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A detailed image of a lithic sample from Obsidian Cliff.




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*Cover photo:*
"Isolation"—Garnet Hill in winter.
Photo ©James Duckworth 2010.


## FEATURES



## DEPARTMENTS

# Origins of a Continent

## Evidence from a Research Experience for Undergraduates Program in Yellowstone

*David Mogk, Darrell Henry, Paul Mueller, and David Foster*

Gray gneiss and pink migmatite veins from the Junction Butte area. Migmatite is a mixed rock. In this case, the pink veins were likely formed by partial melting of the gray gneiss.

Yellowstone National Park is host to some of the youngest and oldest rocks on Earth. The youngest formed in its caldera, while the oldest are preserved along the park's northern boundary from near Gardiner, Montana, to Slough Creek. These Precambrian rocks, from the Archean period more than 2.5 Ga (billion years ago), provide a "deep-time" glimpse into the geologic formation and evolution of the North American continent. Originally formed at Earth's surface, they were buried to depths of 10–25 kilometers (6–15 mi), forming the basement on which younger deposits such as the Eocene Absaroka Volcanics (~50 million years old) and Quaternary volcanic rocks (less than ~2 million years old) erupted. These ancient rocks have been exposed at Earth's surface by the major periods of uplift and mountain building that occurred ~60–80 million years ago in western North America during the Laramide Orogeny and by the inflation of the crust by the Yellowstone hot spot which has been active for ~2 million years. We have undertaken a two-year project funded by the National Science Foundation's Research Experiences for Undergraduates program, to characterize the rock types, compositions, structures, and ages of this unique parcel of ancient continental crust. This project is the most recent effort in a 30-year collaborative research program between Montana State University, Louisiana State University, and the University of Florida. Through field studies, whole-rock geochemical analysis, analysis of mineral compositions, and age determinations, this project fills an important gap in our understanding of the architecture and history of this part of the Archean Wyoming Province (fig. 1), which is one of the core building blocks of the North American continent. The study area lies at the boundary between two *terranes* (fault-bounded areas of distinct rock types) within the Archean Wyoming Province, with the Beartooth Bighorn Magmatic Terrane to the east and the Montana Metasedimentary Terrane to the west, and thus provides a view into the architecture of the nucleus of the North American continent. This project was multi-layered, directed at both basic research and the development of young scientists as they deal with one of the most perplexing problems in the geosciences—the early history of Earth.

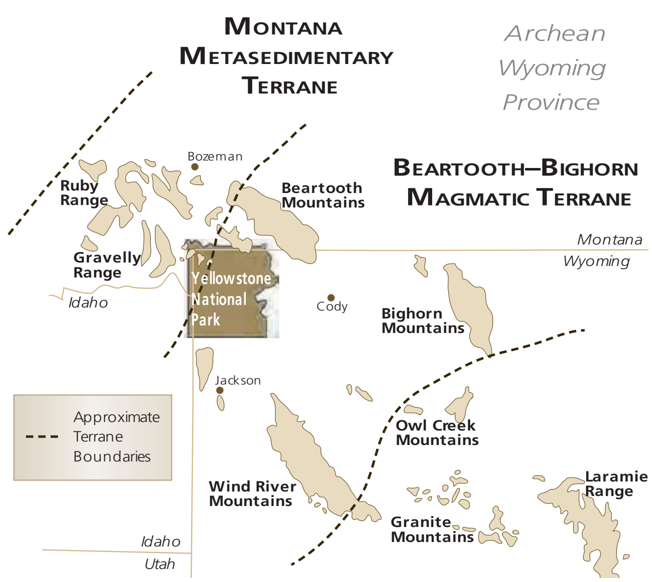



Figure 1. Schematic map of the Precambrian exposures of basement rock in the Wyoming Province (adapted from Mogk et al., 1992; Mueller and Frost, 2006).

## The Science

We have incorporated some of the key research questions into this project that pertain to the geologic record of Yellowstone National Park and, more broadly, to the evolution of North America.

(1) What is the relationship of this suite of Archean rocks to voluminous 2.8 Ga igneous rocks of the main Beartooth massif to the park's east; highly metamorphosed, melted, and deformed gneisses of Yankee Jim Canyon of the Yellowstone River; and dominant 3.2 Ga gneisses and metamorphosed surficial rocks exposed in the Gallatin and Madison ranges west of the park?

(2) What are the ages, source rocks, and depositional environments of the metamorphosed sedimentary rocks found in the Jardine area (including its gold mine), and in the Black Canyon of the Yellowstone River?

(3) What are the composition and age of the igneous rocks in the area, and what do they tell us about the manner in which they formed? Is there a modern analog for this environment?

(4) What is the metamorphic and structural history of this area, and what does this tell us about processes at work deep in the Earth to mature its crust?

(5) How do all these pieces of crust fit together? Did all of the rocks form in one place during the course of geologic time, or were they derived from other locations and environments and were ultimately transported into their present location by faults?

This article outlines a west-to-east transect across the northern part of Yellowstone National Park, through the Black Canyon of the Yellowstone River to Tower Junction and then east along the Lamar River to Slough Creek, a slice across time as well as space (fig. 2). The rocks in this area formed over an interval from ~3.2–2.8 Ga, making them some of the oldest rocks preserved in the North American continent. The great depths at which these rocks formed and/or metamorphosed provides a window into the geologic processes that created the continental crust. The transect provides a cross-sectional view of the architecture of this ancient crust. Each sequence of rocks in this area contains

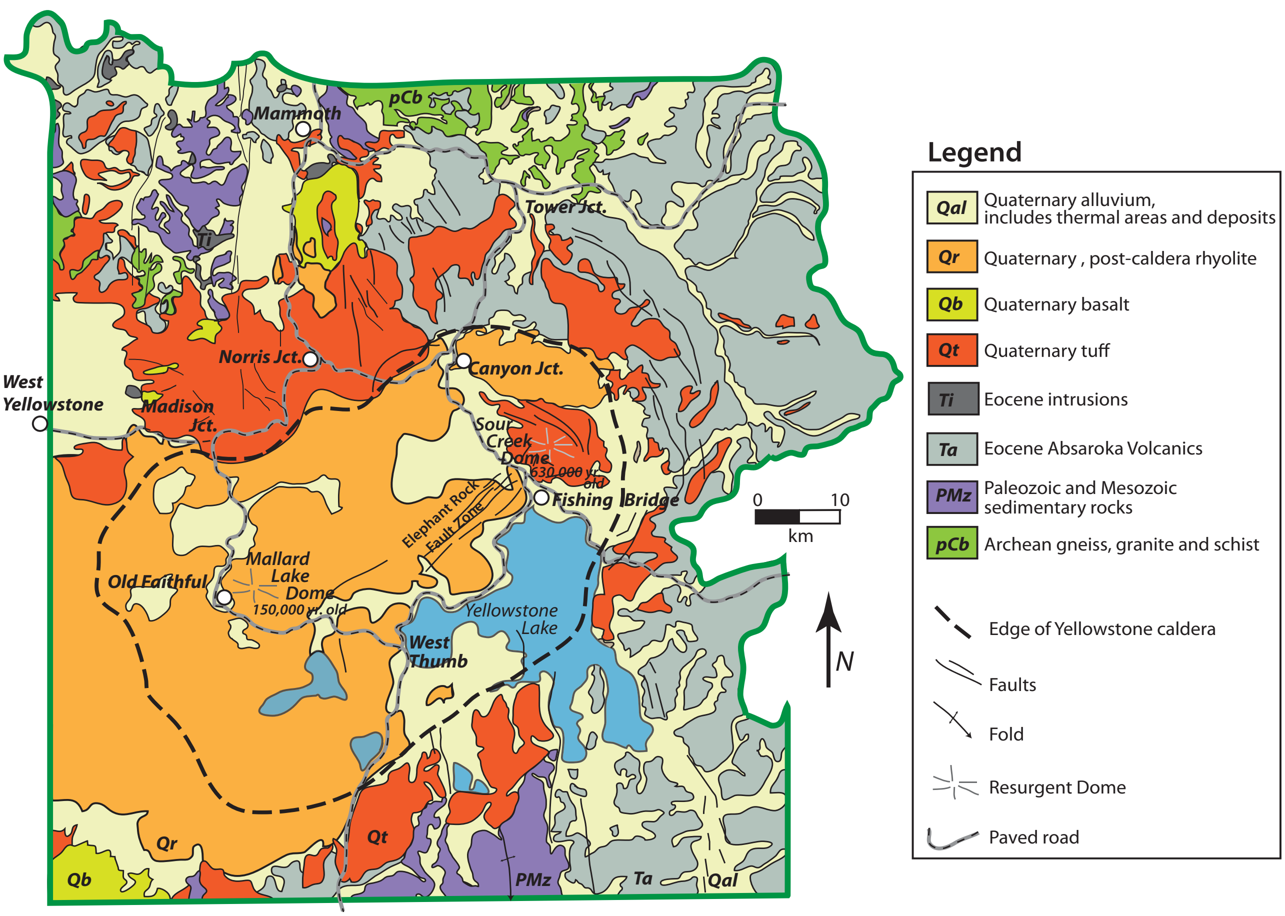



Figure 2. Geologic map of Yellowstone National Park showing the distributions of different rock types and fault structures. The Archean rocks that were the focus of this study (labeled pCb–Precambrian basement) are located on the north park boundary. (Map by D. Foster based on USGS1-7111; includes modifications by Marli Miller, University of Oregon.)

information about crustal genesis (the processes responsible for the initial formation of the continental crust) and crustal evolution (the processes that have transformed this crust throughout geologic history).

## The Black Canyon of the Yellowstone River

The Jardine Metasedimentary Succession (JMS) is composed primarily of biotite schists, quartzites, and minor iron formation. This suite of metamorphosed sedimentary rocks is host to the Jardine gold mine located just north of the park. These rocks were originally deposited as mudstones, siltstones, and sandstones in a marine environment; the iron-rich rocks formed at the sites of hot springs and contain most of the viable gold deposits in this region. The unique feature of these rocks is that they have preserved primary sedimentary structures such as graded beds (coarse grains beneath increasingly finer grains indicating a sequence of deposition in waning energy conditions), cross bedding (indicating direction of water flow), and channels that were cut into earlier layers and deposited coarser materials under higher energy conditions (fig. 3). The coarser-grained sediments contain a high abundance of feldspar grains (referred to as "immature" sediments because they have not undergone extensive weathering), which indicate that they were derived from a local volcanic source area. Elemental analyses of these sediments indicate that their source area had a bi-modal mixture of volcanic rocks—"mafic" basalts (lower in silicon and alkali elements, higher in iron and magnesium) and more silica-rich "dacitic" volcanic rocks (higher in silicon and alkali elements). We interpret these rocks as turbidite deposits from submarine landslides, most likely adjacent to a continental volcanic arc similar to what has formed along the contemporary coast of Washington and Oregon. The metasedimentary rocks exposed in the western part of the study area, near the confluence of Bear Creek and the Yellowstone River, are overall much finer grained, and we interpret them to be part of the furthest extent of a submarine fan, whereas the metasedimentary rocks exposed to the east near the Blacktail Creek and Hellroaring Creek confluences were deposited dominantly as coarser-grained sand deposits in a higher energy environment, perhaps in a setting with a steeper slope, closer to the source area.

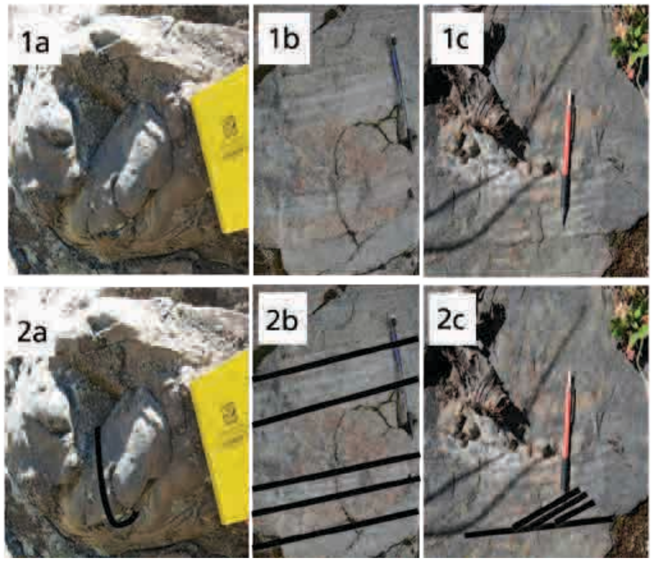


Figure 3. Relict sedimentary features from the JMS (1). Bottom photos (2) highlight the interpreted structure with black lines; (a) bottom of sedimentary layer with a preserved sole mark; (b) interbedded metamorphosed sandstone and shale; metasandstone layers highlighted by gray lamination, metashale layers by garnet growth from clay minerals during metamorphism; (c) relict cross-bedding in metamorphosed sandstone due to flow during deposition.

## Metamorphism of the Sedimentary Rocks

Sedimentary rocks deposited at Earth's surface can be deeply buried in the crust before being uplifted and re-exposed at the surface. Temperature and pressure typically increase as the

## How do we know what the environment of deposition was for these sedimentary rocks?

James Hutton, an eighteenth century Scottish scientist who helped establish the basis of modern geology, remarked "The present is the key to the past." By studying sedimentary deposits and observing first-hand the processes that form these deposits, we can infer that the same processes have operated over the long span of geologic time. Multiple lines of evidence are used to interpret the environment of deposition of sedimentary rocks: the types of rocks (mudstones, sandstones), preserved sedimentary structures that indicate energy conditions at the time of deposition, the types of minerals in the rocks, and the elemental composition of the rocks and minerals. The features preserved in the JMS are similar to turbidite deposits that have formed in deep water marine environments as the result of underwater landslides that occur along a continental margin and are typically triggered by earthquakes. Figure 3 (above) shows representative outcrops that have preserved sedimentary structures which formed almost 3 billion years ago.

Garnet crystals formed by metamorphism in biotite schists of the Jardine Metasedimentary Sequence.


B.PARKS

Photomicrograph of metamorphic minerals garnet, chlorite (light green), biotite (brown), sillimanite (small prisms).

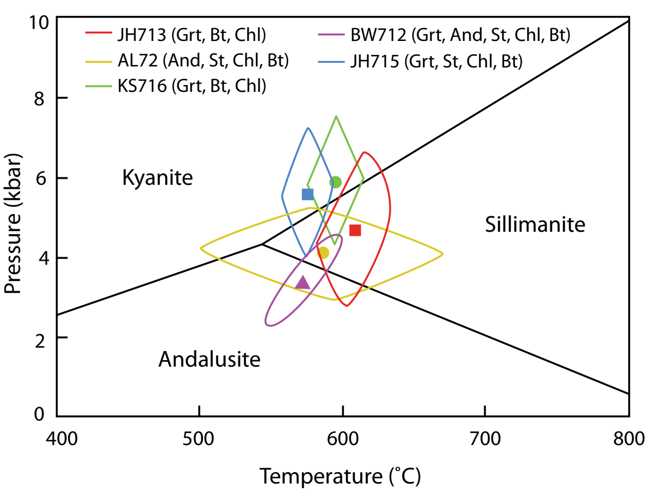



Figure 4. Pressure and temperature estimates determined for samples from the Jardine Metasedimentary Sequence ranging from 572–609°C and 3.5–5.9 kbar (polygons represent range of statistical error). Prepared by Carly Osborne and Julie Baldwin.

sedimentary rocks become more deeply buried, transforming them into metamorphic rocks. Metamorphism involves chemical reactions that result in recrystallization of the rocks, producing "index minerals" that are indicative of the grade (pressure and temperature) of metamorphism. The JMS has recorded relatively low grades of metamorphism in the west near Bear Creek, as indicated by chlorite and andalusite in the metamorphosed mudstones (schists), and these types of rocks increase in metamorphic grade to the east as biotite, garnet, and staurolite also form in the rocks. Metamorphic conditions across the study area have been determined to be in the range of 572–609°C and 3.4–5.9 kbar (1 kilobar is ~1,000 atmospheres of pressure). One kbar pressure corresponds to a burial depth of ~3 kilometers, so the JMS rocks metamorphosed at depths on the order of ~10—18 kilometers (fig. 4).

## Structural Geology of the Jardine Metasedimentary Rocks

Tremendous forces and movement at depth have resulted in the deformation of the JMS rocks. We see the evidence of this in folds and faults. The photograph below shows a set of "kink" or "chevron" folds that have developed. These rocks have experienced at least three distinct generations of folding: the first generation is preserved as rare fold hinges when the two limbs of the fold are nearly parallel; the second includes kink folds that have hinges oriented to the NE–SW; and the third is another set of kink folds with axes oriented to the NW–SE. These folding events occurred, in part, when metamorphic minerals were growing and when the latest folding episodes deformed the pre-existing metamorphic minerals. In addition, the JMS has shear zones, which are characterized by faults and other high degrees of deformation. This deformation is localized along zones of

Chevron folds that developed in the Jardine Metasedimentary Sequence over three generations of activity.

## How do we determine the pressure and temperature of metamorphism?

In a general sense, we know that as the grade of metamorphism increases, metamorphic rocks become increasingly dehydrated as minerals such as chlorite and biotite, with water (as hydroxyl) in their crystal structures, break down and are replaced by anhydrous minerals such as garnet. In addition, individual minerals can readily change their composition in response to changing pressure and temperature by exchanging elements with other minerals; e.g., iron and magnesium are freely exchanged between biotite and garnet. These compositional changes have been carefully calibrated by experiments. We measure the changes in composition of metamorphic minerals (fig. 5) with an instrument called an electron microprobe. By measuring the composition of co-existing minerals, we can calculate the temperature and pressure of metamorphism and, in the case of zoned minerals, can show how pressure and temperature have changed during the progressive stages of metamorphism.

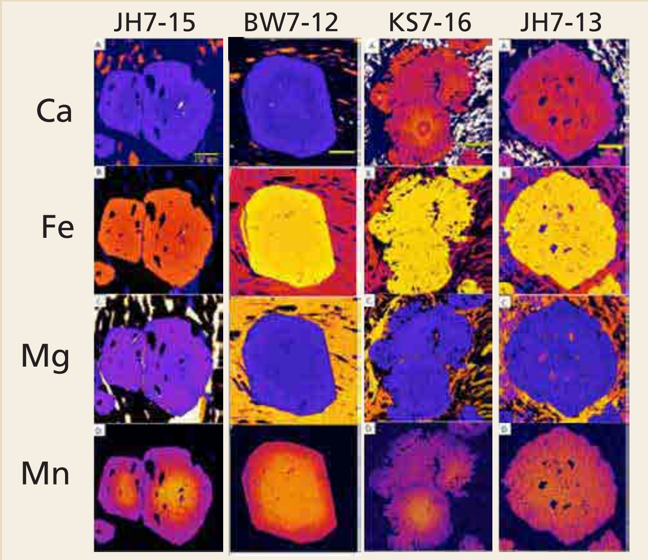
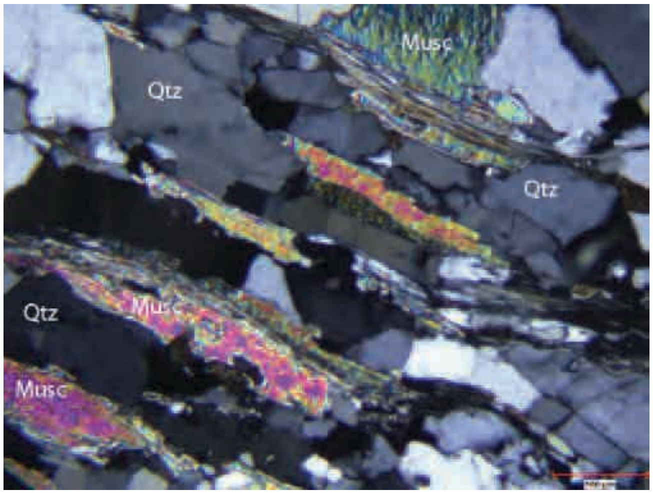



*Figure 5. Compositional profiles of garnets obtained using elemental X-ray mapping techniques with an electron microprobe. Elements that have been mapped include calcium (Ca), iron (Fe), magnesium (Mg), and manganese (Mn). The composition of the garnets responds to changing pressure and temperature during metamorphism.*

weakness where the minerals tend to flow like toothpaste rather than rupture due to changing mechanical properties at high temperatures and pressures. These zones typically are occupied by minerals such as quartz which have undergone intense grain size reduction and micas (muscovite, biotite, and chlorite) which have been rotated and sheared so that the long axes of the minerals are oriented parallel to long dimensions of the zones of deformation. These features occur on a microscopic scale, and are observed with a petrographic microscope to examine the textures of rocks in thin sections (30 micrometers; fig. 6). The fold and shear zone structures in the JMS rocks are similar to the deformation that occurs when modern turbidite fan sediments are scraped off oceanic crust in subduction zones and accreted to a continent. This process of sediment accretion is currently taking place off the coasts of Washington and Oregon and is building the Coast Ranges.




A photomicrograph of quartz (Qtz) with reduced grain size, and muscovite (Musc; pink, elongate) in a shear zone. Field of view is 2.5 millimeters.

### Magmatic Rocks that Cross-Cut Metasedimentary Rocks

The JMS is cross-cut by two ovoid-shaped plutons (bodies of intrusive, igneous rock): the Crevice Mountain and Hellroaring Creek granitic plutons. Pieces of the schist that make up the "country rock", called xenoliths (or foreign rocks), are found as inclusions along the margins of the plutons, and thus, the plutons must be younger than these host rocks. These granite bodies have a very uniform fabric, with little or no preferred orientation of the mineral grains because they did not experience the deformation or metamorphism that occurred in the JMS. These rocks contain sub-equal amounts of quartz, potassium feldspar, and plagioclase feldspar, and less than 5% biotite and muscovite micas. The occurrence of muscovite mica is important because it indicates that some of the source rocks that melted to form the granite are rich in

# How do we know how old the rocks are?

RADIOACTIVE ELEMENTS in nature break down by spontaneous decay to their stable "daughter" elements. By measuring the abundance of the radioactive "parent" element and the abundance of the daughter element that has been produced, and using the half-life of the radioactive element, very precise age determinations can be made. In the case of dating Archean rocks, with ages measured in billions of years, the U-Pb radioactive decay system is very useful. Small amounts of uranium (U) can be incorporated into the crystal lattice of the mineral zircon. Over time, the U in zircon decays to lead (Pb) by one of two reactions involving different isotopes: 238U to 206 Pb and 235U to 207Pb, with half lives of 4.47 Ga and 0.704 Ga, respectively. Zircon is a very robust mineral and there is very little opportunity for these elements to escape the zircon host, so the ages are not readily altered during younger geologic events. We typically collect large volumes of fresh rock, crush them, and use a variety of concentration methods to collect small volumes of zircon that will be used for age dating (zircon is typically <0.1% of a granite). The zircon grains are imaged using scanning electron microscopy and cathodoluminescence techniques to see if the grains are homogeneous or zoned (fig. 9), and then the isotopic ratios of U and Pb are measured using a mass spectrometer. Modern analytical techniques allow us to measure these ratios on specific, micrometer-sized spots using either a tightly focused laser or a beam of oxygen ions. The result is that we can determine the ages of geologic events from the growth zones recorded in the zircons. U-Pb dating of zircons gives us two important time markers in the geologic history of an area: 1) For magmatic rocks, we can determine the age of crystallization of an igneous body as we have done for the Crevice Mountain and Hellroaring Creek plutons and intrusive rocks on Garnet Hill (fig. 7). In some cases, we can see a rounded core in the zircons we've dated, and these are interpreted as "inherited zircons" and give us an indication of the age of the source area that produced the magmas. 2) For sedimentary rocks, zircon grains tend to be concentrated in sandstones during transport and deposition. These are referred to as detrital zircons. By determining a large number (~100) of detrital zircon ages, we can interpret the age(s) of the source area(s) of the sedimentary rocks (fig. 8). The U-Pb age dating done in this project allows us to conclude that all of the igneous bodies, granites and diorites alike, have yielded very precise ages over a relatively short time span of 2.79–2.82 Ga; and the age spectrum of the detrital zircons recovered from the quartzites of the Jardine Metasedimentary Sequence indicate that the source area of these rocks were of ages that are quite unlike the ages observed in the adjacent Beartooth Mountains to the east.

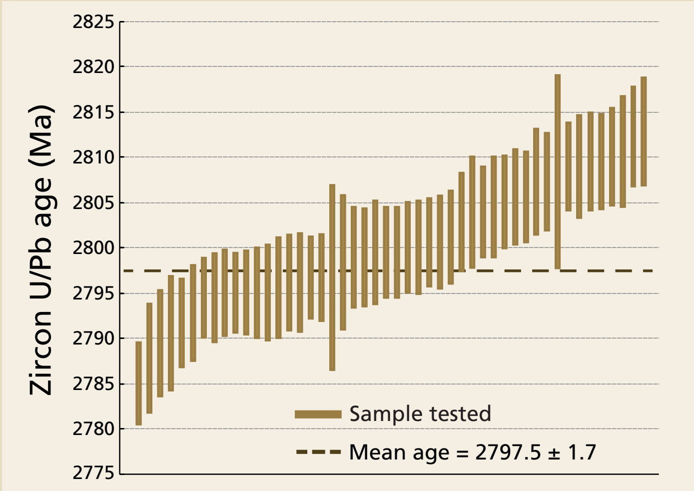



*Figure 7: Replicate age determinations from the U-Pb zircon method obtained using the LA-ICPMS technique for a diorite unit collected on Garnet Hill. The mean age is 2797.5 +/- 1.7 million years (0.06% relative error).*

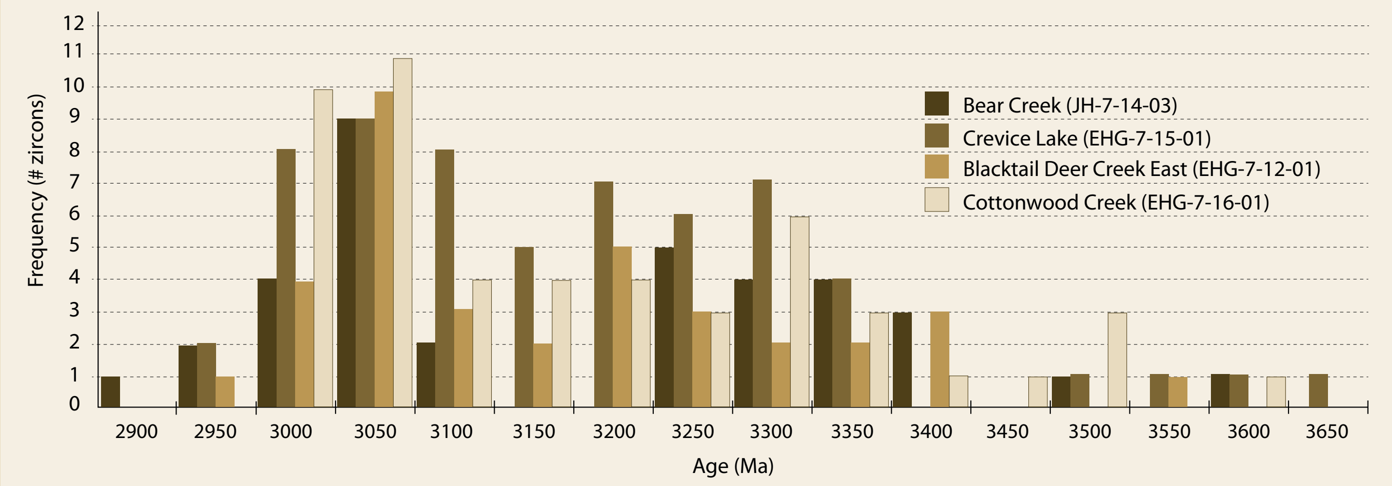



*Figure 8. Summary of age determinations from detrital zircons collected from quartzites in the Jardine Metasedimentary Sequence.*

View of the Hellroaring Pluton on the skyline, viewed from the Hellroaring Creek Trail looking north.

aluminum. This type of granite, referred to as peraluminous granite, is also called an S-type granite, because it was most likely derived from the melting of deeply buried sedimentary rocks. The bulbous shape of these bodies and the presence of muscovite indicate that these plutons were emplaced and crystallized at depths of about 10–12 kilometers (6–7 mi), which corresponds to the shallowest part of the middle crust. The granitic rocks are, therefore, particularly important in the geologic history of the area because they are younger than the JMS that they cut. The age of crystallization for these igneous rocks was determined to be about 2.80 Ga by dating the mineral zircon using the U-Pb method, which is based on the rate at which uranium decays into lead.

Crevice Mountain granite as seen in outcrop, showing gray quartz, pink potassium feldspar, white plagioclase, and dark clots of biotite. Note the homogeneous grain sizes and lack of internal deformation fabrics. Field of view is 10 centimeters. Hand lens shown for scale.

In addition to the granitic rocks, a suite of magmatic rocks of compositions similar to andesites or diorites occur as smaller, lens-like bodies throughout the area. Using the same U-Pb dating method (fig. 9), these rocks were determined to also have an age of 2.80 Ga. These rocks are significant because rocks of similar composition that occur in modern environments are typically associated with volcanic arcs that form over subduction zones where oceanic crustal plates dive under other oceanic or continental crust. Indeed, major and trace element contents of these dioritic bodies are almost identical to modern day diorites that occur in volcanic arcs around the world. This opens the possibility that plate tectonics operated in much the same way 2.8 Ga ago as they do today.

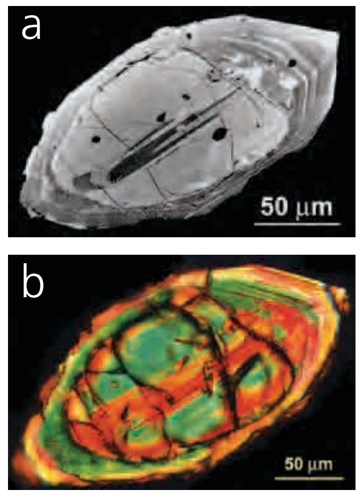



Figure 9. Images of zoned zircon grains (a) using back-scattered electron imaging, and (b) using cross-polarized light on a petrographic microscope. The well-defined compositional zones of the zircons are used to guide isotopic analysis to obtain ages on their cores and rims.

## Garnet Hill Area

A hike around Garnet Hill reveals geologic field relations that are significantly different from the Jardine Metasedimentary Succession to the west. This area is dominated by metasedimentary rocks that include a variety of schists, but also has alternating bands of iron- and silicon-rich sedimentary material that was inorganically deposited. These iron-rich sediments are unlike those deposited today in that they developed during a time when the atmosphere had very little, or no, oxygen. The most important distinction is that these rocks have been injected by a complex of igneous dikes (cutting across layers) and sills (layers parallel) ranging in composition from granite to diorite. The physical conditions of metamorphism of these rocks have been determined to be 560–615°C, 4.0–5.5 kbar, which are at the upper end of the estimates of metamorphism for the Jardine Metasedimentary rocks to the west. The conditions of emplacement of the dioritic igneous bodies have been calculated to be 685–727°C and 5.8–6.5 kbar. These injected igneous rocks have an age of 2.80 Ga, similar to the higher level, ovoid plutons at Crevice Mountain and Hellroaring Creek.

Meter-scale granitic dike cutting pelitic schist on Garnet Hill. Hand lens shows scale.

## Junction Butte Area

Junction Butte is near the confluence of the Yellowstone and Lamar Rivers. The low-lying hills in this area are composed of a unique gray gneiss unit that is cut by small pink migmatite veins (see photo, page 21). This area also contains a unique leucogranite unit that has a sugary-white texture and contains dominantly quartz, potassium feldspar, minor garnet, and virtually no dark minerals such as biotite. The gray gneiss host has yielded a U-Pb zircon age of 3.24 Ga. The pink veins are of granitic composition, and are the result of local melting of the gray gneiss itself. The physical conditions of metamorphism and melting have been calculated to be 821–863$^0$C and 7.0–7.3 kbar. This occurrence represents a deep-seated (21–22 km), ancient segment of continental crust not otherwise observed in the park, and only present in discrete remnants in the adjacent Beartooth Mountains.

## Buffalo Plateau and Slough Creek Area

The Buffalo Plateau–Slough Creek area is separated from the JMS and other units to the west by the Yellowstone River shear zone. It is underlain by a massive, composite pluton that includes a range of compositions—granite, granodiorite, tonalite, and diorite, largely reflecting varying amounts of quartz. Potassium feldspar, plagioclase feldspar, biotite, and hornblende are also common in the Buffalo Plateau–Slough Creek plutons; muscovite (which is common in the Crevice Mountain and Hellroaring Creek plutons) is conspicuously absent. These compositional variants were intruded at roughly the same time because there are instances where each rock type cross-cuts all the other types. Individual igneous bodies occur on a scale of tens to hundreds of meters in length, and in aggregate comprise an igneous body that occurs on a kilometer scale. The interlayering of the many igneous bodies results in a very heterogeneous pluton, and this contrasts with the very homogeneous bodies of granite in the Crevice Mountain and Hellroaring Creek areas. This style of multiple injections of distinct igneous bodies is indicative of emplacement and crystallization at mid-crustal levels (approximately 20 km or more). Significantly, the mineral epidote occurs in many of these plutons, and experimental work suggests that this requires 6–8 kbars of pressure. The major and trace element geochemistry of these plutonic rocks is very similar to the compositions of eroded roots of modern day magmatic arcs, e.g., the Sierra Nevada batholith of California or the Coast Range batholith of British Columbia. U-Pb zircon dating of numerous units in this batholith yields ages of 2.80–2.82 Ga.

## Yellowstone River Shear Zone

A major ductile shear zone has been identified along the Yellowstone River, east of Garnet Hill and west of the Buffalo Plateau–Slough Creek area, marking the boundary between the predominantly metasedimentary rocks to the west and a large, igneous, composite plutonic body to the east. Structural analysis of this shear zone indicates that the eastern block was thrust up and over the western block (a "reverse" sense of movement), and higher-pressure rocks to the east were structurally emplaced over lower-pressure rocks on the west. This shear zone represents a major structural discontinuity in the architecture of the basement rocks in Yellowstone.

The gray gneiss and metasedimentary rocks in the Junction Butte area contain veins and dikes of leucogranite.

Students describing the rocks and structures in the Jardine Metasedimentary Sequence near Bear Creek.

## Putting Together Northern Yellowstone's Precambrian History

The Precambrian history of the northern part of Yellowstone National Park spans an interval of over 400 million years, and provides insights into the processes that formed the North American continent. The following is an overview of the geologic history of this area:

The Junction Butte area is host to a unique suite of gray gneisses that comprise the oldest (3.2 Ga), and deepest (~800˚C and 7 kbar) rocks in the area. These rocks are similar in age and composition to rare enclaves of gray gneisses that occur in the adjacent Beartooth Mountains, and may represent the "basement" on which younger crust formed and the continent grew.

The Jardine Metasedimentary Succession is interpreted as a marine turbidite sequence that was deposited along an active continental margin. There is an overall coarsening of the grain size from west to east, indicating that these rocks were deposited in the farthest to nearest (with respect to an ancient shoreline) parts of a submarine sediment fan. It is remarkable that these metasedimentary rocks were able to preserve their sedimentary structures, and that they only experienced relatively low grades of metamorphism and deformation. The detrital zircon population of the quartzites has a maximum age of ~2.9 Ga, compared to the provenance ages of 3.2–3.3 and 2.8 Ga that dominate in the northern Wyoming Province. We interpret this to mean that these metasedimentary rocks had a source that was far removed from any possible source area in the near vicinity.

The Jardine Metasedimentary Sequence was metamorphosed and deformed prior to intrusion of the igneous rocks. Rocks exposed in the western section, near Bear Creek, are relatively low-grade, and the grade increases to the east to exhibit peak metamorphic conditions of 572–609°C and 3.4–5.9 kbar across the study area. These rocks experienced at least three folding events during their history.

A major crust-forming event occurred at ~2.8 Ga during the emplacement of a variety of igneous bodies. These rocks are of the same age as the voluminous granitic rocks emplaced in the Beartooth and Bighorn mountains to the east. The large composite pluton in the Buffalo Plateau–Slough Creek area contains biotite and hornblende granites, granodiorites, tonalites, and diorites. Its composition and the style of emplacement (numerous sheets of discrete magmas) are similar to those of the Beartooth Mountains, and indicate that these magmas were emplaced at mid-crustal levels (approximately 20 km depths or more). Overall, these rocks are interpreted to have formed in a continental volcanic arc, similar to modern convergent margins (e.g. Cascadia). The Crevice Mountain and Hellroaring Creek plutons, although of similar age, have compositions that indicate they were formed by partial melting of a sedimentary source, and were emplaced at higher crustal levels (~10–12 km). The injected sills and dikes observed in the Garnet Hill area are also of the same age, and were emplaced into the Jardine Metasedimentary Sequence under metamorphic conditions of 560–615°C and 4.0–5.5 kbar (12–16.5 km burial).

The Yellowstone River shear zone east of Garnet Hill is a major structural discontinuity in the crust that separates the low-grade Jardine Metasedimentary Sequence from the higher pressure plutonic rocks of the Buffalo Plateau–Slough Creek area. The sense of movement on this shear zone has the higher pressure rocks thrust to the northwest over the lower pressure rocks. The Jardine Metasedimentary Sequence has a detrital zircon population that was not derived from local sources. So, we interpret the Jardine rocks as travelling far and arriving in their present location prior to the cross-cutting granites aged at 2.8 Ga.

## The Scientists

Through the National Science Foundation's Research Experiences for Undergraduates Program, we sponsored two cohorts of 12 students to undertake the geologic mapping and sampling required to do this research on the genesis and evolution of Archean continental crust. These students were selected from colleges and universities across the country based on their interest in doing "backcountry" geology, and their special interests in geology (e.g., petrology, geochemistry, sedimentary geology, structural geology) that would contribute to the overall research project.

The first group of 12 students started in the summer of 2010, the second in the summer of 2011. During the summer field work, the students developed skills in describing rocks, taking field notes, measuring structural features, geologic mapping, and geochemical sampling. All students formulated individual research questions in the context of the larger research goals, and developed their own research plans. Students were responsible for planning daily logistics about what sites to visit, what to collect, and for what purpose. Students took turns being team leaders to visit key locations and collect samples to address their research questions; the other students served as field assistants to make sure the work was completed. The entire research team spent a number of days on the Montana State University campus doing sample preparation at the end of each field season, which included using diamond-studded rock saws to prepare thin sections, crushing and grinding whole-rock samples for mineral (zircon and mica) separation, and making sample powders using a "shatterbox" for whole-rock elemental analysis. As part of their professional training, lab safety and sample preparation protocols were emphasized to prevent cross-sample contamination.

During the following fall semester, the students received thin sections in order to characterize and describe the rocks by mineral identification and conduct fabric analysis using a petrographic microscope. Based on field and petrographic analysis, some samples were selected for more detailed analytical studies. During the early winter, students attended one of the analytical laboratories at the University of Florida and other research universities to perform: whole-rock chemical analysis using X-ray fluorescence (XRF), geochronologic analysis of zircons using laser ablation inductively-coupled plasma mass spectrometry (LA-ICPMS), and mineral compositional analysis using an electron microprobe (EMP). These data, along with field images, structural data, and maps, were compiled on a project website for use by all students in their individual research projects. All students contributed to writing abstracts about their research results, designed and created posters, and presented the results to professional geologists at the 2011 and 2012 Rocky Mountain Section meetings of the Geological Society of America.

*The results of this research project have answered some fundamental questions about the origins and evolution of the ancient continental crust exposed in northern Yellowstone National Park.*

Students cutting rocks to use as billets to make thin sections for petrographic analysis..

## Conclusion

The results of this research project have answered some fundamental questions about the origins and evolution of the ancient continental crust exposed in northern Yellowstone National Park. We now have clearly identified the rock types, compositions, and ages of key geologic units; we have a better understanding of the structure or architecture of the basement rocks in this area; we have learned more about the geologic processes that formed and transformed these rocks; we have been able to interpret the geologic environment of the formation of these rocks; and we have determined the geologic history of these rocks in comparison to the Beartooth Mountains and surrounding ranges. These data can also help address other geologic and ecologic research questions in the park. How were these "basement" rocks involved in more recent events such as the formation of the Eocene Absaroka Volcanics and the Yellowstone volcanic eruptions? How does the geochemistry of these rocks affect soil formation and bioavailability of essential elements that support the biota in the park's northern range?

In addition to developing the research skills of students in the geosciences, this project has contributed to a more complete understanding of the natural history of Yellowstone National Park and will provide park management with a more comprehensive view of the park's northern range. The full roster of posters presented at the 2011 and 2012 Geological Society of America Rocky Mountain Section meetings can be accessed at: http://serc.carleton.edu/research_education/yellowstone_reu/.

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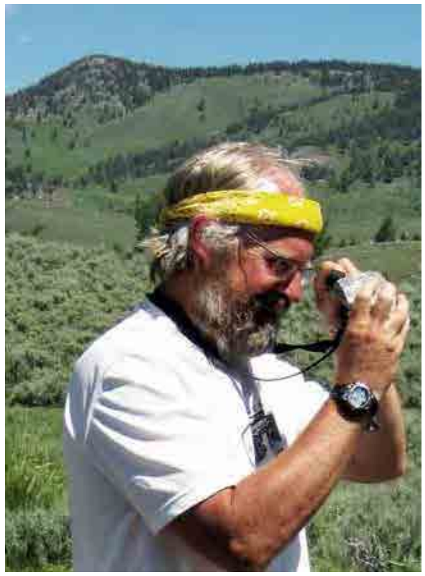

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