Report on the EarthScope Synthesis Workshop:

Life and Death of a Craton: A 4D Perspective on the Role of the Wyoming Craton in the Evolution of North America

January 10-13, 2019; Montana State University, Bozeman, MT

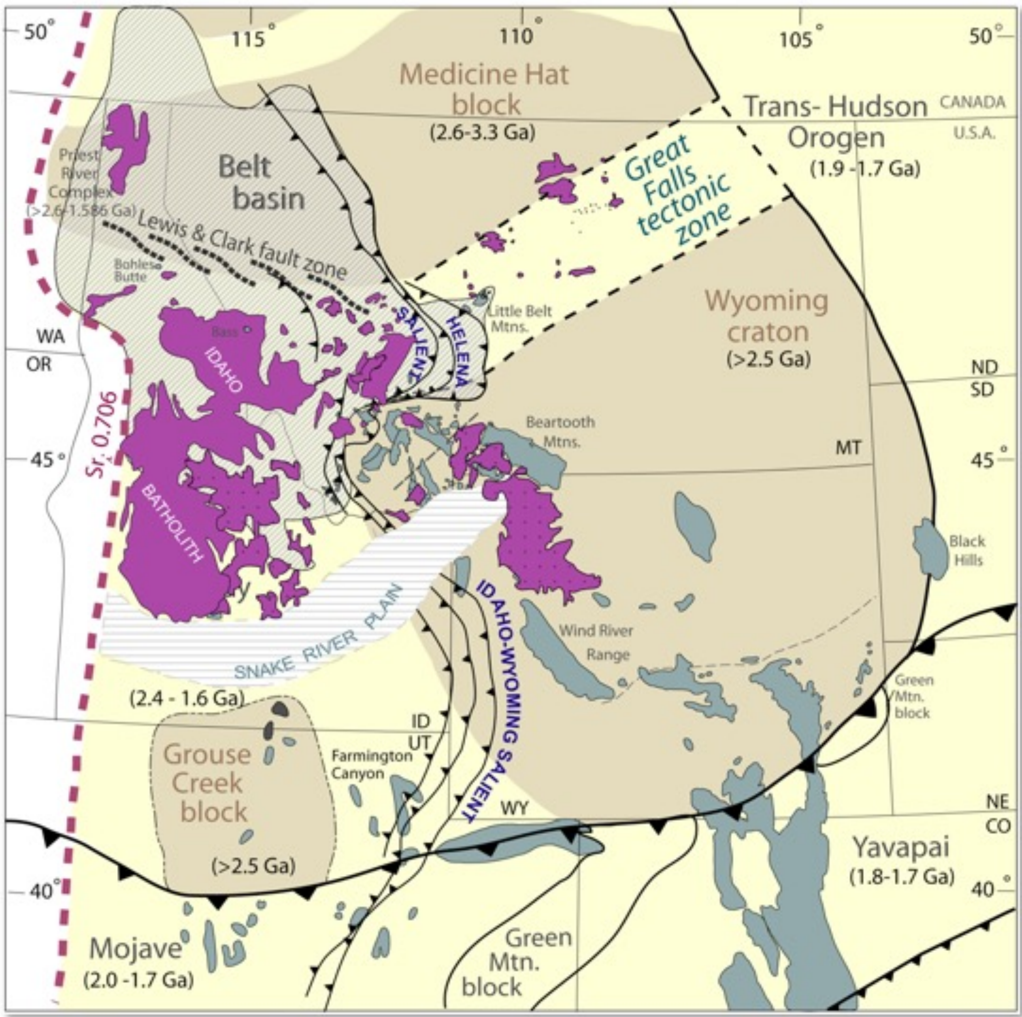

Figure 1. The Wyoming Craton and its neighboring crustal provinces in the western United States (after Foster et al., 2006).

I. Workshop Conveners, Participants, and Organization:

Conveners:

David Mogk, Montana State University
Paul Mueller, University of Florida
Carol Frost, University of Wyoming
Ray Russo, University of Florida

Participants:

Julie Baldwin, University of Montana
Heather Bedle, University of Oklahoma
Paul Bedrosian, Magnetotellurics Expert
Kevin Chamberlain, University of Wyoming
Catherine "Katie" Cooper, Washington State University
Bob Detrick, IRIS
Heather Ford, University California-Riverside
Jennifer Gifford, University of Mississippi
Darrell Henry, Louisiana State University
Gene Humphreys, University of Oregon
Tom Kalakay, Rocky Mountain College
Kevin Mahan, University of Colorado
Suzan Van Der Lee, Northwestern University
Vera Schulte-Pelkum, University of Colorado
Jeff Vervoort, Washington State University
Ryan Wilhelmi, University of Florida

National Office:

Samantha Slease, ESNO
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Workshop Websites

National Office, Synthesis Workshops-- Life and Death of a Craton
http://www.org/research/synthesis_workshops/Life_and_Death_of_a_Craton

Northern Rockies Workshops

2005 Workshop https://serc.carleton.edu/rockies/2005_workshop.html
2019 Workshop https://serc.carleton.edu/rockies/2019_wksp.html

- Workshop Program with all presentations and summaries of discussion groups posted https://serc.carleton.edu/rockies/2019_wksp_program.html
- References—over 500 references were compiled through contributions of the workshop participants and used in this report; this is the place to start for future applications to education and research on the history and architecture of the WC, and on the creation and destruction of cratons in general. https://serc.carleton.edu/rockies/wyoming_craton_references.html

II. Workshop Goals

The 2019 *Life and Death of a Craton: A 4D perspective on the role of the Wyoming Craton in the evolution of North America* workshop was convened to 1) take a reflective look at the scientific advances that have been made over the prior 15 years since the 2005 Northern Rocky Mountains Workshop that were facilitated or made possible through use of the EarthScope facility and related funding, and 2) to define future research topics to build on the knowledge base this research has provided. Topics that were addressed at this workshop included:

1. How to obtain a better understanding of the lithospheric structure and evolution within and adjacent to the Wyoming Craton (WC, Fig. 1). This includes a) imaging of seismic velocity, structure, and thickness of the crust and sub-cratonic mantle, and b) establishing the geochronologic framework of crustal evolution, using isotopic tracers to distinguish source areas and to demonstrate pathways in global geochemical cycling, and determining of the rates of geologic/geochemical processes (from mantle to surface and back).

2. Development of a more complete understanding of: 1) the interaction of the lithosphere with the Yellowstone hot spot and associated Snake River Plain volcanism and 2) the shallow subduction regime of the Farallon plate.

3. How to develop a broader understanding of the deformation of North American continental lithosphere, including ancient deformation associated with the incorporation of the WC into Laurentia and accommodation of the Belt basin; the current state of stress in the lithosphere and its relation to active deformation and the Rocky Mountain seismic belt; reactivation of earlier structures that influenced Laramide, Sevier, and Basin and Range structures and their relation to metallogenesis.

4. Better understanding of 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.

5. Develop education and outreach opportunities to serve educators at all levels.

III. Workshop Program

The workshop program was designed around two themes:
1) The first day of the workshop provided a review of our current understanding of the crust of the northern Rocky Mountains and the Wyoming Craton's (WC) place in that part of North America. Participants presented research results developed under the auspices of EarthScope and NSF more generally that bear on the composition, architecture, and evolution of the crust/mantle system. Presentations were made in the context of the workshop themes and with respect to the 2005 workshop report on the *Northern Rockies* and the 2016 workshop on *Synthesizing Results to Develop a New Community Model for the 4-D Evolution of North America*. Presentations focused on Archean crustal genesis (Archean petrogenesis, tectonics [plates or not]); Precambrian crustal evolution (assembly, reassembly, reworking, mobilization of the crust from

the Neoarchean through to Paleoproterozoic); Post-cratonization geologic history/contemporary structure; and the question: What's Up With the Mantle?

2) The second day of the workshop addressed topical and thematic research areas by working groups that defined a) "Big Questions" that remain to be explored, b) evidence available through science outcomes [maps, figures, graphs, datasets, data-products such as tomograms, etc.], and, c) key findings and interpretations. Topics that were addressed include: Archean-Paleoproterozoic crustal evolution (geochemistry, geochronology, isotopic data); Precambrian to Phanerozoic geology, petrology, tectonics, structural geology, basin formation, magmatism; and lithospheric/mantle structure.

Questions and topics that were addressed by the workshop include:

- 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 craton survival , and how do these compare among cratons of the world (Wyoming, Superior, Slave, Kaapvaal, Pilbara, etc.; Fig. 2)?
- Some cratons have Hadean roots and others do not. Wyoming does—is there any effect on subsequent history?
- When and how has the WC been modified/reactivated chemically and physically?
- What is the role of the WC in the assembly of Laurentia? Why do some Archean cratons resist Proterozoic reactivation, and some don't? What does it mean if the Great Falls Tectonic Zone (GFTZ) and Trans-Hudson orogen (THO) are the same age? How does Wyoming fit in the overall evolution of the "United Plates of America"?
- Is the WC being destroyed—tectonic erosion, foundering, delamination? What is the impact of the Yellowstone "hot spot" and which 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-Purcell Supergroup? Where did all the sediment come from that fills the belt basin? Why are Archean zircons rare in these sedimentary rocks? How did the craton survive such large-scale extension (20 km of sediment)?
- Phanerozoic events: how has the margin of the WC 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.

And, what does recent 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, etc.
b. Paleoproterozoic mobile belts—what is the nature/relationship of GFTZ, THO, southern accreted terranes, supercontinent cycles, etc.

c. Cratonization and geodynamics—when and how did the tectosphere form? How do mantle structure and 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, etc.?
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, what do its current physical and chemical properties imply regarding crustal evolution, and, in particular, how is it related to the origin of the high velocity, thick, lower crust of the WC (aka 7x layer).
f. Interaction of the ancient lithosphere of the WC 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, etc. Consequences for structures, magmatism.

All of the presentations and summaries of group discussions are posted on the Workshop program webpage as they were for the 2005 workshop. The synthesis publication for the 2005 workshop is in the *Canadian Journal of Earth Sciences*, 2006, 43(10): https://doi.org/10.1139/e06-075. Plans for follow-on writing of peer-reviewed reports for a thematic issue of Geosphere and development of theme sessions at GSA and AGU meetings have been completed. Plan to submit and attend!

- *2019 Geological society of America Annual Meeting, T66. Life and Death of a Craton: Implications of Archean Crust-Keel Systems for Crustal Growth, Crustal Preservation, and Mantle Evolution; Conveners Paul A. Mueller, Carol D. Frost, Jennifer N. Gifford, David W. Mogk*

- *2019 American Geophysical Union Fall Meeting, Life and Death of Cratons: Craton Interactions with Collision, Subduction, and Volcanism - Global Perspectives and the Wyoming Province as an Example. Conveners are Emily Chin, Chengxin Jiang, Kevin Mahan, and Vera Schulte-Pelkum.*

IV. Overview of the WC and its Significance to the Evolution of North America and the Origin of Cratons Globally

a) What is a Craton

The workshop began with a brief introduction to the concept of cratons and how that concept has changed over time. The term *kraton* (Greek root means force) was prominently promoted by Stille beginning in the 1930s. Stille built on the similar concept of a *Kratogen* proposed by Kober (1921) to describe a stable sedimentary system (platform) that formed in continental crust as Earth contracted upon cooling. Stille was a *fixist* and did not connect the concept of a stable sedimentary platform with any aspect of the mantle. The Stille-Kober definition of a kraton (anglicized to craton) has given way over time to the present concept of a physically connected segment of continental crust and lithospheric mantle that can reach >300 km into the mantle and has remained physically and chemically isolated from the convecting, asthenopsheric mantle for billions of years, i.e., through multiple supercontinent cycles. At present, all "free-standing" cratons (e.g., Slave, Kaapvaal, Wyoming, Yilgarn, etc.) are Archean and all have keels. Keels have not been associated with post-Archean crust. The chemical isolation of a keel was first proposed for the WC by Mueller and Rogers in 1973. The concept didn't really gain traction in the community until the late 1980s, when Jordan showed that keels could also be seismically distinguished from sub-continental mantle in general. Sub-continental mantle had been known to differ from sub-oceanic mantle since the 1920s. Oddly enough, Jordan used the term tectosphere to describe this volume of sub-continental lithosphere, despite the fact that the term *tektosphere* had been in the literature since the late 1800s to refer to layers in the mantle along continental margins that were solid when the margin comprised a thick sedimentary sequence, but became less viscous (partially molten) when unloaded, i.e., providing a mechanism for rifting (Murray, 1899). In this sense the original concept of a *tektosphere* is the opposite of Jordan's definition of a tectosphere.

b) Geologic Context

The Archean WC (or province) is one of three major Archean cratons in North America (Superior-Rae-Hearne, Slave, and Wyoming). Of these cratons, the WC is the least well characterized and understood, largely because of the greater economic significance of the Archean crust of the Canadian cratons and the Lithoprobe active source seismic studies of continental crust of the Canadian shield. In an effort to better understand the WC's role in crustal evolution in general, as well as its place in North American geologic history, a group of 20 graduate students, faculty, and private sector geologists met in January 2019 in Bozeman, MT under the auspices of NSF's EarthScope program. The goals included reaching a consensus on how the EarthScope-supported research on the WC has shed light on the Life and Death of cratons worldwide. The WC is comprised of Archean crust, parts of which formed as early as 4.0 and continued to evolve magmatically and metamorphically until ~2.5 Ga. The WC has many distinctive attributes, e.g., it is characterized by thicker than average crust (>50 km), particularly lower crust (>20 km), a sub-continental lithospheric mantle keel >200 km thick that formed in the Archean, and evidence that the keel has been eroded (thinned) by fluids emanating from the underlying Farallon slab. The WC is unique geochemically as well, particularly in terms of its U-Pb systematics, i.e., the Mesoarchean crust is characterized by low U/Pb ratios, but high $^{207}Pb/^{204}Pb$ for any given $^{206}Pb/^{204}Pb$ compared to any other craton on Earth (Crustal Pb Paradox, Mueller and Wooden, 1988). As such, the WC provides unique insight into the earliest geochemical cycles on the planet. The individual contributions/presentations made at the workshop are available at https://serc.carleton.edu/rockies/2019_wksp.html and theme sessions will be held at both the 2019 GSA and AGU meetings. Those wishing to make a contribution to the upcoming thematic special issue of Geosphere should contact one of the organizers of the workshop or theme sessions listed above.

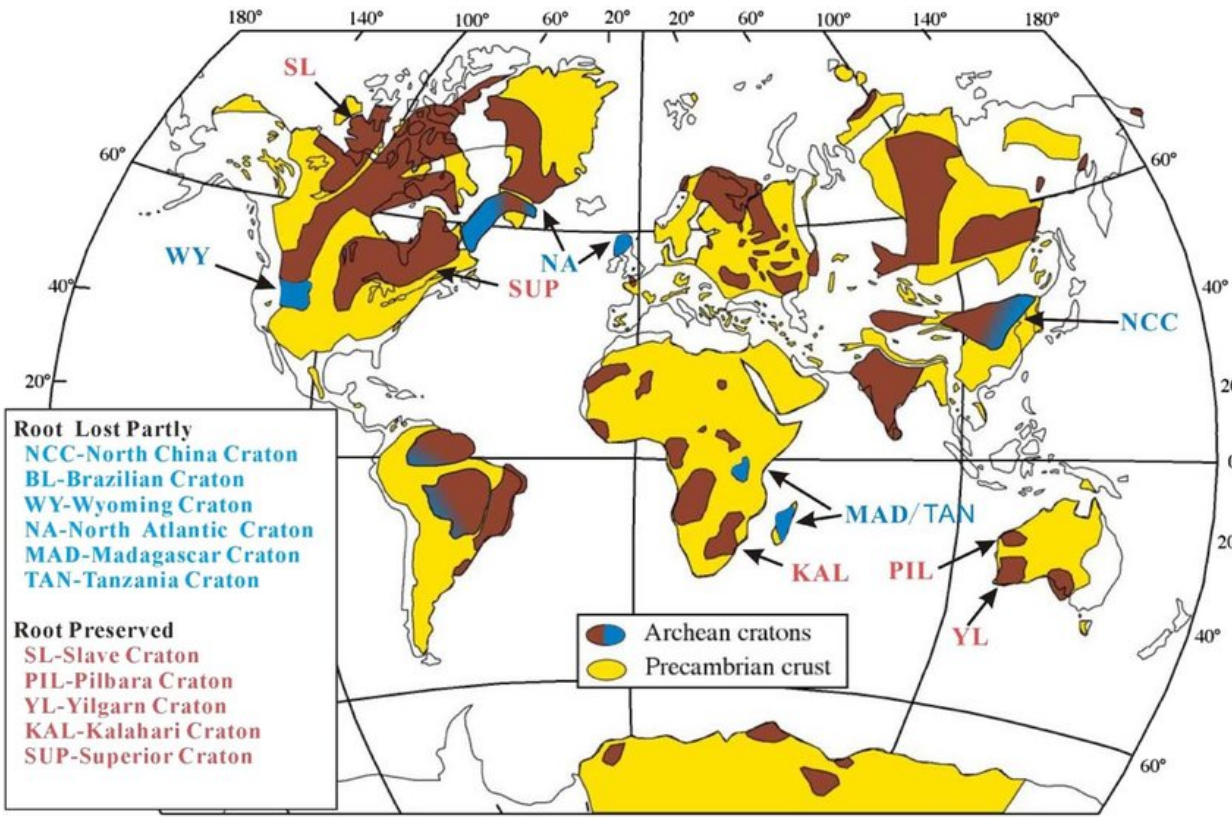

Figure 2. Global Distribution of cratons denoted by their current state of stability (Wang et al., 2018).

c) Why Wyoming?

The Wyoming Province/craton contains one of the longest records of crustal evolution on Earth (Mueller and Frost, 2006). The record extends from 4.0 Ga detrital zircons in Archean quartz-rich meta-sedimentary rocks (Mueller et al., 1998), to 3.8 Ga zircon xenocrysts in Paleoarchean igneous rocks (Frost et al. 2017), to the ongoing interaction with the Yellowstone plume. Lu-Hf and U-Pb isotopic values of Archean rocks suggest that the earliest crust evolved in a plume-like environment and then transitioned to subduction-driven crust production around 3.4 Ga, culminating in a widespread ~3.2 Ga crust-forming event (e.g., Mueller and Wooden, 2012; Mueller et al., 2014). The 3.2 event was followed by an equally widespread subduction related

2.8 Ga event in the northern part of the Province (e.g., Frost and Fanning, 2006; Mueller et al., 2010) and accretion of Neoarchean arc terranes in the southern part of the WC.

The ubiquitous Mesoarchean rocks of the WC are classic Archean TTG (tonalite-trondhjemite-granodiorite) suite rocks that show similar geochemical signatures to modern arc magmas (e.g., enriched LIL, depleted HFSE, etc.). In the southern Beartooth Mountains, these arc-like igneous rocks help define a cross section from the middle to upper crust of a 2.8 Ga continental margin arc, including greenschist facies metasedimentary rocks and granulite facies gneisses and older supracrustal rocks. Neoarchean magmatism and metamorphism is well documented in several places along, and only along, the borders of the Province. Accepting the detrital zircon record as a fair sampling of the Archean crustal growth episodes that entailed felsic magmatism, several prominent episodes are evident: 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 Province-wide quiescence (e.g., 2.8-3.1). Paleoproterozoic (1.7-1.9 Ga) mobile belts now surround the Province along its margins (e.g., Trans-Hudson orogen, Great Falls tectonic zone, Cheyenne Belt, Farmington zone, Hartville uplift; Fig. 1), but Proterozoic and younger magmatism, other than mafic dikes, is confined to the WC's outer margins, documenting the robustness of the craton's Archean keel.

V. Workshop Discussions

Prior to deployment of the Transportable Array in the northern Rockies, a workshop was held in 2005 to seek consensus on the major problems the participants viewed as important to understanding the evolution of the northern Rocky Mountains (NRM). Key questions were enumerated in six themes, many of which involved the WC and resurfaced for this workshop, including: how the WC influenced the later tectonic evolution of the NRM, including the development of the Yellowstone hotspot; what special attributes of the NRM lithosphere allowed development of the 20 km thick Belt-Purcell Supergroup; role of reactivated ancient structures in modern tectonics and seismicity; the role of cratonic lithosphere in limiting the eastward transport of Phanerozoic accreted terranes; and what unique opportunities for outreach characterize the NRM region. All participants in the 2019 workshop were given copies of the 2005 report. With this information as a base, a set of revised focus issues were developed during the workshop via breakout discussions, which were organized so that individuals had the opportunity to participate in more than one session.

The following "raw product" briefly relates the topics addressed in the breakout sessions and their notes and suggestions for future studies. The notes are largely unedited and, as you will see, there are some contradictory ideas and observations expressed when notes from individual sessions are compared. No attempt has been made to homogenize these summaries. These notes are also on the workshop website. Questions and concerns about individual issues should be addressed to the group participants. The first set of breakout sessions was organized around disciplinary groups:

1. Geochemistry, Geochronology, and Petrogenesis of Archean-Paleoproterozoic crustal evolution: Mueller, Frost, Mogk, Vervoort, Gifford, Wilhelmi.

Big questions addressed included:

- What is the rate of continental crust production, when and how much?
  - Impacts on and by the structure and rheology of the mantle
- How do we generate continental crust: How do we get from basalt to TTGs to granites? Melt mantle, get basalt (not recorded); melt basalt get TTGs? How are granites related to these precursors?
- What are the dominant ages in the WC?
- What is the significance of the Pb isotope signature in the WC?
- How do we interpret Hf and Nd model “ages”? Remember these are qualitative models, not ages.
- What is the rate of crustal recycling and what evidence do we have of this?
- Geophysicists: How deep is the Moho? 40km line for Moho? We have grey gneisses that are thought to be 12 kb (35 km) mid-crustal rocks. How do we reconcile that? Where are the roots?
- Geophysicists: What/where is the evidence for the western edge of the craton?
- Geophysicists: What/where is the evidence for the eastern edge of the craton?
- If we are extracting this amount of crustal material from the mantle, what kind of impact would that have on the currently visible geophysical characteristics?

Key Findings:

- Events that formed the WC appear to be episodic.
- Hf isotopic data from Eoarchean-Hadean detrital zircons suggest the Eoarchean-Hadean crust of the WC was derived from a chondritic mantle at 4.0 Ga; evidence of involvement of DM (depleted mantle) begins to appear at ~3.8 Ga.
- Dominant ages within the WC are: 1) 3.2-3.4 Ga TTG plutonic rocks form the earliest craton-wide magmatic event, 2) at 2.8 Ga, an equally widespread event produced most of the current exposed crust; 3) less widespread events include 2.6 Ga and a last gasp of igneous genesis at 2.5 Ga around the margins of the WC. Detrital zircons are dominantly 3.2 Ga. Xenocrysts within younger rocks range from 3.2-3.8 Ga.
- Dominant exposed crustal rocks are 2.8 Ga TTG and granites.
- Recognized evidence of Eoarchean/Hadean crystals (~4.01 Ga detrital zircons) within WC
- The area of the WC that includes 3.2-3.5 Ga gneisses encompasses the MMT (Montana metasedimentary terrane) and the BBMZ (Beartooth-Bighorn magmatic zone).
  - Began forming crust at >3.6 Ga
  - 3.2-3.3 Ga first main generation of crustal creation; dominantly TTGs?
  - Between 3.2 to 2.8 Ga, seem to have the same geodynamics and magmatic products, i.e., no change in the mechanism of crustal formation.
  - 2.8 Ga crustal formation; predominantly granitoids?
  - 2.7 Ga Tetons granulite facies metamorphism, intrusions
    - 2.701 Ga Stillwater Complex

        - 2.75 Ga Blacktails/Gravelly
    - 2.6 Ga batholith intrusions (continental arcs?) Wind River, Granite Mountains, Laramie Range
    - 2.55-2.45 Ga final intra-crustal magmatic anatexis and high to low grade metamorphism (granulite → hydrothermal)
        - 2.4 Ga garnet age in Ruby Range of the MMT
        - Zircon overgrowth rims and monazite Ruby Range and Tobacco Root Mountains
    - Episodic additions to the crust that create a larger whole
    - Paleoproterozoic metamorphism corresponding to the formation of the GFTZ
- The MMT records younger deformation events (i.e. 2.45 Ga, 1.7-1.8 Ga)
- Detrital zircon record really begins to pick up globally at 3.8 Ga

2. Tectonics and Structural Geology (**Precambrian to Phanerozoic geology, petrology, tectonics, structural geology, basin formation, magmatism:** Baldwin, Chamberlain, Henry, Kalakay, Mahan, Bowen.

Key questions on tectonics and structural geology that were addressed include:

- How and when was the WC incorporated in Laurentia, and what can the WC tell us about its incorporation and supercontinent cycles in general?
- What is the role and mechanism of the Paleoproterozoic shear zones and mobile belts that surround the WC? What is their extent, what type of tectonic environments (collisional sutures, accreted arcs?), what is the timing of (re)activation?
- How can paleodepth of exposures in the WC inform re its tectonic history? Much of the WC was at depths of 10 km or less over much of its history, however, some deep exposures of crust have been exhumed and preserved.
- What is the significance of mafic dike swarms that cut across the WC?

3. Geophysics (**lithospheric/mantle structure**: Bedle, Cooper, Russo, Van der Lee, Schulte-Pelkum, Ford, Humphreys, Detrick, Bedrosian.

science contributions include:

- The “big questions” are: When and how did the craton form? Do modifications that we see at the surface coincide with what we see at depth, and vice-versa? What is the evidence for the destruction phase of the craton? A compilation of tomographic models is needed to get a better idea of what the mantle keel looks like. What is the influence of the Yellowstone system? Are other cratons (Mojave, North China Craton, Superior, Slave, Kaapvaal) similar or different than the WC, and in what ways?

- The bottom half of the WC is not stable anymore. The lithosphere is still there, but the bottom half was altered, so it doesn't show up on S-velocity tomographic models. It is the same rock, but has been fertilized.
- Mantle structure reflects a cratonic lithospheric that has been modified by the Laramide (based on tomography).
- Internal lithospheric structure (mid lithosphere discontinuities--MLDs), but unsure of origins (see also data from receiver functions, RFs).
- There are better constraints on the some Proterozoic sutures through MT, but lacking in some places.
- The east-west divide (hydration?) in crust and uppermost mantle (west does not have physical characteristics of a craton)
- Crustal structure and uppermost mantle (100 km depth and shallower): WC is bisected by the Laramide deformation front, low velocities to its west, high velocities to its east.
- Laramide has destroyed the craton from moho ~100 km and has reset the garnets, changed lithology, and density. Hydration from the Laramide might also be making the craton weaker.
- Yellowstone has not yet destroyed the craton, but has significantly modified the crust

Topical Break Out Groups

A second set of breakout group discussions focused on cross-cutting topical questions:

4. Formation of a Craton (**Facilitator:** Gene Humphreys; **Recorder/Reporter:** Bob Detrick; Dave Snyder, Heather Ford, Gene Humphreys, Dave Mogk, Darrel Henry, Bob Detrick, Paul Mueller, Jeff Vervoort.

Central questions addressed: a) the timing and processes of cratonization; b) when and how did the WC form; and c) what is the evidence for temporal and volumetric growth of the WC.

- What processes were responsible for early (3.2-3.5 Ga) cratonization vs. later (2.8 Ga)?
- Mechanisms for creating crust - which apply?
  - SAGduction model (differentiation of a magma ocean)
  - Stagnant single plate - plume model (stewing?)
  - Slab stacking model
  - Modern plate tectonics/subduction model
- When does it become a craton?
- How do you form a thick root? And how do MLDs form (mid-lithosphere discontinuity)?

What are the key data/evidence available and what hypotheses are compatible?

- By ~3.2 Ga a depleted mantle appears to heavily contribute to growth of the WC; result of melting and cooling of mantle from 4.0 Ga

- 3.2 Ga and 2.8 Ga magmatic events look like they formed by similar processes, but not similar time frames. Rates of magma production are different - over 100s m.y. in case of 3.2 Ga but a few 10s of m.y. for 2.8Ga?
- What marks the end of the cratonization process? Is there enough late granite (~2.5 Ga) to constitute a bloom? If so, what is the significance of such an event?
- Southern accreted terranes formed around 2.7Ga - pieces mechanically connected, not geochemically related.
- Slave craton xenoliths and zircons suggest roots of cratons may form by underthrusting and imbricating of continental and oceanic plates (2 x 100 km = 200 km).
- Accretion of Sierra Madre block with proto-WC may be an example of this. Multiple such events may be responsible for formation of MLDs (mid-lithospheric discontinuity)
- Half of the crust has eroded away (assuming a pre-erosion thickness > 50-55 km)
- Relatively thick continental crust (~40 km) existed by 3.2Ga, but maximum thickness is unconstrained.

Key Findings:

- Summary of model for formation of :
- Six stages (days) of craton formation:
  - (1) 4-3.6 Ga mantle cooling, melting and development of depleted mantle,
  - (2) 3.6-3.2 Ga melt crust to form TTG,
  - (3) 3.2-2.8 Ga hiatus with sedimentation, platform formation and slow uplift,
  - (4) ~2.8 Ga major granite event forming (drip tectonics or subduction?);
  - (5) 2.7-2.5 Ga terrane accretion along southern boundary; formation of root by underthrusting of cont. slabs and formation of 2.6 Ga subduction-related granites,
  - (6) 2-55- 2.45 Ga last gasp of crustal formation (mainly a metamorphic event) - completion of cratonization.
  - On the 7th day the craton rested for 600 Ma before Paleoproterozoic orogenesis affected its margins.

5. **WY Craton Structural and Geological Synthesis of Modifications (Facilitator: Jennifer Gifford; Recorder/Reporter: Jennifer Gifford, Paul Bedrosian:** Ray Russo, Ryan Wilhelmi, Jeff Vervoort, Julie Baldwin, Paul Bedrosian, Kevin Chamberlain, Kevin Mahan, Vera Schulte-Pelkum.

Integration of geophysical data with structural/geochemical/geochronologic data is essential. Integrating geology with geophysical data for an overarching description of what is occurring within the WC is essential to provide the synthesis needed to define/constrain the role of the WC in continental assembly/disassembly.

Central Research Question/Problem:

- Define the boundaries of the WC. What is the timing? What does geophysics tell us about those boundaries?
- Crustal geological/geophysical synthesis of crustal knowledge

  - Integrated, updated picture of crustal thickness in comparison to surface geology
- Pull together available geophysics to put together Moho map for craton. Compare to surface maps of craton, version A vs. version B.
  - Synthesis of major structures: kinematics, sense of shear, etc.
- What is the stratigraphic record? Uplift and erosion history.
- Modification of the margins and the WP role in the formation of Laurentia
- What is the cratonic core and what/where are the surrounding Proterozoic belts
  - Variable interpretations on some (western and eastern) boundaries. Challenges along the nexus between Farmington, GFTZ, Grouse Creek Block. (GFTZ west of Farmington?)
  - Boundary between BBMZ and SAT - can we see it and what does it say about this area

What are the key data/evidence available?
- Active source seismic: Wind River COCORP, SAREX, CDROM at Cheyenne Belt?, Bighorns active source, COCORP(?) line(s) through Williston Basin (Northern Montana/North Dakota, Braile [1989], Steinhart and Meyer [1961], McCamy and Meyer [1964]; also Southern Canada, Braile [1989] and Hajnal et al. [1984])
- Passive source seismic: Billings array near Yellowstone, Bighorn project, Deep Probe passive, CDROM passive, Yellowstone networks, TA, CIELO if Heather Ford participates; peripherally IDOR, Snake River
- Potential field data: MT (US Array, YS, NOD, BB), gravity, aeromagnetic
- Walk around the edge Proterozoic belt by Proterozoic belt. Compare and contrast. Mueller et al. [2002, 2005]
- Put the WC in the bigger context of Laurentia
- Internal structure and shear zones and seismic anisotropy in crust, 7x extent as known
- Mueller (2002, 2005) - Little Belt Mountains. GFTZ - Grass Range xenolith - Gifford et al (2014)
- Collation, synthesis, and update of surface geologic data, structural data, xenolith data (opportunity/extra push to get some data sets published).

6. **Destruction of cratons--Wyoming as a case study (Facilitator: Heather Bedle; Recorder/Reporter: Carol Frost Tom Kalakay:** Heather Bedle, Katie Cooper, Carol Frost, Suzan van der Lee.

Brief Description of topic: Cratons are characterized on the surface by long-term lack of deformation and magmatism of Precambrian rocks, and geophysically by ~200 km thick cold lithosphere, and sedimentologically by traditional stable platform stratigraphy. Are cratons destroyed? If so, how?

Central Research Question/Problem:

What do we mean by "decratonization"? Modified or overprinted to the point that it won't act like other cratons. Wyoming in many respects is no longer like a craton. What happened? Test: can you make a modified lithosphere that is still there, but is invisible seismically? What would be the evidence on the surface?

Are there other regions that are no longer long-lived? How are they modified?

What are the key data/evidence available?

- A standard craton: what is its structure? 200-250 km lithosphere. These areas tend to be Archean *and* Proterozoic.
- Wyoming and north China look different. N China craton evidence is from xenoliths that indicate a change in thickness of lithosphere.
- Compare and contrast with North China craton. (NCC destruction timing ref - Zhu et al., 2012 (and references therein) - https://www.sciencedirect.com/science/article/pii/S0024493712002034)
- Current knowledge about Wyoming lithosphere structure (Shen and Ritzwoller 2014 at 75, 90, 120 km)
  - Western "red" lithosphere and eastern "blue" lithosphere
  - Blue is distinct from rest of N. American craton-not as fast
  - When and how did it get this way (assuming it was originally dark blue)
  - Produce a map with red/blue on top.
  - Note that orogenic margins of Wyoming dip outward, ex along Cheyenne Belt. LB arc of GFTZ underlain by "fossil" slab dipping north, away from the WC) This may indicate that Wyoming is the more stable block during these collision events.
- Data from xenoliths; MT xenoliths, State Line, Leucite Hills
- Data from geologic events that may reflect "decratonization"
  - Did Sevier just lap onto craton or is it a response
  - Laramide basement involved uplifts
  - Sevier contraction dies out in Eocene and Laramide takes over in Cretaceous in MT and by Paleocene in WY
  - Eocene volcanism; Absaroka, Rattlesnake Hills, Devil's Tower, Leucite Hills
  - Eocene extension-western MT core complexes that manifest extension, others extend into the Beartooth block
  - Western interior deposition-or is it a response; how does the sedimentary cover reflect modification
  - Basin and Range--affects Tetons, base of Bridger Range, EQ reflect some of this modern B&R extension (Clarkson EQ, Hebgen Lake fault is orthogonal to fabrics)
  - Yellowstone track--Ray Russo's work on influence on basement and mantle anisotropy
    - Geodetics--up and down motions at Yellowstone (and also in Powder River basin related to coal bed methane water withdrawal and recharge

- Arc is to the west thru the Cretaceous and also Boulder batholith
  - Flat Farallon slab
- Metasomatism of base of lithosphere
- Shatsky complement mechanically removes lithosphere?

Key Findings:

- Two outcomes: A) comparison with North China Craton and other cratons (surface data of reworking and tomographic models of crust/mantle); B) modifications to the WC can include hypothesis testing of geodynamic models, how they are supported by surface and geophysical data.

7. Education and Outreach Opportunities [Moderator: *Elisabeth Nadin, ESNO*]

What's Happening Now?

- Science Nuggets on funded research were accepted by ENO until Feb 1, 2019. A "nugget" on the Little Rocky Mountains and GFTZ by J. Gifford was included.
- Canada in 3D is an example of incorporating geophysical data in creating a 3D geologic model
- SERC website is a place to post teaching activities

How can we best translate our exciting new science into E and O products?

- Teaching tectonics focuses on plate boundaries--we need more activities on cratons and continental interiors, including the nature and evolution of cratons. What are the features, surface and subsurface? How to cratons differ from each other?
- Pick a place and get local people interested in geoscience that wouldn't otherwise run into it. News articles, public lectures, museum exhibits. GSA 2019 will have a session to identify top areas of geoheritage. Trail guides (see MT geoheritage).
- A model is provided by Chris Condit (UMass)-dynamic digital maps can be used to create virtual field trips
- Citizen science projects.
- Need more integrated approach to teaching undergraduate geoscience.

Opportunities for Targeted Audiences

- K-12 Teachers/Students
- Undergrad (recruitment, REU's etc.)
- Graduate Training
- Journalists/Policy Makers
- General Public

Action Plan

The following is a summary of follow-on activities planned by participants of the workshop:

1. Number of synthesis journal articles were outlined that include:
    a. Formation of the —an integrated timeline of crustal genesis and evolution from 4.0-2.45 Ga.
    b. Modification of the : geophysical imaging of the 3D structure of the lithosphere of the primarily with geophysical imaging.
    c. Destruction of the and comparison with other cratons (North China Craton)
    d. A general interest article on the Birth and Death of a Craton is proposed to be submitted to EOS.
    e. A themed journal volume in *Geopshere* has been approved.

2. Follow-on theme sessions are proposed for the fall GSA and AGU meetings. These are:

- 2019 Geological Society of America Annual Meeting, T66. Life and Death of a Craton: Implications of Archean Crust-Keel Systems for Crustal Growth, Crustal Preservation, and Mantle Evolution; Conveners Paul A. Mueller, Carol D. Frost, Jennifer N. Gifford, David W. Mogk

- 2019 American geophysical Union Fall Meeting Life and Death of Cratons: Craton Interactions with Collision, Subduction, and Volcanism - Global Perspectives and the Wyoming Province as an Example. Conveners are Emily Chin, Chengxin Jiang, Kevin Mahan, and Vera Schulte-Pelkum