Yellowstone Science

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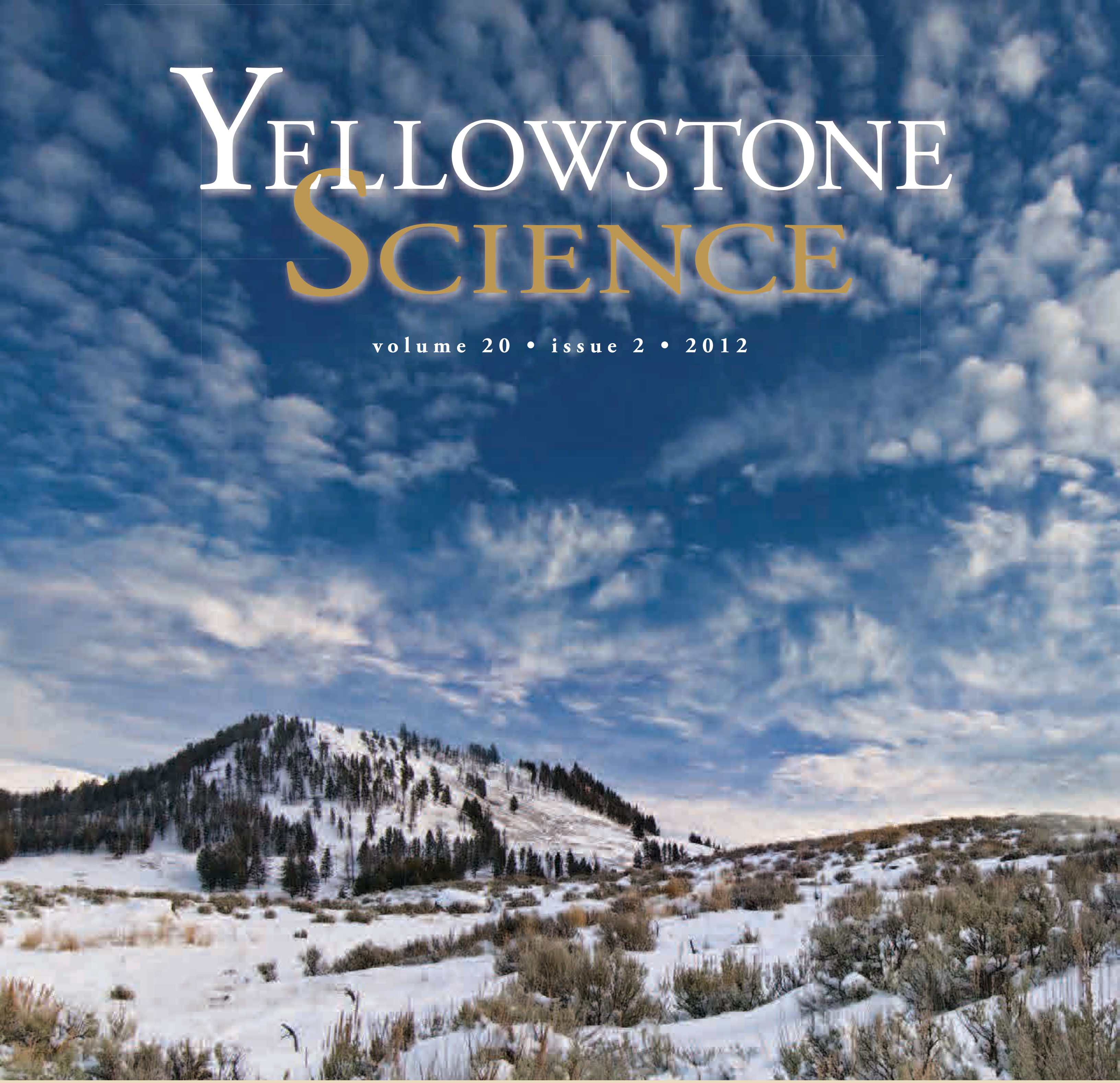

Archeology of the Airport Rings Site

An Interview with Suzanne Lewis

Following the Path of Stone

Origins of a Continent

Intruding through the Precambrian rocks in the northern part of Yellowstone, two bodies of igneous rock—the Crevice Pluton (right) and the Hellroaring Pluton (left)—are examples of how new developments are constantly intruding to reshape Earth as well as bodies of scientific knowledge. The plutons were photographed by researchers in the Research Experiences for Undergraduates project featured on page 22.

Just a Status Report

Several years ago, I was having a conversation with one of the geologists in Yellowstone about the history of science. We reflected on how so many closely held views and interpretations about the fundamental nature of the planet and its life forms have given way as new information becomes available. Each era has its own "science," because the purpose of scientific inquiry is not just to discover new information, but to allow our understanding of the world to change because of those discoveries. As the geologist remarked to me: "Science is just a status report." It reflects our understanding of the world now—in this time. The research that we present in this issue takes us back along various geological and social timelines and shows how the earth has changed, and how we humans have changed upon it.

In a National Science Foundation Research Experience for Undergraduates project, students from across the country have helped to determine the type and composition of the rocks that are literally the foundation of Yellowstone. Their research reveals the conditions under which these rocks were formed and tells us more about the evolution of the North American continent. At the same time, the record left in stones which have been moved and shaped by human hands tells us about the evolution of North American culture.

In both Michael Livers' graduate research on the Airport Rings stone circles and Amy Bleichroth's analysis of obsidian found at a Hopewell site in Indiana, we learn about the lifestyles and movements of early people through the area that is now Yellowstone National Park. Livers' work adds to what we know about how early people used the resources of the area and poses research questions that could confirm the presence of native populations earlier than previously documented—helping us to extend our knowledge of people's historical impact on this land.

The responsibility for managing those human impacts has a shorter history, but one that is no less dynamic for its brevity. During her eight-year tenure as Yellowstone's first female superintendent, Suzanne Lewis had to reconcile the science and values of today with the habits and understanding of the eras that came before. In her interview for the Yellowstone Oral History Project she shares with us some of the challenges she faced when questioning traditions and moving forward with new science.

On October 8–10, 2012 park scientists and staff will join other regional land managers and researchers in Mammoth Hot Springs, Wyoming at the 11th Biennial Scientific Conference: *Greater Yellowstone in Transition: Linking Science and Decision Making*. This conference will provide an opportunity to exchange information relevant to management and to identify resource challenges that require new research. The forums and presentations will bring the latest "status reports" out of the field laboratories and classrooms and into the park. The observations and scientific analysis that are shared will help to establish management targets or desired conditions, examine the interactions between humans and the environment, and determine how best to continue scientific exploration.

We hope you enjoy the issue.

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a periodical devoted to
natural and cultural resources

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A detailed image of a lithic sample from Obsidian Cliff.

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FEATURES

DEPARTMENTS

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Submissions are welcome from all investigators conducting formal research in the Yellowstone area. To submit proposals for articles, to subscribe, or to send a letter to the editor, please write to the following address: Editor, *Yellowstone Science*, PO Box 168, Yellowstone National Park, WY 82190. You may also email: yell_science@nps.gov.

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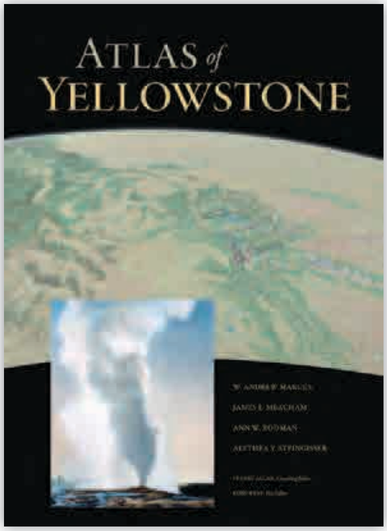
Cover photo:
"Isolation"—Garnet Hill in winter.
Photo © James Duckworth 2010.

News & Notes



Atlas of Yellowstone Now Available

The *Atlas of Yellowstone* is the first comprehensive atlas of a national park. The atlas, published earlier this year, represents a major collaboration between the University of Oregon and Yellowstone National Park. Over 100 researchers from the National Park Service and the region's universities, agencies, and institutes contributed their expertise and knowledge to this publication. The *Atlas of Yellowstone* will be a 300-page reference volume that uses rich graphics to examine a wide range of topics from art to wolves, provides new references maps for the region, and provides a rich understanding of the unique place of Yellowstone in the world.

The *Atlas of Yellowstone*'s content covers topics relevant to Yellowstone National Park, Grand Teton National Park, and the surrounding Greater Yellowstone Area. The content is broadly organized around four themes:

- connections between Yellowstone, its region, and the world;
- the dynamic, ever-changing nature of the Yellowstone landscape over time spans ranging from days to millions of years;
- the interaction of humans and nature throughout the region; and
- the importance of Yellowstone National Park and its region as natural and cultural resources.

Early production work on the *Atlas of Yellowstone* project was made possible by a seed grant approved by the board of the Yellowstone Park Foundation, and funding by *Eyes on Yellowstone* made possible by Canon.

2012 Summer Bison Count

Yellowstone National Park's 2012 summer bison survey estimates a parkwide population of 4,230, a 14% increase over the 2011 estimate of 3,700. The results are based on aerial surveys conducted in June and July 2012.

The count includes approximately 2,630 adult and yearling bison, and about 600 calves of the year observed in June. The current population is concentrated in two herds, with an estimated 2,600 bison in the northern herd and 1,600 in the central herd.

The rate of population change observed this past year is within the expected range for wild bison. Rates of change in wildlife populations over time reflect the combined effects of reproduction and mortality, and are heavily influenced by each specific population's age structure, plus a variety of environmental conditions.

The peak population recorded during the summer surveys was in 2005, when the population was estimated at 5,000 bison.

Ongoing population monitoring efforts include an annual winter count, typically conducted around December each year. Population estimates from summer and winter annual surveys are used to inform adaptive management strategies under the Interagency Bison Management Plan (IBMP). Specific management actions may be modified based on expected late winter population levels as corroborated by the summer population estimate.

The IBMP is designed to conserve a viable, wild bison population while helping to protect Montana's brucellosis-free status. IBMP-cooperating agencies include the National Park Service, the USDA Forest Service, the USDA Animal and Plant Health Inspection Service, the Montana Department of Livestock, the Montana Department of Fish, Wildlife and Parks, the Intertribal Buffalo Council, the Confederated Salish Kootenai Tribes, and the Nez Perce Tribe.

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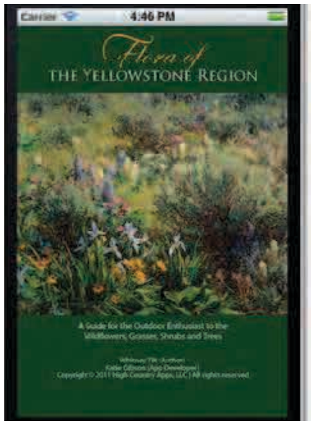
NPS

Adult bison with one the 600 calves of the year.

Shorts

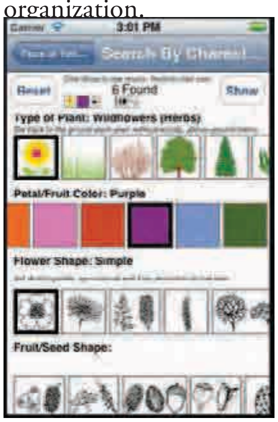
Review: Flora of the Yellowstone Region Mobile Application



It has long been the practice of *Yellowstone Science* to review or feature books that contribute to our readers' understanding of the science being performed in Yellowstone, or the natural and cultural resources we protect. As technology changes, so do our available sources of information. With that in mind, we present our first review of a mobile application (app).

Bozeman-based High Country Apps has released Flora of the Yellowstone Region, an interactive app for smart phones and tablets. Flora of the Yellowstone Region covers 300 wildflowers, trees, shrubs, and grasses commonly found in Yellowstone National Park and the surrounding national forests of Idaho, Montana, and Wyoming.

Though there are other Yellowstone-focused apps avail-able, Flora of the Yellowstone Region is not designed for trip planning or general park information—it is designed as a digital field guide. The guide presents photos and illustra-tions of the plants, easily understood descriptions, distinctive field marks, preferred habitats, and supplemental informa-tion on each plant's ecology and cultural use. We selected three reviewers to explore the app and report back to us, one interpretive ranger, one resource specialist, and one guide from a partner organization.



Reviewers found that the app was easy to use and deemed it appropriate for professional guides as well as novice nature enthusiasts. They liked the search key which allows the user to select flower color, leaf type, and other characteristics to quickly identify unknown plants. For example, you may be on a hike, look down and see a plant, but not know its name. It could be tall and thorny, sticky with black berries, or perhaps sweet-smelling with square stems. Using the app, you can select what you do know, and all plants matching your description will be displayed. You can also search by environmental parameters such as elevation, habitat, and time of year.

On the technical side, the entire app is stored directly on the mobile device, designed for use with or without call service or data connection. This is a particularly useful feature in areas with poor or intermittent wireless access—like Yellowstone trails. The app is available for a variety of platforms and operating systems, including Apple and Android devices, and Kindle Fire.

Working with local plant experts, the designers have developed similar region-specific flora apps for Glacier National Park, the Colorado Rockies, and the Wasatch Range. For additional reviews and information on price and offerings, go to http://www.highcountryapps.com/.

-Yellowstone Science

An All Girls Expedition

Founded in 1999, Project Exploration is a nonprofit science education organization whose mission is to ensure that communities traditionally overlooked by science—espe-cially minority youth and girls—have personal experiences with science and scientists. Project Exploration's All Girls Expedition is a two-week session for high-school girls from Chicago public schools. The Expedition has brought 72 girls to participate in Yellowstone since 2007 The expedi-tion begins in Chicago with intensive class work in which the participants learn practical geology, biology, evaluation, and field skills. Then the team spends a week working in the field alongside scientists.

The nine participants in the 2011 All Girls Expedition arrived in Yellowstone with program coordinator Elsa Rodriguez and Heather King, a PhD candidate in the Department of Organismal Biology and Anatomy at the University of Chicago. On July 20, the group contrib-uted to the work being done by Yellowstone's geology pro-gram in the ongoing mapping the Mammoth Hot Spring Terraces. The girls received an introduction to the geology of Yellowstone National Park and the surrounding landscape from park staff. Yellowstone geologist Cheryl Jaworowski and student technicians Laura Bueter and Emma Reinhart explained the significance and goals of the Mammoth Hot Springs mapping project, as well as how to orient and read maps. The girls learned about a technique to visually estimate the area covered by flowing thermal water and colorful microbial mats at Canary Springs. Along with the two student technicians, each of the girls estimated the flow area of the Mammoth Terraces by using a geologic map as a base and drawing their estimates with a pencil.

The estimates derived from the Project Exploration students' maps ranged from 10,260 to 49,240 square meters, with most between 14,000 and 20,000 square meters, while those of the two Yellowstone geology technicians were 15,900 and 21,300 square meters. This project helped the Yellowstone geology program to assess the usefulness and accuracy of this technique. Even with these variations in area, it can provide a map of hydrothermal activity that complements the photographs and observations of National Park Service interpretive rangers.

COURTESY OF PROJECT EXPLORATION

Kyra W. completes her classroom preparations before heading out to Yellowstone for field work.

—The 2011 All Girls Expedition team: Constance Robinson, Jackie R., Xhaidt T., Kennedy W., Kyra W., Morgan W., Robbie L., Shelby G., and Ana L.

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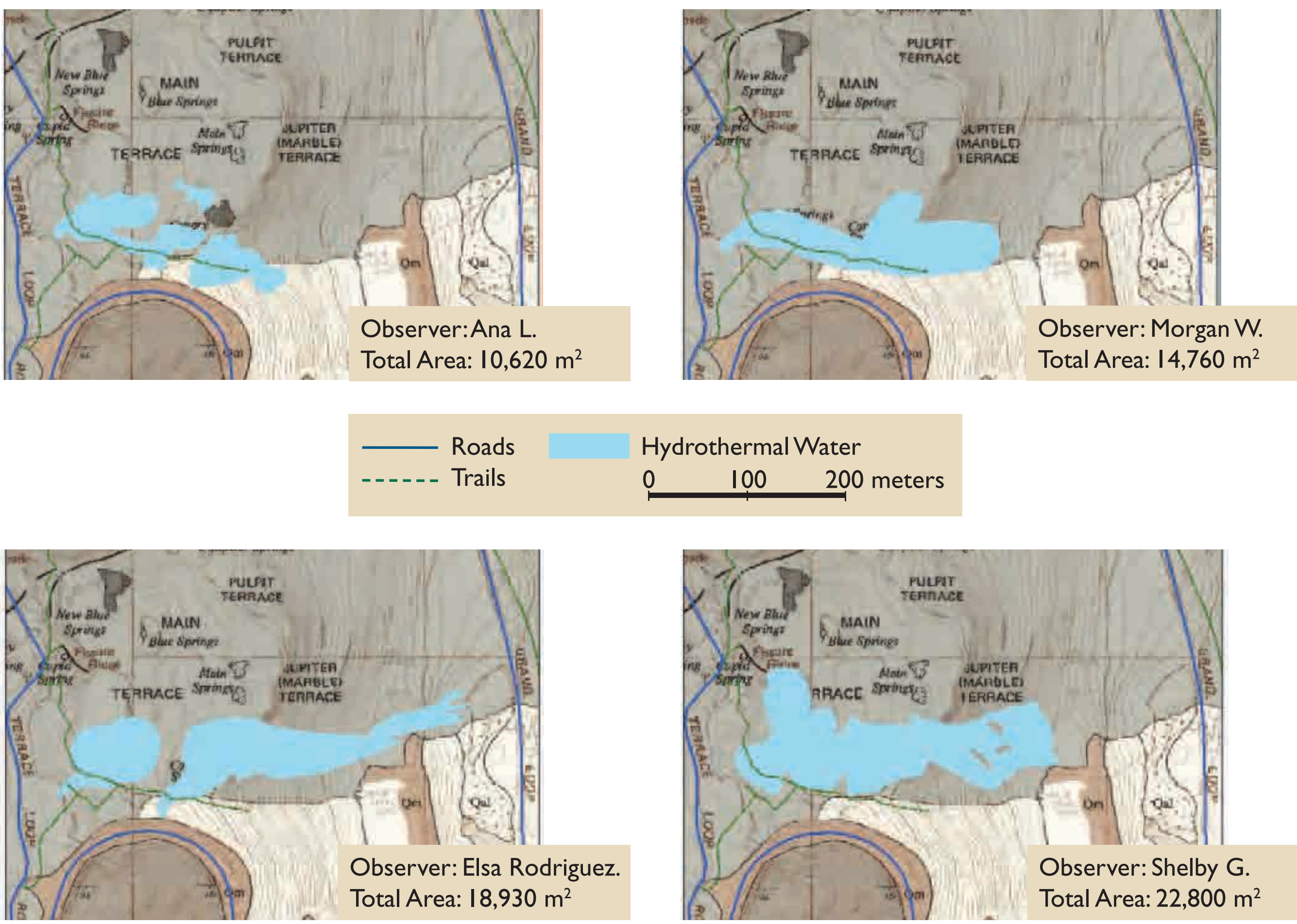


Geology technicians converted each student's illustrations into digital shapes, then produced maps of their estimations of the thermal waters of the Trail/Canary springs area.

Stone Circles in Yellowstone

Archeology of the Airport Rings Site

Michael Livers

LIVERS

Overview of the project area at the Airport Rings Site.

The upper Yellowstone River Valley was occupied for thousands of years by hunter-gatherer populations prior to the twentieth century. The river provides a natural corridor for the migration of animals and people obtaining resources along the valley (Hale 2003). This is evident from archeological sites such as the Carbella buffalo jump, which shows stratified occupation going back more than 6,000 years, and Larry Lahren's Myers-Hindman site, with over 7,000 years of continuous occupation. Lahren's Anzick site, located north of the upper Yellowstone River Valley, is the only Clovis-age burial that has been documented in North America, dating to 10,680±50 BP (Lahren 2006).

Within Yellowstone National Park, the Osprey Beach site (Shortt 2001) and others at Yellowstone Lake provide evidence of use that began more than 8,000 years ago. However, life in the valley differed from that in the park's upland interior. One form of cultural remains left by early inhabitants that changes with the transition from the valley to the interior are the stone rings they used to hold their tipis in place, going back at least 3,000 years. Although nearly nonexistent at higher elevations of the Greater Yellowstone area, probably because of a lack of rocks, stone rings have been documented in lower, glaciated areas on the park's periphery.

Stone circle sites have been recorded on both public and private land in the upper Yellowstone River Valley. Nearly all of them have been found within six miles of a buffalo jump site, but that may simply reflect a bias in survey practices. Records at the Montana State Historic Preservation Office show that more than 100 tipi ring or stone circle sites have been identified in Park County. Although some Plains Indians sites have been documented with hundreds of rings, indicating large communal gatherings or repeated visits to the locations, the stone circles found in and near Yellowstone have generally been single rings or a few rings clustered together, suggesting seasonal use of the area by small groups of foragers.

The University of Montana Yellowstone Archaeological Project (MYAP), which provides field work opportunities for students and information about the park's archeological resources for the National Park Service, identified five sites with a total of 32 stone circles northwest of Gardiner, Montana, during the 2007 and 2008 field seasons. All of the sites are in well-protected settings, generally with water and a good view on one side and a hill or enclosed valley on the other. The one referred to as Airport Rings contains the oldest recorded evidence of human use at the five sites, with radiocarbon dating of a charcoal sample from a hearth indicating occupation about 4,500 years ago.

YELL-02738

A tipi interior showing cooking and sleeping areas set out in a circular arrangement. Unknown photographer, 1870.

Prehistoric Stone Circles

The conical tipis once found on the Great Plains in great numbers were constructed from cured animal hides sewn together and stretched around wooden poles that had been lashed together at a central point. Not all tipis were anchored by rocks and not all stone circles found today were left behind from tipi use. A stone circle may be evidence that an area was used for a hide boiling pit, a sweat lodge, a medicine wheel, or an animal corral. Rocks have sometimes been found around the base of wikiups, which were conical lodges constructed entirely of wood poles and have been documented in the park much more frequently than stone circles (Malouf 1958). However, all of the stone circles referred to in this paper are considered tipi rings because of their size and the presence of a central hearth and domestic artifacts found nearby.

When Plains groups began using stones to hold their tipis in place is not known. In their report on Paleoindian campsites in the Hell Gap Valley of southeastern Wyoming, Irwin-Williams et al. (1973) suggest that the arrangement of nine rocks in the Frederick component of the excavation (6,400–6,000 BP) was similar to the stone rings found in later Plains sites. This could indicate tipi use occurring during the Early Archaic Period (7,000–5,000 BP); however, archeologists generally associate stone circles with tipi adaptations that occurred during the Late Archaic Period (3,000–1,500 BP) (Frison 1991) because of the wealth of artifacts occurring in the later cultural periods. The research results presented in this paper suggest that use of tipis, or some other structure that needed rock weights, may have begun much earlier.

Some of the oldest verified stone circle sites are located on the Northern Plains (i.e., Montana, Wyoming, North Dakota, and Alberta, Canada), but only a few from before 2,000–3,000 BP have been identified. The Cactus Flower site, which is considered the oldest documented tipi ring on the Great Plains, was discovered in 1969 and excavated by John Brumley on the Suffield Military Reserve in southeastern Alberta. Occupation during the McKean Phase is indicated by diagnostic artifacts and radiocarbon dates around 4,200 BP (Brumley 1975), but based on the span of the McKean Complex (5,000–3,000 BP), most archeologists generally accept that the site could be as old as 5,000 BP.

The oldest dated stone circle site in Montana (site 24BH2317) is located in Big Horn County and associated with a similar period. It was tested in 1984 by Steve Aaberg and in 1998 by John Brumley and Ken Dickerson. A charcoal

…the stone circles found in and near Yellowstone have generally been single rings or a few rings clustered together, suggesting seasonal use of the area by small groups of foragers.

YELL 8166/W.H. JACKSON

The conical tipis of the Great Plains were sometimes anchored by rocks, leaving behind the stone circles we find today. Those circles may indicate the location of temporary encampments like this one, of the Washakie band of Shoshone in August 1870, located near Camp Brown (present-day Lander, WY).

YELL-33367-2/A.L. HAINES

An unidentified man points to a stone cooking circle unearthed near Corwin Springs and the park's northern boundary in 1962.

sample from a hearth feature within one of the rings had an uncalibrated AMS (accelerator mass spectometry) date of 3,9 0±60 BP and a one sigma calibrated date of 4,275– ,430 BP (Brumley and Dickerson 2000). Archeologists compiling known dates from these sites have concluded that stone circle formation increased after 2,000 BP as a result of shifting subsistence strategies for bison hunting.

Even with the documentation that now exists on stone circle interpretation and history (Livers and MacDonald 2009), these features often pose interpretive challenges. The circles themselves do not always provide the information needed to understand the contextual and temporal association of the mobile groups that used tipis. As anthropologist Fred Schneider pointed out:

> *"Past investigations of tipi rings usually focused on excavation of ring interiors, and they commonly placed a test unit over the center of the ring. Literature published prior to 1970 shows that many early investigators did not make use of screens but simply chunked out or skimmed the soil with shovels. It is no wonder that many archeologists reported a paucity of artifacts and became disenchanted with tipi rings and their excavation" (Schneider 1983).*

Boundary Lands Project Area

With an average elevation of 5,270 feet, the boundary lands are in the lowest and driest portion of the park. The area has sloping alluvial fans and flat terraces with beds of silt and sand that were deposited about 10,000 years ago when the adjacent Yellowstone River was dammed by a landslide at Yankee Jim Canyon. Surrounded by the Rocky Mountains, the river valley itself is in a High Plains setting where a sagebrush and short-grass prairie developed around 5,000 years ago. The surface vegetation remains predominantly sagebrush grassland community, with stands of sagebrush up to eight feet tall, indicating the relatively dry and unchanging nature of the area. Limited pine growth marks the adjacent slopes and drainages, while a few riparian tree varieties grow along the river.

The archeological record of the region depicts seasonal hunter-gatherer movements based on subsistence and procurement of plants. The wide variety of flora and fauna would have provided potential subsistence during different times of the year (MacDonald and Hale 2011). However, the plant resources available in the upper Yellowstone River Valley are poor compared to those of higher elevations in the park and other intermountain regions. The first people in the area would have also relied on animals for food. The ecosystem is currently home to many large mammals (bison, elk, moose, bighorn sheep, deer, antelope, grizzly and black bear, mountain lions, coyotes, and wolves), as well as a variety of birds and other small animals, but these population distributions may have been different in the past (Frison 1991).

We would expect to find evidence that lowland valley areas like the boundary lands were occupied during winter, when human movements were more restricted and the need for shelter greater (Madsen and Metcalf 2000; Larson

LIVERS

Montana Yellowstone Archeological Project participants excavate a stone circle in Feature 6 at Airport Rings.

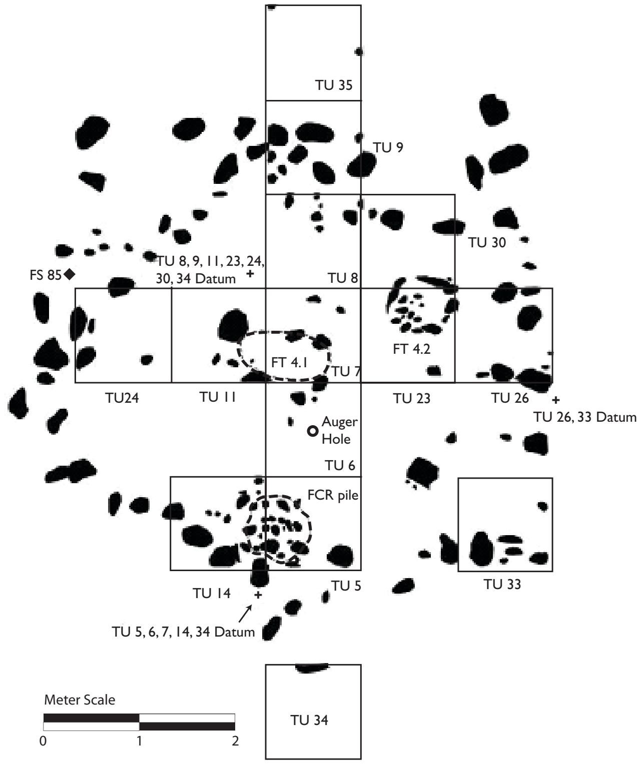


Figure 1. Final excavation planview for Feature 4.

Results of the lithic sourcing demonstrate a well-established Late Prehistoric trend toward use of material from Obsidian Cliff … but also raw stone from more than 100 miles away.

and Francis 1997). Given the evidence of more than 10,500 years of human occupation in the Greater Yellowstone Area (GYA), we would also expect to find cultural and technological innovations representing all periods of prehistory.

First identified in 1986 by avocational archeologist Tom Jerde, the Airport Rings (site 24YE357) is on a glacial bench that would have been protected by a high rocky ridge, a stream, and its view down the steep slope to the Yellowstone River valley as it extends northward. A large historic trash scatter encroaches minimally into the prehistoric component, which is located on a heavily cobble-strewn, Late Pleistocene glacial outwash channel and includes a sparse lithic debris scatter around 11 stone circles.

The MYAP survey recovered from the surface scatter several scraping tools and a Late Prehistoric tri-notched projectile point that has been chemically sourced to Obsidian Cliff. To assess eligibility for the National Register of Historic Places, we used 39 test units, each one square meter to obtain excavation samples. In an attempt to uncover a central hearth feature that would support our hypotheses about the site's function, we excavated longitudinal cross-sections in three of the stone circles, two of them roughly 25m^2, and the third, half as large. We excavated other test units to the north and south of each stone circle so that we could evaluate how the area outside the circles may have been used (fig. 1).

Artifact and Sample Analysis

Results of site excavation proved rewarding, with the recovery of 10 projectile points, over 600 flake artifacts and tools, and faunal remains and floral specimens from soil test-samples (table 1). We sent the botanical remains to PaleoResearch, Inc., of Colorado for analysis, charcoal samples for radiocarbon dating to Beta Analytic, Inc., of Miami, Florida, and select volcanic artifacts to Richard Hughes for chemical sourcing.

Results of the lithic sourcing demonstrate a well-established Late Prehistoric trend toward use of material from Obsidian Cliff (Davis et al. 1995), but also raw stone from more than 100 miles away. Sourcing results for the exotic stone tool artifacts matched the poorly known Grasshopper Knob dacite source in west-central Montana and the Bear Gulch obsidian source in Idaho. The presence of materials at the site from these sources is indicative of a system of trade with neighboring groups, domestic mobility, or both.

Table 1. Summary of excavation results, Airport Rings (24YE357).

Feature ID #	Size (m²)	Sample size	Feature (% excavated)	Artifacts	Lithics/m²	Interior	Faunal	Botanical
4	19.6	14	71.4	350	25	2 hearths	Bison, large mammal	Juniper, sagebrush
6	19.6	12	61.2	178	14.8	none	Unidentified	N/A
8	22.9	13	56.7	155	11.9	1 hearth	Large, medium mammal	Willow, sagebrush
Total	62.1	39	62.8 (avg.)	683	17.5 (avg.)	3 hearths	Bison, other unknown mammals	3 fuel sources

Fire features from stone circle Feature 4: FT 4.1 (foreground, next to photo board) and FT 4.2 (top). View east from western edge of stone circle.

Analysis of the faunal samples indicated that site occupants fit the highly mobile, Plains bison, hunter-gatherer model, subsisting on bison and other large- to medium-sized mammals. Macrofloral analysis of soil samples obtained from the fire features in the stone circles pointed to the use of locally available plants (e.g., juniper, sagebrush, willow) as fuel sources, but did not produce substantial evidence of plant processing at the site.

The overall lack of lithic artifact diversity and low volume of artifacts suggest that the campsite received only short-term use. Analysis of the lithic flaking debris indicates that the late stages of tool manufacturing occurred most often during site occupation, while obsidian, likely from Obsidian Cliff, was the favored stone. The relative absence of tools in the recovered assemblage suggests that while site occupants likely performed daily tasks, this campsite was not designated for a specific task such as hide processing or tool manufacturing. Analysis of the diagnostic projectile points provided relative chronological dates and strong evidence of subsistence activities focused on hunting.

The excavations at the three stone circle features provide evidence for Middle Archaic, Late Archaic, and Late Prehistoric occupation episodes. Radiocarbon analysis of charcoal samples from the three hearths provided one date around the beginning of the Middle Archaic Period and two for the Late Prehistoric Period that were within 100 years of each other, supporting the trend of increased occupation and use of the GYA over the last 1,000 years.

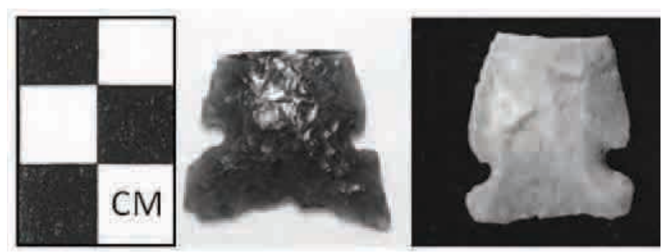
None of the recovered projectile points were complete, having been damaged in some way during their use. Although the points were likely associated with use of the hearths, their chronology covers periods not supported by the hearths' radiocarbon dates, suggesting a possible alternative interpretation. The best type affiliations associated with these point fragments put the seven diagnostic artifacts into five possible phases covering the range of dates from 5,000 BP to 400 BP.

Explored Features

One of the stone circles that was tested (Feature 4) appears to have been occupied on at least two and probably three occasions beginning as early as about 4,500 years ago. More lithic artifacts were excavated from Feature 4 than from the other two stone circles combined.

The presence of two hearths within the roughly 25m^2 circle indicates that the site was probably used during late fall to winter. The more recent of the hearths (Feature 4.1), located 10 cm below the surface at the center of the circle, yielded a conventional radiocarbon date of 3 0±40 BP (Beta-251175). The three projectile points found in association with this hearth were also of probable Late Prehistoric age and

Overview of the Feature 6 stone circle excavation site.



Examples of Late Prehistoric projectile points, including a tri-notched obsidian point (left) and a side-notched point recovered from Feature 6 (right).

LIVERS

Moving the stones (arrows) of Feature 8 indicates that they were covered by a layer of ash that is absent from the soil below them (dotted lines). The ash indicates a hearth site.

support an occupation approximately 500–1,500 years ago. Short-term use is suggested by the hearth's shallow maximum depth (~5 cm), the small number of rocks lining the hearth, and the low density of fire-cracked rock, charcoal, and artifacts. However, the low density of artifacts could be a result of the feature having been cleaned out after use. The stones used in cooking pits were often placed on a bed of hot coals, and if the rocks cracked from overheating, they may have been removed or a new pit would be dug (Francis 2000; Frison 1991).

The Late Prehistoric occupation at Feature 4 may have been the first since the older hearth (Feature 4.2) was created. The older hearth was found off-center within the stone circle, close to Feature 4.1, and 12–14 centimeters below the surface [Photo 3]. Wood charcoal from Feature 4.2 yielded a conventional radiocarbon date of 4,520±40 BP (Beta-250333) with a 2 sigma calibrated result of CAL BP 5,310–5,0 0. With large rocks placed around the hearth walls and several sandstone pieces lining the pit's northern interior, it resembles the Archaic Period rock or sandstone slab-lined roasting pits recorded in the northwest uplands of Wyoming. Soil samples and projectile points found at the site, including a possible Middle Archaic Oxbow point base of translucent obsidian, substantiate terminal Early Archaic to early Middle Archaic use of the hearth and possibly of the stone circle itself.

The interior of Feature 6, the smallest of the stone circles, was completely excavated. This enabled researchers to address potential sampling bias in the excavation methods used at the other two stone circles. The small number of lithic artifacts recovered during excavation of Feature 6, which suggest a single occupation episode, include a nicely worked Late Prehistoric arrow point from a tan, fine-grained orthoquartzite and a fragment of a possible Avonlea or other Late Prehistoric arrow point. Both of these projectile points indicate a Late Prehistoric occupation, perhaps 1,000 to 1,500 years ago, although researchers were unable to identify fire features that might corroborate the period of use.

At the center of the third stone circle (Feature 8), a hearth (Feature 8.1) packed with charcoal and fire-cracked rock was excavated, indicating an intensive and hot fire. Charcoal from the hearth yielded a conventional radiocarbon age of 270±50 BP or AD 1630–1730 (BETA-25033). The 2 sigma calibrated radiocarbon age is CAL AD 1480 to 1680 and CAL AD 1770 to 1800. In association with the hearth, excavation revealed at least two large cobbles atop an ash layer up to 15 centimeters thick, indicating that the layer formed during site occupation. The radiocarbon data from the charcoal sample and the distribution of ash in association with the hearth suggest that this stone circle likely experienced a single winter occupation during the terminal Late Prehistoric to Contact period, approximately AD 1480 to

Although the accurate association of buried cultural materials with surface materials is difficult, the overall chronological trend … leaves open the possibility that the Airport Rings site contains the oldest known stone circle on the Northern Plains by several hundred years…

LIVERS

Michael Livers and MYAP participant Jacob Adams during the survey in Yellowstone.

1630. The lack of stratification within the hearth and low artifact count from the stone circle excavation also suggest a single occupation rather than multiple uses over time.

Conclusion

The University of Montana field work at the Airport Rings site included the first intensive excavations of stone circles within Yellowstone National Park as well as within the upper Yellowstone River Valley. The goal of the project was exploratory and allowed for the interpretation of archeological data that helps paint a picture of daily life at the site during multiple prehistoric occupations. Results of the data analyses have provided preliminary explanations regarding period of use, probable seasonality, intersite patterning, the subsistence strategies used by hunter-gatherers in the area, and mobility patterns associated with stone raw material procurement.

Although the accurate association of buried cultural materials with surface materials is difficult, the overall chronological trend in the upper Yellowstone River Valley supports long-term use of stone circles in the boundary lands area, where circles have been dated from the Late Archaic to the Late Prehistoric, with the latter also yielding a Middle Archaic hearth. While this leaves open the possibility that the Airport Rings site contains the oldest known stone circle on the Northern Plains by several hundred years, it is highly likely that the Late Prehistoric stone circles overlay an early Middle Archaic occupation on the landform. Establishing an association of the Middle Archaic hearth with the stone circle formation now found on the surface may be impossible, but future research at the site could attempt to identify additional subsurface rocks and artifacts arranged in a circular pattern to confirm use of a stone circle structure about 4,500 years ago. YS

Acknowledgments

MYAP success would not be possible without the contributions from Assistant Professor Doug MacDonald, both YNP Resource and Compliance staff—Elaine Hale, Tobin Roop, Robin Park—and funding from Ann Johnson and Mary Hektner, also of YNP. A special thank you goes to the dozens of undergraduate and graduate students participating in MYAP over the years. Additional acknowledgments go to Beta Analytic, Inc. (Miami, Florida), for conducting radiocarbon dating, while Richard Hughes (Berkeley, California) performed X-Ray Florescence analysis of selected igneous materials from the project area. Linda Scott Cummings and Kathryn Puseman of PaleoResearch, Inc. (Colorado), conducted the ethnobotanical identification.

COURTESY OF THE AUTHOR

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Following the Path of Stone

Obsidian Artifacts from Indiana Sourced to Yellowstone Plateau

Paul K. Doss and Amy Bleichroth

At the University of Southern Indiana (USI) Department of Geology and Physics, geology majors nearing the end of their undergraduate education are required to synthesize their coursework into a focused and integrated scholarly inquiry that is a hands-on and in-depth investigation of a geological topic of interest and significance. They must prepare and present this "capstone project" in both written and oral formats.

As an undergraduate, Amy Bleichroth had an interest in the geological facets of archeology. For her capstone coursework, Bleichroth and I, as her advisor, designed an investigation into the stratigraphic origins of the different rocks used for tool-making by Native Americans and native peoples around the world. Bleichroth investigated sources of chert, jasper, flint, quartzite, obsidian, and other types of stone commonly used by Native Americans and found in archeological contexts.

Identifying the geological sources of stone tools uncovered at archeological sites is a form of forensic geology that has proven to be a valuable contribution to archeological interpretations that might otherwise be speculative. Geologic sourcing of lithic artifacts helps to reconstruct exchange patterns, illuminate cultural interactions, and map trade routes of prehistoric peoples. During Bleichroth's final year at USI, she learned of some obsidian artifacts archived at the university that had been uncovered at a nearby archeological site. Obsidian sourcing has proven particularly useful due to the limited geography of obsidian outcrops and the homogeneity of the rock itself. Obsidian artifacts are found throughout prehistoric Hopewell sites along rivers in the Midwestern United States (Davis et al. 1995). However, the closest surface outcrop of obsidian is at least 1,800 kilometers (1,100 mi) away from the sites where these obsidian artifacts occur.

Together, Bleichroth and I developed a project that would use geochemical analyses to identify the origin of obsidian used in artifacts recovered from the Mann site in Posey County, Indiana. This project tested the hypothesis that the obsidian artifacts found in Indiana originated in the Yellowstone Plateau, even though Yellowstone National Park is nearly 2,500 kilometers (1,600 mi) from Posey County, Indiana, and Bear Gulch, Idaho, is 2,700 kilometers (1,700 mi) distant. The experimental design helped formulate the objective: to apply obsidian sourcing by specific geochemical analytical techniques in order to identify the origin of obsidian for artifacts recovered from the Mann site. This project showed the applicability of geological forensics in furthering our understanding of the direct linkage among widely separated cultures thousands of years before the present. It applied concepts of historical geology, stratigraphy, mineralogy, petrology, and archeology, in a single, integrated study.

The Mann Site

The Mann site in Posey County, Indiana, is one of the largest and most complex Hopewell tradition sites known in the Midwest. It served as an important ceremonial center during the Middle Woodland Period (200 BC to AD 500). The site extends over 1.5 kilometers (1 mi) along a high terrace bordering the floodplain of the Ohio River, about 15 kilometers (9.4 mi) upstream from its confluence with the Wabash River (fig. 1). The Mann site is remarkable for the quantity and diversity of exotic materials, the tremendous investment in mound and earthwork construction, and the range of activities evident on the site. It is distinguished from other Hopewell sites by its size, intensity of occupation, and complexity (Ruby 2006). The diversity of artifacts tells us that people of different cultural and social affiliations were attracted here and traded a large variety of exotic goods from sources far outside the region.

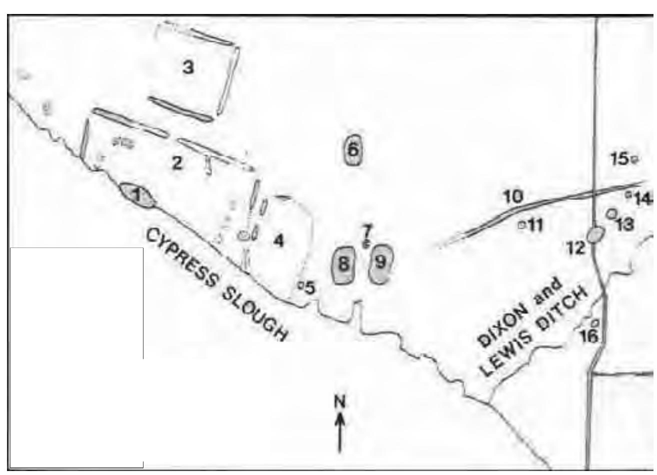

Figure 1. Map of the Mann site in southern Indiana. Numbers identify the constructed earthen structures, including notable mounds. Modified from J. Kellar (1979).

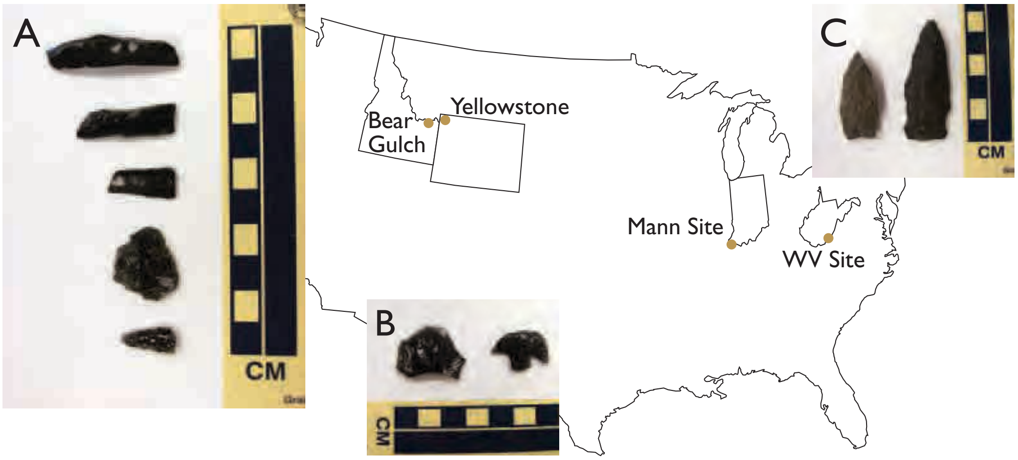

Figure 2. (A) Samples from the Mann site. Geochemical signatures indicate origins from the Obsidian Cliff flow and the Bear Gulch, Idaho, site in the Centennial Mountains. (B) Samples from the Obsidian Cliff flow on the Yellowstone Plateau. (C) Basalt artifacts found in West Virginia, lithic source unknown.

Methods

Part of the capstone project was to guide the student through the administrative elements of professional research as well. I guided Bleichroth through the preparation of a grant proposal to USI's Endeavor Program, a program designed to assist undergraduate scholars in pursuit of their research. It is a competitive program, and not all students receive funding, but she was successful in obtaining financial support to contract geochemical analyses of obsidian. Five obsidian artifacts (three blades, one biface tip, and one sherd) of unknown origin, from the extensive collection of artifacts uncovered at the Mann site in Indiana, were submitted to the Northwest Research Obsidian Studies Laboratory for nondestructive x-ray fluorescence analysis (fig. 2). XRF can accurately measure trace element concentrations in any fine-grained solid, and is well suited to analysis of obsidian and fine-grained volcanic rocks such as basalt. Analyses were also generated for some other known and unknown artifacts so that we had a greater breadth of geochemical results to ponder. Two obsidian artifacts (one basal-notched stunner or blunt, and one sherd) known to originate from the Yellowstone Plateau and two fine-grained volcanic artifacts (basalt biface points) from West Virginia were used for reference and comparison.

Just like with DNA "fingerprinting," trace element concentrations of obsidian sources form a catalogue of known "geochemical fingerprints." The diagnostic trace element ratios that characterize the unknown samples are then compared directly to the catalogue of known obsidian sources. Specific and diagnostic trace element ratios such as zirconium versus strontium (Zr/Sr) or rubidium (Zr/Rb) allow researchers to match sample concentrations with known obsidian source concentrations. Ultimately these matched geochemical fingerprints to indicate, with a very high degree of certainty, the geologic sources for the obsidian used to manufacture the artifacts.

Results

XRF analyses identified two distinct geochemical signatures among the five obsidian artifacts from the Mann site, both of which were correlated with known obsidian sources in Wyoming and Idaho (Table 1). Four Mann site samples, three blades and single sherd (Mann 61b–61e) were traced to the Bear Gulch source in eastern Idaho. The Bear Gulch site in the Centennial Mountains (also known as the Camas/ Dry Creek source) lies within the uplifted terrane of the Yellowstone Hotspot track, and its obsidian is often found paired with artifacts traced to Obsidian Cliff in Yellowstone National Park, Wyoming. The single biface tip sample from the Mann site (Mann 61a) was traced directly to Obsidian Cliff. Trace element concentrations of the four samples sourced to Bear Gulch (Mann 61b–Mann 61e) and the Obsidian Cliff sample (Mann61a) exhibit marked differences in rubidium (Rb), strontium (Sr), yttrium (Y), zirconium (Zr), and niobium (Nb). Strontium and zirconium, which show the most diagnostic trace element signatures, served

Table 1. X-ray fluorescence analysis on Mann site artifacts and reference samples.

Sample	Artifact Type	Strontium	Zirconium	Obsidian Source
Mann 61a	Blade	9 ± 9 ppm	167 ± 7 ppm	Obsidian Cliff-YNP
Mann 61b	Blade	48 ± 9 ppm	301 ± 7 ppm	Bear Gulch, ID
Mann 61c	Blade	50 ± 9 ppm	306 ± 7 ppm	Bear Gulch, ID
Mann 61d	Sherd	45 ± 9 ppm	291 ± 7 ppm	Bear Gulch, ID
Mann 61e	Biface tip	46 ± 9 ppm	290 ± 7 ppm	Bear Gulch, ID
YELL 1	Sherd	8 ± 9 ppm	175 ± 7 ppm	Obsidian Cliff-YNP
YELL 2	Basal-notched blunt	8 ± 9 ppm	180 ± 7 ppm	Obsidian Cliff-YNP
WV 1	Basalt biface point	100+ 9 ppm	54+ 7 ppm	Unknown
WV 2	Basalt biface point	62+ 9 ppm	58+ 7 ppm	Unknown

as the primary "signature" linking the Indiana artifacts to known sources on the Yellowstone Plateau.

The Bear Gulch samples (Mann 61b-61e) have average strontium concentrations of 47+9 ppm, and average zirconium concentrations of 297+7 ppm. The Obsidian Cliff sample has a strontium concentration of 9+9 ppm and a zirconium concentration of 167+7 ppm. The two analyzed obsidian artifacts that were known to originate from the Yellowstone Plateau were also traced to Obsidian Cliff in Yellowstone National Park with strontium concentrations of 8+9 ppm and a zirconium concentration of 175 and 180+7 ppm. These trace element concentrations correlate with known concentrations of the Obsidian Cliff Lava Flow (Davis et al. 1995). As expected, the two fine-grained volcanic artifacts from West Virginia had significantly, and distinctly, different trace element signatures, and likely originate from a geologic source in the eastern US, as yet to be determined.

Conclusions and Implications

Bleichroth's project included a review of previous work on sourcing Midwestern artifacts. Our geologic source determinations for obsidian artifacts from Posey County, Indiana, correlate with results of previous lithic sourcing studies done on Hopewell obsidian artifacts in the Midwest (Griffin et al. 1969, Hatch et al. 1990, and Hughes 2006). Geochemical characteristics of the various artifacts are distinct, and we were able to conclude that the five obsidian artifacts from the Mann site do originate from the Yellowstone Plateau. Though we cannot determine with complete certainty the events that brought this obsidian to prehistoric people in the Midwest, Early Hopewell obsidian studies have hypothesized that the obsidian could have been obtained in a single acquisition event. However, multiple Hopewell obsidian artifact occurrences have since been identified, and could indicate that repeated procurement expeditions or "down-the-line trade" provided the obsidian found in these sites (Davis et al. 1995). Because our study identified obsidian sources that correlate to Hopewell obsidian artifacts from other archeological sites in Ohio, Illinois, and Indiana, it is reasonable to assume that inhabitants of the Mann site were involved in the same trade or lithic procurement activities as the rest of the Hopewell culture in the Midwest during the Middle Woodland Period.

This project serves as a valuable example of integrated research for an undergraduate geology major being mentored through the classic steps of the scientific method. Bleichroth made an observation—"obsidian artifacts were found at a Hopewell archeological site in southern Indiana, but there are no nearby sources of obsidian." From that observation we formulated a hypothesis—"the obsidian used for those artifacts originated on the Yellowstone Plateau." We designed an experiment to analyze trace-element concentrations by nondestructive XRF analyses for comparison to known obsidian sources. Finally, we interpreted the results to conclude that our hypothesis was correct. The fact that earlier scientific literature showed other Hopewell obsidian had been traced to Yellowstone demonstrated a certain "surrogate" reproducibility to the work. Bleichroth disseminated the research in a professional presentation at a meeting of the Geological Society of America.

In addition to the incredibly valuable educational experience gained by Bleichroth, this project also contributed to the scientific knowledge base for both geology and archeology. We now know with certainty that an important cultural site, the Mann site, was engaged in some form of transportation and/or commerce over 2,000 years ago; acquiring and bringing natural resources more than 2,500 kilometers (1,600 mi) from the Yellowstone Plateau into what is now southern Indiana.

YS

Acknowledgements

We would like to thank Dr. Michael Strezewski, Assistant Professor of Anthropology at the University of Southern Indiana, for allowing us access to the Mann site artifacts. We also thank the Department of Geology and Physics and the Endeavor Program at the University of Southern Indiana for funding the chemical analysis.

Paul K. Doss is a professor of geology at the University of Southern Indiana.

Amy Bleichroth graduated from the university of Southern Indiana in 2012.

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Passion and Hard Work

An Interview with Retired Superintendent Suzanne Lewis


NPS

Official portrait of Superintendent Suzanne Lewis, 2008.

When Suzanne Lewis retired from the National Park Service on March 2, 2011, she and her husband, Michael Hurrell, returned to live in Pensacola, Florida, near Gulf Island National Seashore, where her career began in 1978 as a seasonal park ranger. She later served as superintendent at Glacier National Park and then, starting February 10, 2002, at Yellowstone.

In the fall of 2010 and again this past summer, Charissa Reid interviewed her for the park's oral history program. *Yellowstone Science* staff selected and edited the following excerpts from those transcripts.

Tense Meetings and Difficult Decisions

***Yellowstone Science*(YS):** What is the thing that you want people to say, "Suzanne Lewis, she was the superintendent who…"

Suzanne Lewis (SL): I'm going to tell you one that I think few people know. And it really was a very significant moment. I'm at a meeting and hear people talking about mining material for the road projects in Yellowstone at Sylvan Pass. I'm looking around the room and I don't see anybody who's acting like that might be an odd thing. Well, I probably didn't hear that right, so afterward in [Deputy Superintendent] Frank Walker's office I said, "Did I hear that we mine rock on Sylvan Pass and haul it for road projects?" Frank says, "Yes." I said, "Don't you find that odd?" And Frank says, "They've been doing that for a long time up there, Suzanne. It's the source for all the roadbed material."

There were a lot of reasons behind it, but mostly it was that the distance to material for doing roads is a pretty long way outside the park, adds millions of dollars onto a road project. This is perfectly good material here and we want to redo this road anyway so … .

YS: So it doesn't matter?

SL: Yes. I brought up that I was concerned about this and we were going to need a series of meetings to get to what were going to be our alternatives. Oh my gosh, this set off this huge conflict because the road builders immediately go into the defensive mode and YCR [Yellowstone Center for Resources] into the aggressive mode. And I was naïvely thinking, how could we not be all together on this—should we all read the Organic Act?

I was too new to Yellowstone to know how sensitive this was going to be, so I set off a pretty good internal firestorm. I think sometimes I hurt employee feelings because I didn't have a lot of patience with the "Let me tell you what it was like in 1953." I'd listen to a little bit about that but I'd usually say, "Help me understand what that story's going to mean for me right now." I was getting a lot of push back, so I said, "We're going to hold a meeting in Bozeman and everybody who thinks they've got a stake in this is going to sit around the table and at the end of the day were going to have made some decisions."

NPS

A 2005 road improvement project at Sylvan Pass.

So I brought in Federal Highways, YCR, and Maintenance. It was a pretty tense meeting. We came back from lunch and everybody's energy in the room was way down. I said, "I don't know what times your flights are scheduled, but we are not leaving here until we make decisions. What we need to do is get started on where we are going to get roadbed material because we are not going to get it at Sylvan Pass anymore." And I looked at the two regional directors of Federal Highways and said, if you have serious disagreements about this you need to tell me right now. And both of them said, "We understand and we agree."

It's one of many great moments because it was a practice that was having very unacceptable impacts on water quality and it was just fundamentally the wrong thing to do in a national park. And it contrasts with that "Oh, that Suzanne, she must love snowmobiles. She doesn't care about the park." I do, but stopping the mining at Sylvan Pass is more important than whether snowmobiles get banned.

YS: Was there ever a time when the science made your job more difficult?

SL: Well, science will challenge anybody's job because often times we have a misperception of what science provides. It's not going to tell you, "Yes, do this," or "No, don't do that." The National Park Service did away with their park-based scientists in the early 1990s, but Yellowstone, because of its recognition for having a superior program for many years, was able to hold onto a group of professionals to remain on staff. Yellowstone not only had the record of extremely good science happening in the park, it had a long and successful track record of that science being published in peer-reviewed journals, and that's critical in decision-making, critical in the, recognition and importance of a science program in the park. It lends more credibility when you are basing your decisions on a body of science that has been developed around an issue or a topic.

YS: Were there times you had to make decisions that you didn't want to?

SL: Well, certainly that winter when we had to send more than 1,000 bison to slaughter was the most difficult moment in my entire career. We had no alternative. We hadn't created enough of a group of people to try to work through it in a different way. For me, personally and professionally, that was it. I was never going to do that again. You cannot, test and slaughter brucellosis out of a herd. I felt very confident about the science that I'd been provided on that.

The bison issue was the most difficult issue I worked on at Yellowstone because it involves so many fractured relationships and, the values associated with that species and how that species has been managed over time in that particular geographic location. So, it began, what became three years of very intense meetings, very emotional meetings. I think it begins with getting in a room with those people whom you are most in conflict with. I think it's important to show these individuals and groups as much respect as you can for their values, even when they conflict with what you're having to do as a decision-maker in the park.

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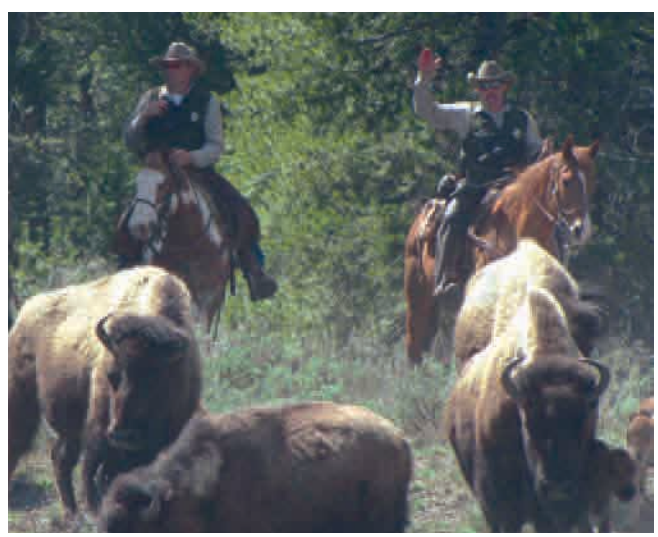


NPS

Bison hazing operations at the west boundary of the park are a collaborative effort between federal and state agents.

NPS

President Barack Obama and Superintendent Lewis during a visit in August 2009.

The debate over who will govern this country, which directly impacts who will govern national parks, is real, and it's in the workplace every day and that goes home with you at night.

Bison and brucellosis is an issue that you're going to measure your success in very small increments. You're not likely to get overnight transformational change in how people feel, and, you tactically take every small step you can to create that tolerance, and continue the intensive study and science that have been grounding that issue for almost two decades, whether you're looking at the genetics of the herd in Yellowstone or the quarantine studies that are done. The science is pretty good on understanding what will or will not transmit brucellosis; you've got to continue to study that in order to remain credible. There's a lot more support for the issue, but you're always going to have the conflict with folks who really fear the damage, the economic damage that it could create with cattlemen or property damage, and I think that's a part of why you have to continue to do the science.

I think all National Park Service jobs are pretty stressful jobs because people are so highly dedicated to the mission of the park service, and so passionate about what they do. The debate over who will govern this country, which directly impacts who will govern national parks, is real, and it's in the workplace every day and that goes home with you at night. Where is the money going to come from to take care of the park, to fulfill the vision, to fulfill the passion behind what a park and staff do every day?

YS: With dwindling budget resources, how do you see programs like Cultural Resources faring?

SL: The cultural resources in Yellowstone really play a vital role in how people feel about the park. When visitors come and enjoy the park, they engage with the structures and the stories of Yellowstone, because it is, in many ways, a built environment. I think that the biggest challenge facing cultural resources is that the historic structures, the historic objects, the archives are going to need a lot of attention and a lot of funding to make sure that on the 200th anniversary of the National Park Service, there is that same strong cultural sense of place at Yellowstone.

Budging on the Budget

YS: How do you know when to lock everybody in a room and say we have to make a decision by the end of the day?

SL: I think I could sense when the time was right. Did I have the right people in the room? Did we have enough of the facts out on the table? Had enough of the people around the table vented? I'm going to take the emotional temperature in the room and use that to create circumstances where we're not leaving until we make a decision.

I felt that early on I was trying to pull together a management team that was not very together when I got here. Frank [Walker, Deputy Superintendent] and I had been working on that for a little over a year and we were in a really bad budget situation. I'd been trying to get people to talk about how are we going to make these decisions to get to a balanced budget and everybody was pretty much in their foxhole. Nobody had any solutions. At that time, our budget

B. GREENBURG

Historic structures like the Old Faithful Inn are among the cultural resources that steadily draw park visitors.

was probably near 30 million dollars. I couldn't get anybody to dig deep, to lead, be the first one to give and hope that you get in return. It was the last day of our focus meetings and I got very emotional. I had tears rolling down my face and I said, "You folks are killing me. For you to act like you are being so mistreated because the park only has 30 million dollars. Do you know how many units of the National Park Service don't have 3 million dollars to take care of their parks?" And I said, "Don't tell me, 'But we're Yellowstone and we're special.' We have so much to be grateful for and we have flexibility because we do have such a large budget."

I was so emotional it freaked them all out. But on the next day, we got working on some solutions about how we were going to make the budget and what was the fair and right thing to do—and people budged. And in Yellowstone, a budge is a mile.

You can't overplay your emotions. There'd be times I'd want to do it and I'd walk away and not do it because I'd be taking the temperature and think they aren't ready—they don't want to hear it. They're angry right now. They don't want to make any more decisions today. They don't want me putting them in a corner.

But I expected the whole time that you do not have to agree with the decision but you'd better represent honestly the facts behind that decision when you leave this room. You can tell your employees, "I didn't agree with it but here's why it was made." If you whine and martyr yourself and it gets back to me, I find that to be chicken and very unprofessional behavior. There were plenty of times when I would say why I didn't like what Washington had done, why I don't agree with the regional director, but I would always explain what I understood to be the basis of the decision. I always owned it. I hate it when people go, "You know management." That's just cheap. It cheapens you as a supervisor, as a leader.

YS: One of the results of the recent survey showed that National Park Service employees are less than satisfied with the information received from management about what's going on in the organization.

SL: Well, it all kind of gels around this issue of stress and the pressure that people feel when we are feeling very put upon. You hear employees say, I'm doing the best I can with what I've got. I think in a place like Yellowstone it just takes constant attention to create environments in which people can get more comfortable pushing outward and not pulling inward. And that's tough to do, because when I would hear employees say, "I don't have enough information"—well, information on Yellowstone and what management is doing is everywhere, but it's difficult to put your arms around, and we've begun to not trust that information or not feel like you have access to what was behind that decision. I think that information explosion has an unintended consequence in that employees want that information to be personally conveyed to them.

So how do you go about training and encouraging supervisors to make it as personal as you can? I think the results of that survey say we have got to learn to value that a big part of supervisors' job is to try to bridge that communication gap with employees and make it more personal.

Challenges to Yellowstone Traditions

In 2002, when Proctor and Gamble began running a television commercial that appeared to show a park ranger pouring Metamucil into Old Faithful as he explained that the product keeps the geyser "regular," Superintendent Lewis received complaints from people who mistakenly assumed that the National Park Service had allowed this commercial to be filmed in the park and benefitted from it financially. Proctor and Gamble was eventually persuaded to add a disclaimer: "Dramatization—Please Obey Park Service Rules."

SL: I did have a bad reaction to that commercial. We do have problems with people throwing things into geysers. And it was my first experience of getting really angry emails. I knew that being Yellowstone superintendent would be controversial. But until you get sloshing around in it, you don't know it. This is not a parade where you get to blow kisses. You're usually ticking a lot of people off.

When somebody asked what's the thing you're going to miss the least, I said, I won't miss the unbridled anger. I won't miss those encounters with people who, no matter what, they're not going to have a rational conversation

B. GREENBURG

Lewis addresses the crowd at the grand opening of the Old Faithful Visitor Education Center on August 25, 2010. Seated behind her (l-r) are retired Yellowstone Historian Paul Schullery, Assistant Secretary of the Interior for Fish, Wildlife and Parks Tom Strickland, National Park Service Director Jon Jarvis, and (then) Chairman of the Yellowstone Park Foundation Bannus Hudson.

I knew that being Yellowstone superintendent would be controversial. But until you get sloshing around in it, you don't know it. This is not a parade where you get to blow kisses.

with you. I have had my life threatened since I've been at Yellowstone. I didn't take that very seriously at first. But Obie [Rick Obernesser, now Superintendent at Wrangell-St. Elias National Park] and Tim [Reid, now Chief Ranger] were kind of shocked when I said, "I've been throwing those letters away for a few years."

YS: Was there ever a time that you thought, "I just don't want to do this anymore"?

SL: I didn't ever have the "I don't want to" but I did have a lot of the "I just don't think I can do it anymore—I'm exhausted, I'm angry"—being yelled at, pushing the rock up the hill—a little further—in Washington. Working with the Bush administration for eight years was the hardest thing I have done in my life—an administration that was extremely well-disciplined when they came into office, very focused on their agenda. So you had to figure out a way to try to build a relationship to where they at least had some, I wouldn't say trust, but there's got to be some level of respect.

Those are the hard days—the days that make your game a lot sharper than days you surround yourself with people who think like you—days where everybody goes, "Mirror, mirror on the wall, who's the fairest of them all? Oh, look, we are!" That's not what will sustain the park service in the long run. It doesn't have the depth we are going to need for lots of different kinds of people to love national parks.

COURTESY OF S. LEWIS

Lewis broadcasts a live message from Yellowstone National Park to Beijing, China in May 2007.

NPS/PEACO

Superintendent Lewis discusses park infrastructure with Vice President Joe Biden, his granddaughter Naomi Biden and Yellowstone maintenance employee Zach Jerla.

Then there was the cell tower—lots of angry email. A lot of people still don't want to see the use of that technology in the park. They don't want to be around it. They came here to not see that. And then there are people who are blind to it—"See what? This device is my life."

We're going to have to challenge our traditions. When the visitor says I need and I want, we tend to hear that in terms of our own experience in parks—well, I didn't need that and I didn't want that, therefore you shouldn't have it. You can't just say, "In my opinion" and hope for anything good to happen in the long run.

Advocacy Groups and Snowmobiles

SL: I didn't use the media or allow advocacy groups to use my voice to do the proverbial "You're wrong!" that would bring 24 hours of drama into the media. If you thought headlines were going to help you get an issue resolved in the park—they don't anymore. I said to an advocacy group that was angry with me, "You have no idea how Washington can punish this park. You don't understand the intricacies of where our money comes from and how you get approvals and how all of a sudden, none of that's happening for you anymore." Even though you are dealing with these larger, more strategic issues, back here there's 800 people who are just trying to take care of the park every day. And to do that they have to have resources and support behind them at the regional and Washington level.

It's hard for advocacy groups to realize that it isn't about the environment. If you talk about climate change, it will not be about the environment, it will be about the politics of

Lewis was named "Flying Eagle Woman" by the Blackfeet tribe in a naming ceremony at Waterton Lakes, May 2001.

At Ptarmigan Tunnel in Glacier National Park during a backcountry trip, June 2000.

Rappelling at the Grand Canyon in March 1980.

Kayak trip, Kinta lake, Glacier National Park, October 2001.

the environment. Look at the majority of stories coming out of the Gulf oil spill—they were about the government; they weren't about fundamental environmental policies. So if they cut parks severely in the next five years but they've also cut public education and health care and everything else—how big do you think the superintendent is going to be with the "I don't have enough money to run this park"?

Lewis escorts (then) Secretary of the Interior Gale Norton on a snowmobile tour of Yellowstone in 2005 amidst continuing debate over appropriate winter use.

Certain people felt that it was my job to fall on my sword—one must do that in public, and they'd like to reshoot the take over and over again. I don't have the style or the personality and I just don't think it's effective. You can figure out ways to work with people, even people who have different values.

Some leaders have the skill and the desire and the style that says, "I'm just going to go for broke and this is what's most important." I'm the one who says, "We've got to have enough credibility in Washington to get support on all the 150 other things that are really important in addition to snowmobiles." It's just how politics work.

I'd never been on a snowmobile before I got here. There was no limit on the snowmobiles coming into the park, no guiding, and the park was open 24 hours a day to snowmobiling. Why? It was tradition. So it was critical to get control of this thing. The Bush administration would never allow snowmobiles to get banned. We needed to focus on managing this and figure out what, if any, leeway are we going to find in this administration.

The park will be more threatened if we can't find new alliances. As hard as these gateway communities have been—even when they could hardly wait to take my head off over an issue—I never felt unwelcome. And there's going to come

I just would want employees to know how much I admired them. I love passion and I love hard work. I love watching people enjoy what they do. Every park I've ever been at I had that… .

a day when the park really needs these gateway communities to help the park. If the park were to have to really curtail services—really change—there will be no stronger partner in pushing back than the gateway communities. But, at the same time, I don't think they'll stop suing.

YS: How do the many lawsuits against the park affect your job as a manager?

SL: Litigation does absorb a great deal of staff time, and your time as the superintendent, and it does have the ability to change how you manage a species or an issue. But in some ways they make you sharper in terms of process. Most of the lawsuits during my time were disputing a decision based on a process, and usually how we went through an Environmental Impact Statement—and that will make you much sharper in how you prepare to make a decision under the National Environmental Protection Act.

Moving Forward

YS: Do you have any regrets?

SL: I have no regrets. I think that even when you're in the moment in Yellowstone, and those moments can be quite painful and disconcerting, you have to be able to self-assess and say, "What am I going to do differently?" and "I've got to move forward, no matter how hard it is"—no matter when the *New York Times* calls for you to be fired.

YS: Was there anything you wish you could have done that you weren't able to accomplish?

SL: There'd be a number, but the one that might surprise people is the inability to resolve the infrastructure issues in Canyon. The cabins are horrible, built in the 60s, yet visitors love them in a weird way—they're the lowest priced lodging you can get in the park, and so there's people who go back there year after year. There's a little bit of yard and they can sit out on the little stoops—but that infrastructure is so bad. It would not be my desire to increase development in this park to reflect increasing visitation, and this isn't about wanting fancy lodging, it's just that we need all that occupancy—that's the biggest lodging area in the park. I do think it'll be resolved in the new concession contract but I wished I'd gotten it settled in terms of how we were going to finance it; I wish I'd gotten it set up politically.

YS: You have a new job starting this fall—is that right?

SL: I will start teaching, this fall, at the University of West Florida. I'm going to be teaching the history of the National Park Service and lecturing on conservation law and policy. I also serve on three nonprofit organization boards—for the Sonoran Institute; for the University of Florida, overseeing the, care and maintenance of the historic resources in St. Augustine; and for the University of West Florida, overseeing all their business enterprises.

Those things interest me, but I'm a potter and Michael's a stained glass artist and I have fantasies about just making pottery and enjoying myself. Michael has always been a really strong Habitat for Humanity supporter and he's given up an awful lot in the years that we've been at Yellowstone and so for him to get to do things that he wants to do and for which he's the big Kahuna— it just couldn't get any better for me. I would like that a lot.

YS: You'd like to be introduced as Michael Hurrell's wife?

SL: I think that would be nice.

YS: So do you have a parting message for park employees?

SL: I just would want employees to know how much I admired them. I love passion and I love hard work. I love watching people enjoy what they do. Every park I've ever been at I had that, and I think the message would be—do good things, take care of yourselves a little more. The park needs the best of you but the park can't get the best of people if they don't take care of themselves. I'm a horrible example. I work too much. You have to give people permission to look after themselves a little bit more—Yellowstone's going to be here a long time.

YS

NPS

Celebrating the return of the Yellow Buses in 2007.

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 period of uplift and mountain building that occurred ~60–80 million years ago in western North America during the Laramide Orogeny and the uplift 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.

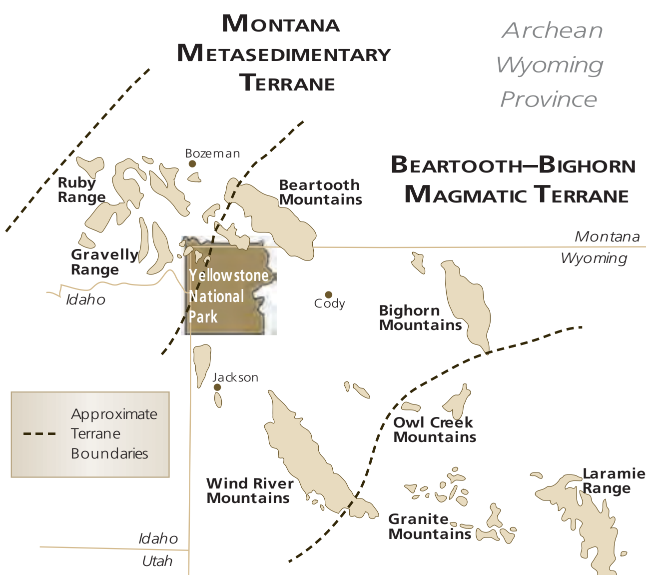


Figure 1. Schematic map of the Precambrian exposures of basement rock in the Wyoming Province (adapted from Mogk et al., 1992; Mueller and Frost, 2006).

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

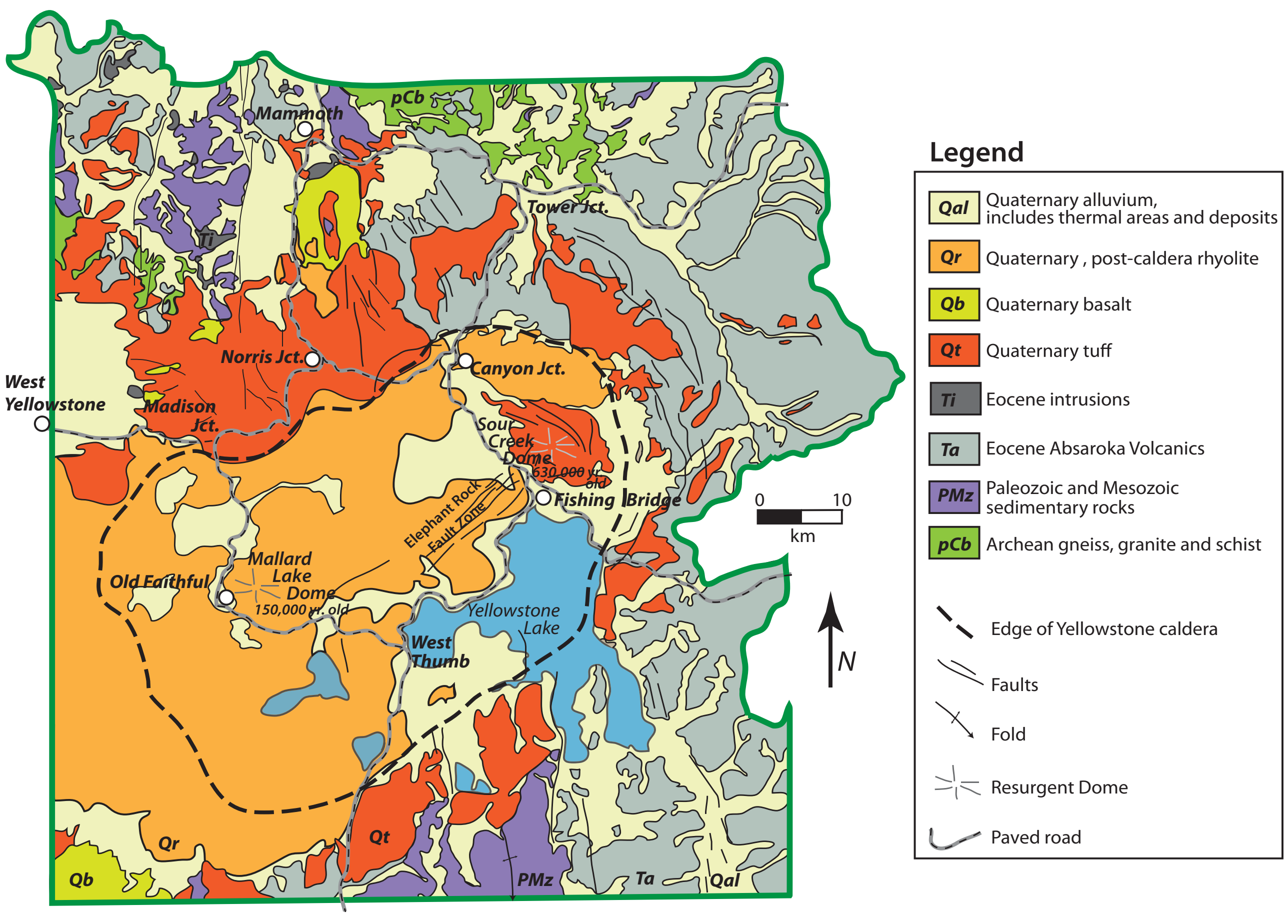


Figure 2. Geologic map of Yellowstone National Park showing the distributions of different rock types and fault structures. The Archean rocks that were the focus of this study (labeled pCb–Precambrian basement) are located on the north park boundary. (Map based on USGS1-7111; includes modifications by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

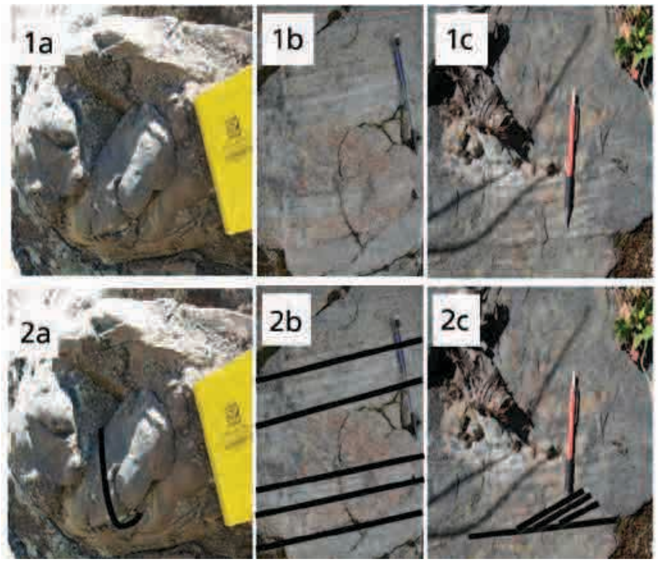


Figure 3. Relict sedimentary features from the JMS (1). Bottom photos (2) highlight the interpreted structure with black lines; (a) bottom of sedimentary layer with a preserved sole mark; (b) interbedded metamorphosed sandstone and shale; metasandstone layers highlighted by gray lamination, metashale 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

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 modern 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).

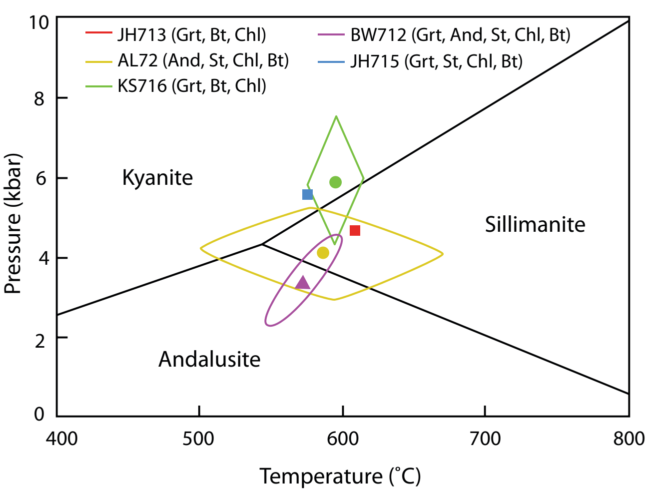


Figure 4. Pressure and temperature estimates determined for samples from the Jardine Metasedimentary Sequence ranging from 572–609°C and 3.5–5.9 kbar (polygons represent range of statistical error). Prepared by Carly Osborne and Julie Baldwin.

the 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.

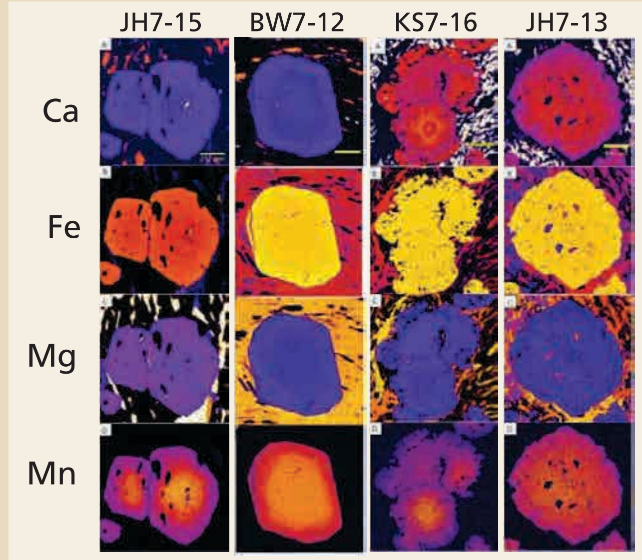
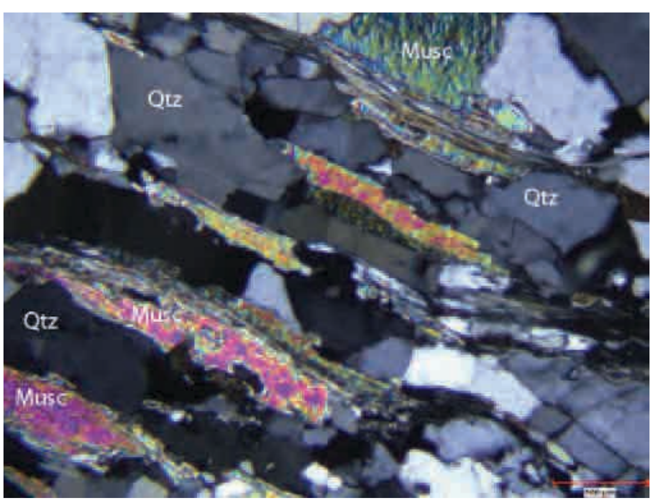


Figure 5. Compositional profiles of garnets obtained using elemental X-ray mapping techniques with an electron microprobe. Elements that have been mapped include calcium (Ca), iron (Fe), magnesium (Mg), and manganese (Mn). The composition of the garnets responds to changing pressure and temperature during 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; gray) with reduced grain size, and muscovite (Musc; pink, elongate) in a shear zone. Field of view is 2.5 millimeters.

Magmatic Rocks that Crosscut Metasedimentary Rocks

The JMS is crosscut 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: ^{238}U to ^{206}Pb and ^{235}U to ^{207}Pb, 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.

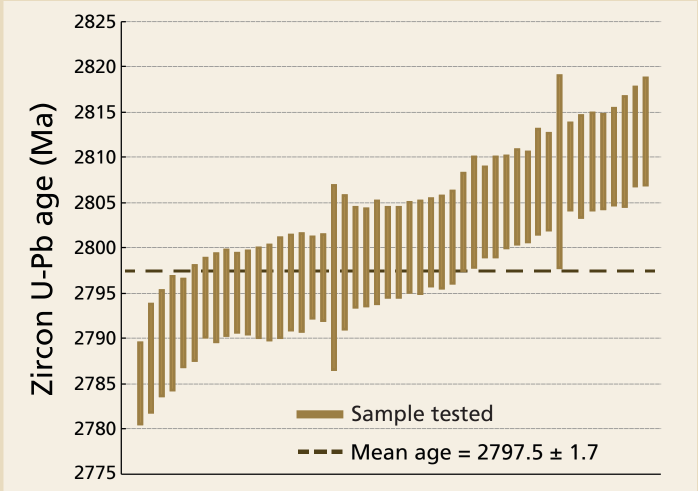


Figure 7: Replicate age determinations from the U-Pb zircon method obtained using the LA-ICPMS technique for a diorite unit collected on Garnet Hill. The mean age is 2797.5 +/- 1.7 million years (0.06% relative error).

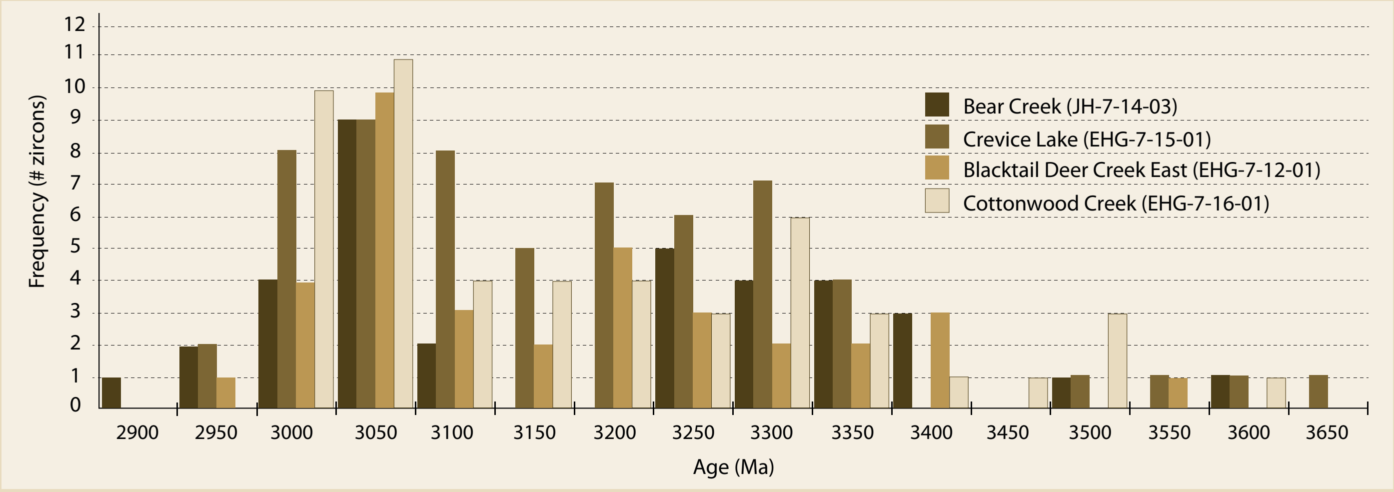


Figure 8. Summary of age determinations from detrital zircons collected from quartzites in the Jardine Metasedimentary Sequence.

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 cm. 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 it does today.

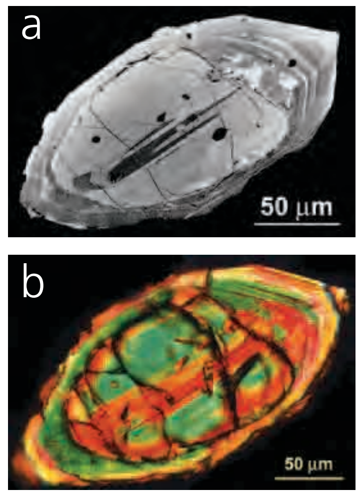


Figure 9. Images of zoned zircon grains (a) using back-scattered electron imaging, and (b) using cross-polarized light on a petrographic microscope. The well-defined compositional zones of the zircons are used to guide isotopic analysis to obtain ages on their cores and rims.

Garnet Hill Area

A hike around Garnet Hill reveals geologic field relations that are significantly different from the Jardine Metasedimentary Sequence 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 were 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 (bottom, pink layer) 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^{o}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 crosscuts 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 Sequence 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 populations of the quartzites have a minimum age of ~2.9 Ga, which is significantly older than the 2.8 Ga ages of the granitic rocks of the adjacent Beartooth Mountains. 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 crosscutting 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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Paul Mueller is a professor of geology at the University of Florida. He is a geochemist and geochronologist with long-time interests in Archean crustal genesis and evolution. Primary research activities involve application of whole rock geochemistry (major and trace element) and isotope systematics (geochronology and isotopic tracers) to the processes and history of crustal evolution.

Darrell Henry is a professor of geology and geophysics at Louisiana State University. He has worked in the Beartooth Mountains and surrounding Archean basement for 30 years. He is a metamorphic petrologist with interests in the development and applications of quantitative thermobarometry to tectonic problems. His other research interests focus on the characterization of detrital minerals, particularly tourmaline, to interpret provenance and geologic history of a wide range of geological settings.

David Foster is a professor of geology at the University of Florida. He studies the tectonic evolution of continents, mountain belts, and extensional basins. He uses thermochronology, structural geology, and isotope geochemistry to understand the evolution and deformation of continental crust. He has projects in western North America, Australia, Africa, and New Zealand.

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From the Archives

Marguerite "Peg" Lindsley (circa 1923) was one of the first women hired by Yellowstone National Park as a ranger-naturalist. Yellowstone's early appointment of women in natural resource professions—like geologist Isabel Wasson and ranger-naturalist Herma Albertson—was a part of the first wave of women who officially participated in park management. Currently, about a third of National Park Service rangers and a quarter of National Park Service superintendents are female.

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