Mammoth Hot Springs

Where change is constant

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STaRRS students get their first panoramic view of New Trail and Canary hot springs, the first stop for photo point data collection on each expedition.

While change is evident in geothermal features throughout Yellowstone, one of the most rapidly and dramatically changing sites in the park is at Mammoth Hot Springs. Visitors to the springs never see the same scenery twice. Even if you are an infrequent visitor, you may notice that the springs seem different each trip. Perhaps the water has changed course, is flowing in a new location, or has ceased to flow altogether. Maybe you notice that the colors seem different than the last time you stood in that spot. Occasionally, you can no longer access a familiar area due to shifts in the springs and the resulting mineral deposition that sometimes engulfs the boardwalk.

The seeming incongruity between memories of favorite springs and their present appearance can be baffling and disorienting. Rangers at the visitor center at Mammoth are veterans at fielding questions such as: "What happened to the hot springs?," "Are they drying up?," or "They sure aren't what they used to be!" The reply is that change is the only constant. The terraces at Mammoth are a direct product of the springs themselves, comprised of calcium carbonate ($CaCO_3$) mineral deposits called travertine that precipitate directly from the hot water (Bargar 1978). While the springs may look very different over time, the total amount of water flowing into and through the entire Mammoth system is relatively constant (Sorey 1991). Yet this has been a difficult concept for visitors to see and, therefore, believe.

To help resolve this "seeing is believing" issue, an integrative Student-Teacher-Scientist Partnership (STSP) was established in 2008 among Yellowstone National Park rangers, university geoscience and education researchers, and a group of 4th to 8th grade teachers and students. The partners work together to answer real-world questions about a phenomenon or problem the scientist is studying (Tinker 1997).

Called STaRRS (Students, Teachers, and Rangers & Research Scientists—Investigating Earth Systems at Mammoth), this STSP was designed to achieve several goals: (1) establish a connection with university researchers so that students in grades 4–8 would develop a deeper understanding of research taking place in Yellowstone; (2) have more year-round observations and data coverage at Mammoth for the university research team; and (3) expand the *Expedition: Yellowstone!* curriculum to include more specific scientific investigations.

The National Park Service established *Expedition: Yellowstone!* in 1985 as a curriculum-based, multi-day education program to provide four- and five-day overnight experiences in the park to investigate natural and cultural resources. For more than two decades participants have gathered pH and temperature data at Mammoth. In addition to the regular curriculum, STaRRS students made observations and collected data on a few key physical, chemical, and biological parameters at strategic sites along the hot spring drainage systems at Mammoth. These sites, called photo points, provided visual data to help park visitors and scientists monitor geothermal change over time.

Use of Mammoth Hot Springs for a scientific and educational partnership

Mammoth Hot Springs has long generated interest for visitors because of its renowned terrace-shaped travertine mineral deposits (Bargar 1978). It provides an exceptional combination of natural and logistical attributes for use as a natural teaching and research laboratory for the STaRRS program.

The effervescent release of carbon dioxide (CO_2) from the spring water results in rapid travertine precipitation (5 mm/day or ¼ in/day), which is composed of the calcium carbonate minerals aragonite and calcite (Fouke et al. 2000; Kandianis et al. 2008). Travertine precipitates in a variety of distinct crystalline shapes and forms that systematically change from upstream to downstream within each drainage flow path (Fouke et al. 2000). Each type of travertine is associated with discrete communities of heat-loving microorganisms (thermophilic bacteria and archaea) that grow in communities referred to as microbial mats and exhibit a wide variety of colors and shapes. They grow even more quickly than the remarkably high rate at which the travertine mineralization takes place (Fouke et al. 2003; Fouke in press). Although there are many travertine-depositing hot springs throughout the world, Mammoth is unique because of the long-term protection from human impacts afforded by the National Park Service. Mammoth has the added benefit of year-round access to the Lower and Upper terrace boardwalks, which provide safe access for visitors, students, and professional groups. Furthermore, its proximity to gateway communities make Mammoth an accessible centerpiece for integrated teaching and research.

The geology of Mammoth Hot Springs

The spring water at Mammoth is derived from rain water and snowmelt that flows from the southern margin of the Gallatin Mountain Range into the deep subsurface along associated fault systems. Estimates of how long it takes water to make this hydrologic transit range from less than 2,000 to more than 11,000 years (Rye and Truesdell 2007). During

Figure 1. Geographic map of hot springs along the Upper Terrace Loop on the Highland, Angel, and Main terraces at Mammoth Hot Springs. Photo point locations are shown. *Inset:* Location of Mammoth Hot Springs in Yellowstone National Park.

At many locations within the Mammoth complex, as much as one meter of travertine accumulates in a single year.

this travel time, the water flows through and dissolves limestone and evaporite rocks that were deposited approximately 350 million years ago during the Mississippian Period (Sorey 1991). The groundwater is heated to more than 100°C (212°F) by rock heated by the underlying Yellowstone hotspot, which causes it to rise again to the surface through large subsurface fracture systems at Mammoth. During this underground journey, the spring water becomes super saturated with dissolved carbonate minerals and CO_2 gas. The groundwater emerges from the vents at Mammoth at 73°C (163°F) and a neutral pH of 6. The CO_2 immediately degasses from the water, causing a rapid increase in the water's pH and creating conditions favorable for rapid $CaCO_3$ mineral precipitation (Friedman 1971). This process forms the hallmark travertine terraces at Mammoth. The resident bacteria and archaea populations are an important part of this $CaCO_3$ precipitation process, resulting in the long-term accumulation of thick travertine deposits (Kandianis et al. 2008).

At many locations within the Mammoth complex, as much as one meter of travertine accumulates in a single year (Fouke et al. 2000; Kandianis et al. 2008; Veysey and Goldenfeld 2008). In geologic terms this travertine growth occurs at light speed. On average, this is one million to one billion times faster than limestone deposition in most other geological settings, such as the deep sea floor or in caves. In fact, the only reason that travertine has not covered all of Yellowstone is that the flow paths at Mammoth Hot Springs are small and the drainage systems flow in one place for only a relatively short period before switching to another location. Over time, this has formed a succession of travertine limestone deposits at Mammoth and at Gardiner, Montana. The Gardiner travertine ranges in age from approximately 20,000 to 39,000 years old, while the travertine at Mammoth ranges in age from 0 to nearly 8,000 years before present (Sturchio et al. 1992, 1994; Butler 2008; Vescogni 2009). The travertine terraces at Mammoth are 73 meters thick and cover an area more than 4 square kilometers (Allen and Day 1935; White et al. 1975). The terraces at Gardiner, which are now part of a privately-owned quarry, are comparable in size (Sorey 1991).


STARRS PHOTO POINT 5

Orange Spring Mound is the site of photo point 5. It was chosen for both ease of access and recent visible activity.

Systems geobiology research at Mammoth Hot Springs

The systems geobiology research group at the University of Illinois at Urbana-Champaign includes geologists, geochemists, microbial ecologists, genomocists, physicists, and educational specialists. Their research at Mammoth focuses on ways in which the environment influences and controls microbial life, and microbial life influences and alters the environment. Understanding the carbonate rock record and the relationships between the biotic and abiotic components of the hot spring ecosystem can assist in understanding modern and ancient geological landscapes on Earth and potentially other planets. The group's research is producing models of water-mineral-microbe interactions that predict system-scale dynamics across large dimensions of time and space in a wide variety of natural environments around the world.

The Illinois research group developed a model that can effectively track and predict interactions between water, minerals, and microbes that influence travertine deposition (Fouke et al. 2000, 2003; Fouke in press). From this work, four parameters were identified that control travertine deposition: (1) temperature, (2) pH, (3) flow rate and flow dynamics, and (4) system composition—contextual observations of travertine (shape and form), microbial mats (color, shape, size, growth rates), and distance along the drainage system from the source. Since the spring is constantly changing, the location within the hot springs where a particular parameter, such as a change in pH, is observed is also associated with changes in travertine formation and microorganisms (Veysey et al. 2008).

Fouke et al. (2000) developed a model of the hot springs that aids in understanding these complex systems

Facies	Vent	Apron and Channel	Pond	Proximal Slope	Distal Slope
Temp °C	73–71	70–60	59–45	44–35	35–28
pH	6.0	6.1–6.5	6.6–7.2	7.3–7.7	7.8–8.1
Minerals	aragonite	aragonite	aragonite and calcite	aragonite and calcite	calcite

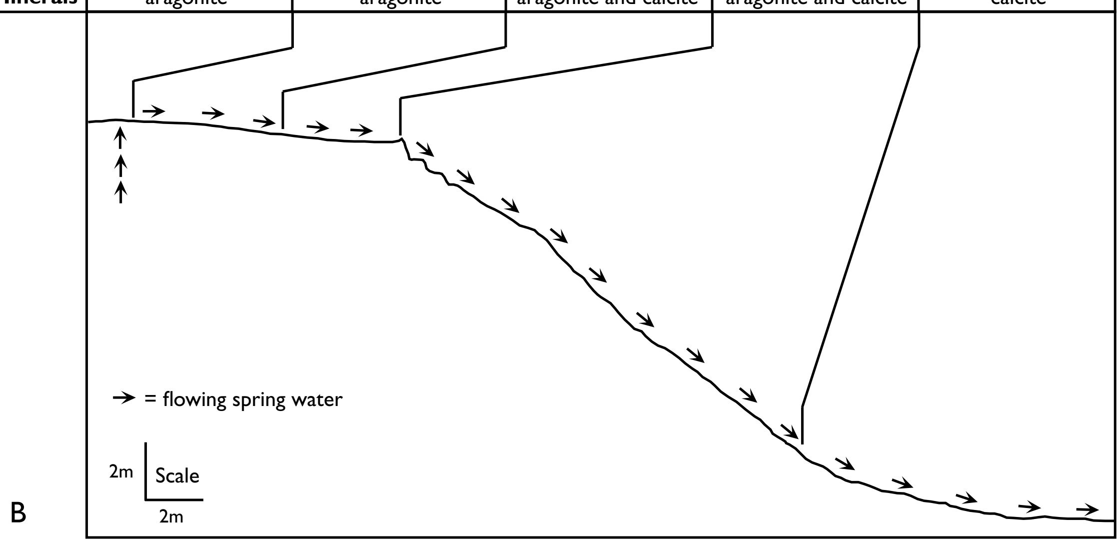

Figure 2. (A) Field photograph of Angel Terrace Spring AT-1 at Mammoth Hot Springs (modified from Fouke et al. 2000, 2003; Fouke in press). (B) Schematic cross-section of Spring AT-1 indicating the basic physical and chemical attributes of the travertine and spring water within each travertine depositional facies (modified from Fouke et al. 2000, 2003; Fouke in press).

by grouping the travertine into packages of mineral deposition along the main spring water flow path (fig. 2). Called "facies," these groupings of travertine are defined by specific rock characteristics (i.e., crystal size, shape, structure, porosity, and chemistry) that represent the sum total of the physical, chemical, and biological processes active in the hot spring environment (Fouke et al. 2000). The travertine facies model is manifested as distinct packages of $CaCO_3$ deposited along a primary flow path within any given hot spring system and has been consistently observed around the world (Veysey et al. 2008). This facies model includes five distinct groupings: the vent, apron and channel, pond, proximal slope, and distal slope (fig. 2). Students and teachers in the STaRRS partnership used this model to learn about the hot spring systems, develop questions, design and carry out experiments, and develop a deeper understanding of the system.

The STaRRS partnership

The curriculum development and educational tools chosen for this STSP partnership were based on four dimensions: (1) the existing *Expedition Yellowstone!* curriculum, (2) the systems being studied by the university research team, (3) the cognitive and social needs of the students, and (4) specific safety issues in regard to conducting research in an area with thermal features. For example, instead of using thermometers that required insertion into the spring water, the students used infrared thermometers to take surface temperatures a few meters from the water. Use of tools that can measure from a distance, while not as accurate as probes, enabled the students to monitor springs that might otherwise be unsafe due to very hot water and fragile deposits and to gather data without altering the travertine formations.

The equipment needed to measure the water temperature and pH, travertine shapes, and microbial mat colors and shapes is relatively inexpensive and easy to use by teachers and students at a broad range of scientific expertise and grade levels. Use of a limited collection of measurements and the travertine facies model allowed teachers in grades 4–8 and their students to develop a basic operational understanding of the system.

During the 2008–2009 school year, nine public and private 5th–8th grade school groups participated in three aspects of the STaRRS partnership: (1) they helped to collect photo point images; (2) they obtained specific temperature, pH, atmospheric, and hot spring flow data within a 50 centimeters x 50 centimeters (20 in x 20 in) transect at locations in two different hot spring systems; and (3) they developed testable scientific questions and then conducted experiments in the field to test their hypotheses. The students completed analysis and synthesis of their data and observations immediately after returning from the field. The on-site experience culminated in student presentations. Further analysis and more formal presentations were made later to a wide range of audiences in their home communities. The students investigated a broad array of topics, such as the effects of humidity and flow rate on water temperature, pH, and microbial communities. The resulting list of scientific questions generated by students was remarkably similar to the questions driving ongoing university-level research at Mammoth.

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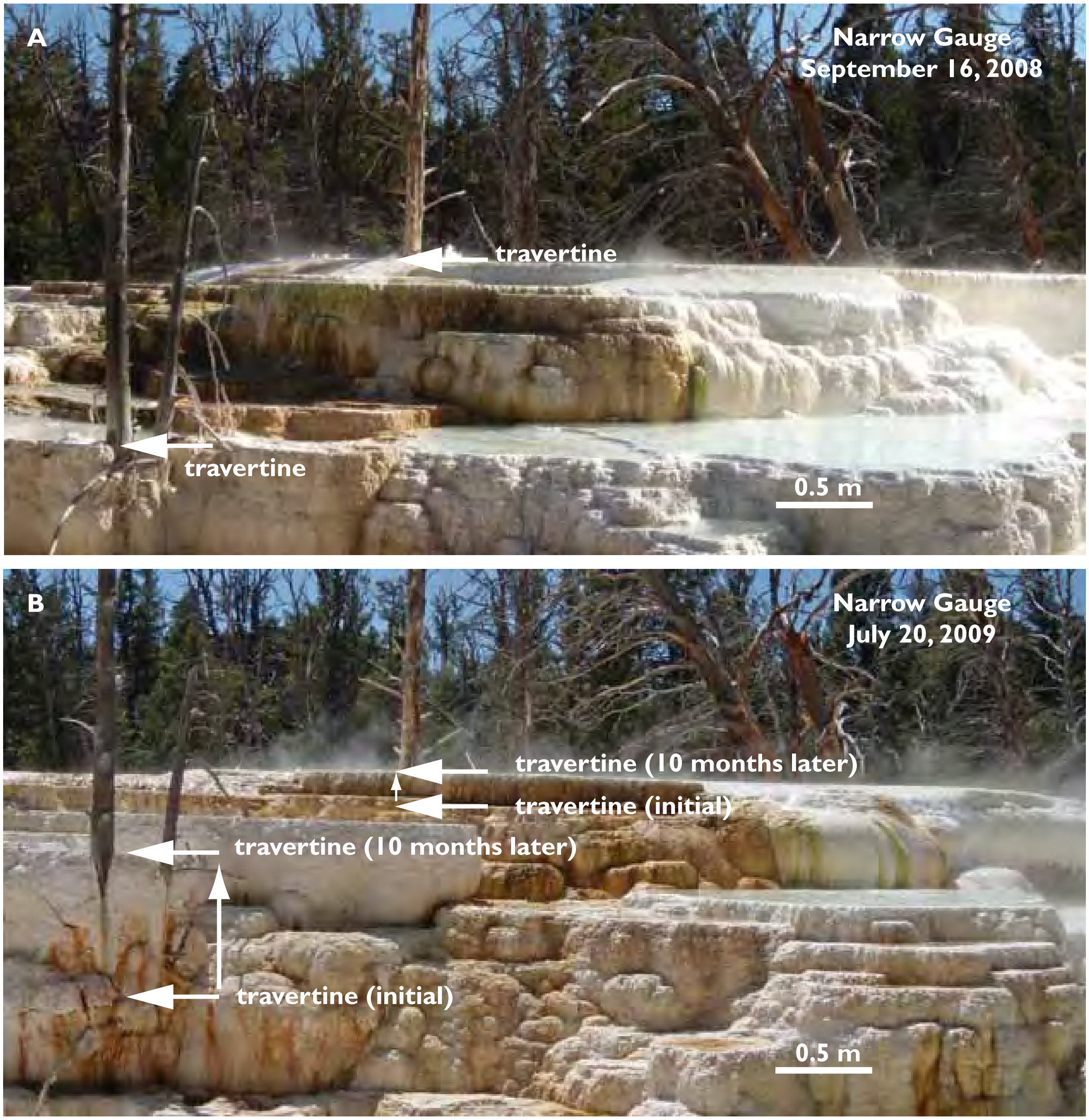
A STaRRS student checks the pH of Narrow Gauge Hot Spring.

Photo points

Photo points are designated locations where a standard digital camera (*Expedition Yellowstone!* STaRRS students used the Nikon P60) is used to capture a series of identically framed images over an extended period of time. These carefully selected sites have specific characteristics and importance for a given scientific field study. After months or years, the sequential images are combined into a time-lapse movie, providing invaluable information about springs, including simultaneous travertine and microbe growth dynamics.

The use of a long-term photographic record (photogrammetry) had been applied at Mammoth previously. A single location below the vent at Canary Spring in 2004 to 2006 was used in a recent study by the Illinois research group in collaboration with National Park Service rangers (Veysey and Goldenfeld 2008). Over a period of two years, 25 images were taken, aligned, and synthesized into a time-lapse movie that has been used in numerous educational and scientific forums and can be viewed at: http://guava.physics.uiuc.edu/projects/YNP/YNP_virtual_mammoth.html. However, logistics permitted only a limited number of images to be obtained over this two-year period. This resulted in irregular time gaps in recording the flow dynamics, microbial growth, and mineral deposition within the spring system. Optimally, this type of photographic record would include more frequent images taken over several years from several locations. This enhanced coverage could be augmented with photo point images and observations collected by STaRRS groups. The establishment of simple yet accurate protocols helps ensure that the images taken will be appropriate for scientific data collection.



STARRS PHOTO POINT 7

Figure 3. Photo point field photographs taken at Narrow Gauge, Mammoth Hot Springs, (A) September 16, 2008, and (B) July 20, 2009. Note the remarkable 0.3–0.6 meters (approximately 1 to 2 feet) of travertine accumulation that took place over 10 months.

The STaRRS photo points

In July 2008, rangers and Ana Houseal set up eight photo point locations along the boardwalk at Canary Spring, Narrow Gauge Terrace, and Orange Spring Mound (fig. 1). In February 2009, when New Trail Spring (fig. 1) began to show signs of increased flow, two photo points were added along the boardwalk overlooking the spring. The photo point locations were selected so that (1) they were on a boardwalk or approved hiking trail for easy relocation and access, (2) the field of view contained an easily identified object to serve as a scale marker that could be used to align photos and measure changes, and (3) the camera brackets would not detract from visitors' view of the hot springs. The locations were also selected with the understanding that the springs are constantly changing, and some initially promising locations of strongly flowing spring water may not produce long-term results while slower flowing spots may end up becoming very active.

Of the eight photo point locations, the most striking example of the dynamic results provided by the photo point approach was the sequence taken at one of the three Narrow Gauge sites (fig. 3). Figures 3 and 4, which were created from photos collected by several different groups of STaRRS students and teachers, demonstrates how quickly travertine can accumulate. Over a 10-month period at Narrow Gauge, the thickness of the travertine increased from approximately 0.3 to 0.6 meters (1 feet to 2 feet; fig. 3).

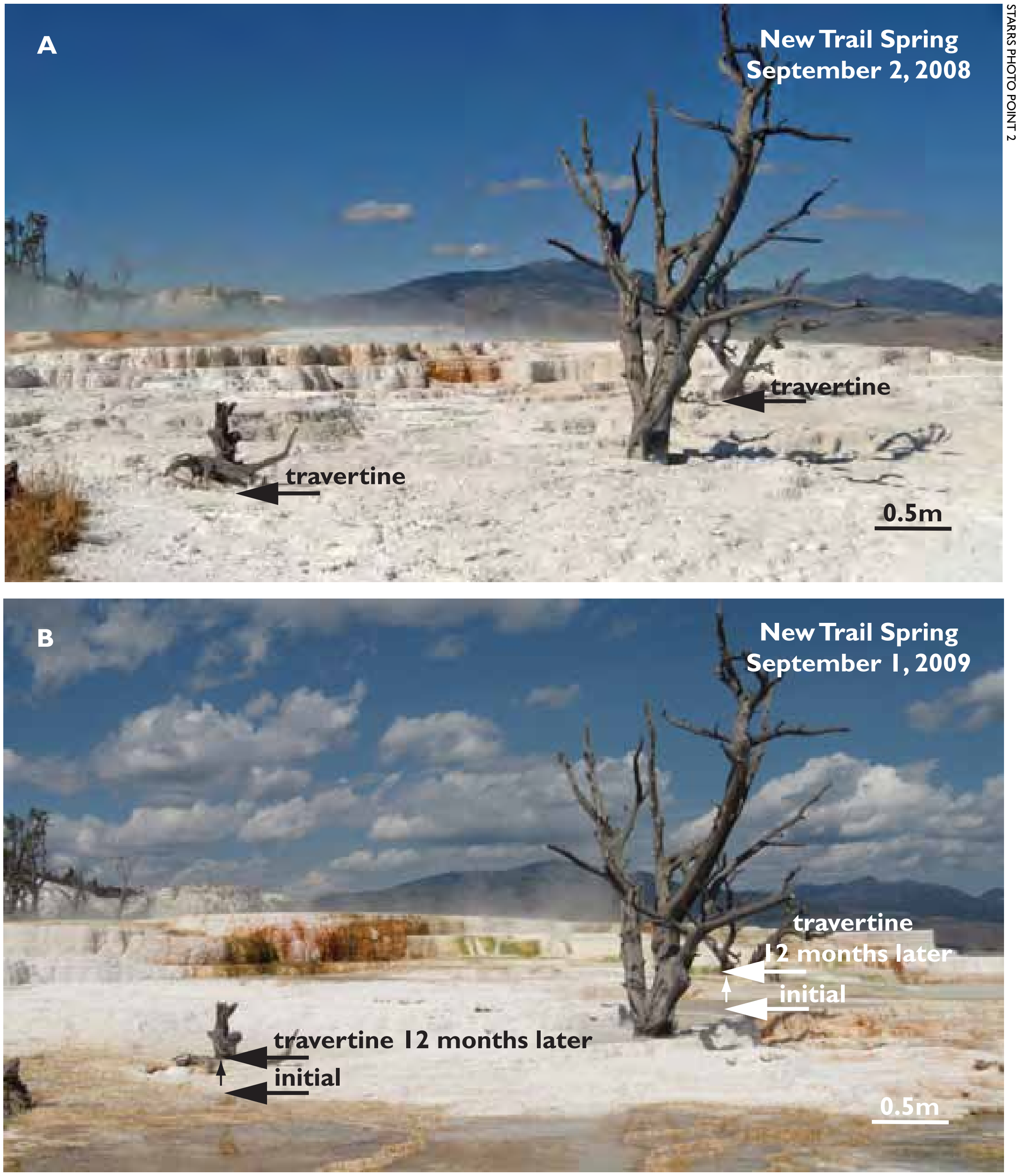


Figure 4. Photo point field photographs taken at New Trail Spring, Upper Terrace Boardwalk, Mammoth Hot Springs, (A) September 2, 2008, and (B) September 1, 2009. Note the travertine accumulation in the foreground and background, demonstrating the changes in flow direction and volume that took place over 12 months.

Benefits of the STaRRS partnership

The STaRRS partnership is now using the photo point image database before and after student expeditions to create interest, extend thinking, and deepen conceptual understanding related to the hot spring system. Having students gather images in the field and compare their images to those taken previously has helped reinforce understanding of the types and magnitude of the ecosystem processes active at Mammoth Hot Springs. Benefits for Yellowstone's Division of Interpretation include the use of photo point images for other school groups and ranger-led talks. Eventually, images may also be used in an interpretive display to help visitors understand the rapid changes occurring at Mammoth. The photo point images add to the growing collection of hot springs data, ready for use in the development and investigation of new hot-spring geobiology research.

Yet the true potential for student contributions to science using this model could be far greater, reaching beyond Mammoth and Yellowstone to other environments around the world. The STaRRS contribution has shown that time-series photographs captured by elementary students can be used to generate basic data useful to students and scientists. The tools and skills required to engage in this type of data collection (digital cameras, simple brackets, and computers) are readily available. Students and teachers are eager to find opportunities to engage in meaningful, real-world scientific research. The limiting factor need only be the imagination. The STaRRS model developed at Mammoth Hot Springs could easily be applied to other settings and provide insight on topics such as glacial retreat, post-fire plant succession, erosional processes, and even rising sea levels. This approach will also work in complex systems where change is constant but challenging to monitor. Schools and children are everywhere and elementary-aged students may be the world's most underutilized natural resource.

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A STaRRS student checks the temperature in the distal slope near Orange Spring Mound.


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