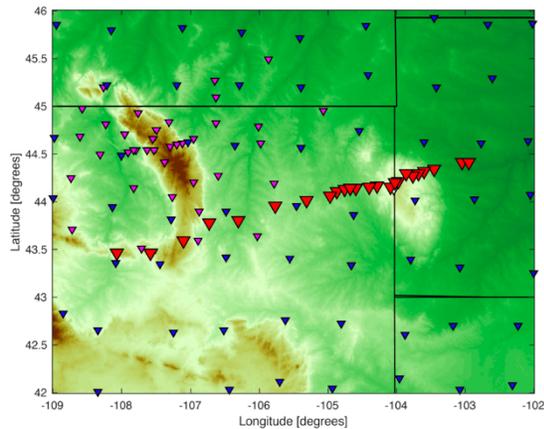


Figure 2. Locations of seismometers installed during the CIELO seismic experiment (red, inverted triangles). Locations of other broadband seismometers, including TA (blue) and BASE (magenta) are also shown.

The basement-involved uplifts within the Wyoming craton during the Laramide implies that cratons can be modified, and tomographic imaging of the subsurface supports this assertion. Yet seismic tomography also images high velocities under portions of the craton that extend to 250 km depth. This region of high velocity has been interpreted to be either a stable piece of lithosphere, which may or may not be original to the craton, or a weakened remnant in the process of delamination. The proximity of the block's edge to the Black Hills suggests that the block itself may have played a role in the easternmost Laramide-associated uplift. In September 2017, 24 broadband seismometers were installed across the eastern half of the Wyoming craton (Figure 2). The experiment, named *Crust and lithosphere Investigation of the Easternmost expression of the Laramide Orogeny (or CIELO)*, is

slated to operate continuously for 2 years. Preliminary P-wave travel time results are consistent with a +2.5% anomaly over the upper 200 km of the mantle that sharply terminates at the western edge of the Black Hills. Ps receiver functions show rapid lateral variations in crustal thickness beneath the Black Hills, with a minimum of 39 km along the western edge, which is co-located with the margin of the high-velocity feature, thickening to a maximum of 58 km along the eastern edge of the mountains. There is also strong evidence for anomalous discontinuities within the mid-crust across the Black Hills. These preliminary results show that there is pronounced and complex structure both the crust and upper mantle, suggesting a connection between the uplift of the Black Hills and the internal, potentially modified structure of the craton.

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RAY RUSSO

THE TRANSPORTABLE ARRAY – A UNIQUE CAPABILITY FOR THE EARTH SCIENCES COMMUNITY

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The EarthScope Transportable Array (TA) is a large mobile array of 450 high-quality broadband seismographs with real-time telemetry that is designed to image Earth structure, characterize regional seismicity, and study large, distant earthquakes. Beginning in 2004, these seismographs rolled across the lower 48 states from west to east in a continuous field operation, occupying more than 1700 sites with a station spacing of 70 km. After a deployment of two years, each instrument was moved to the next site on the eastern edge of the array. The TA finished its work in the Lower 48 states in 2015 and was redeployed in Alaska where it is currently operating. The TA, and the complementary Flexible Array, enabled a broad range of remarkable science, well beyond that envisioned when EarthScope was proposed, including imaging crustal, upper mantle and deeper Earth structure using both teleseisms and novel approaches such as ambient noise tomography, characterizing regional seismicity (location and size of events) and associated source mechanisms, and studying large distant subduction earthquakes through back projection and array beam forming techniques.

The TA is unique in many aspects that distinguish it from PI-driven temporary deployments such as those supported by PASSCAL or permanent global networks like the Global Seismic Network. The TA can be deployed on a regional or subcontinental scale, it is installed and operated by professional crews working year-round, it provides data in real time, and, as a community experiment, all data are immediately open and available to anyone. The TA provides additional capability through its structured methodology for conducting large experiments and its novel approaches to sensor emplacement, power generation, real-time data transmission, and multisensor integration. Implementing the TA has involved a large-scale system development and engineering effort to meet the challenges of deploying stations in both the continental United States and at remote locations in Alaska accessible only by helicopter. The TA has developed an integrated, streamlined process for station surveying, permitting, construction, and deployment, employing multiple field crews for full-time field operations. The hallmarks of the TA project included innovation, efficiency, and large-scale deployments for obtaining high-quality, large-scale observations. This new capability, developed as part of EarthScope, has allowed IRIS to support large national or international community geophysical experiments at a scale far exceeding what individual PIs can achieve, enabling researchers to pursue exciting new scientific problems and develop new analytical and data analysis techniques.

No new projects comparable in scale to the EarthScope TA have been funded in the U.S, although the Canadians are planning a project modeled after the TA in the Canadian Cordillera (CCArray) and a new TA-like effort is getting underway in China with an even larger, denser array of stations. The need for TA-like capabilities has been identified in other international planning efforts within the geosciences community (e.g., the Subduction Zone Observatory [SZ4D] and the Global Array of Broadband Arrays [GABBA]), but no firm plans are in place. As a result, there is a danger that the technical and management expertise in U.S. community to conduct TA-like experiments in the future will be lost.