GEOLOGY

Project title: Volcanology and Petrology of the Yellowstone Plateau Volcanic Field

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Objective: To understand the origins and eruptive mechanisms of late Cenozoic volcanic activity in the region of Yellowstone National Park and to complete systematic geologic-mapping studies carried out intermittently in the park region since the 1960s.

Findings: No new work was done on this project in 2001. USGS Professional Paper 729-G has been published and contains the principal results of this work.

Project title: Preservation of Organisms in Sinter, and Study of Sinter Textures

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Objective: To compare the preservation of plants and arthropods in sinter deposited by Yellowstone hot springs, with fossil preservation in the Early Devonian Rhynie chert of N. Scotland.

Findings: Closely comparable textures have been recognized in the Early Devonian Rhynie chert and Yellowstone sinters. These observations are used as a modern analogue for our project work on the Rhynie chert. The work suggests that the fossils in the Rhynie chert were rapidly silicified in relatively cool (<50:c) Si-rich hot spring waters.

Project title: Quaternary Geology and Geo-ecology of the Greater Yellowstone Area

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Objective: To document and determine the Quaternary geology and history of Yellowstone, the relation between Quaternary geology and ecology of Yellowstone, and the neotectonic features of Yellowstone, including faulting, and caldera unrest based on Yellowstone Lake and River level changes.

Findings: The landscapes of the Greater Yellowstone ecosystem (GYE) are shaped by geologic processes of volcanism, faulting, and uplift, all of which we associate with the Yellowstone hotspot. As the North American Plate moved SW, hotspot volcanism progressed NE and arrived at Yellowstone 2 Ma. Thousands of feet of recent uplift of the GYE have resulted in ongoing erosion of deep, steep-walled valleys in readily erodible rock.

Modern and Pleistocene weather and resultant vegetation patterns strongly relate to hotspot topography and its Snake River Plain track. Moist Pacific airmasses traverse the Snake River Plain and rise onto the Yellowstone Plateau and adjacent mountains to produce deep snows, and east of the mountains, a precipitation shadow. Such deep orographic snows produced extensive Pleistocene glaciers that covered the core GYE and produced many of the landscape features on which modern soils have formed, as well as outwash gravels (commonly covered with sagebrush–grassland) and silty lake sediments (commonly covered by lush grassland such as Hayden Valley).

Rhyolitic hotspot volcanism constructed the Pleistocene Yellowstone Plateau. Streams eroding the steep edges of this plateau form scenic canyons and waterfalls. Rhyolite is poor in nutrients and forms sandy, well-drained soils that support the monotonous, fire prone, lodgepole pine forest of the Yellowstone Plateau. Older andesite and other rocks surround this plateau and support more varied vegetation, including spruce fir and whitebark pine forests broken by grassy meadows. Upwelling waters heated by hotspot magmas drive Yellowstone's famed geysers, hotsprings, and mudpots that provide habitat for specialized, primitive ecosystems of algae and bacteria.

Human settlement and use of the GYE reflects the hotspot processes of uplift, volcanism, and faulting. Uplift formed a remote highland from which streams drain radially outward like spokes from a hub. Humans have settled around Yellowstone along these drainages and established roads, irrigation systems, and political associations along them. Decision making involving the GYE is complicated by multiple jurisdictions athwart his hotspot highland, including 18 counties, 7 National Forests, 3 states, and 2 National Parks.

Project title: Groundtruthing Study of Aster and Aviris Remote Sensing Data for Hydrothermal Systems in Yellowstone National Park, Wyoming

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Objective: We obtained detailed site surveys and collected samples of soil and deposits of several selected hot springs and geysers in the Lower, Midway, and Upper Geyser Basins. The site surveys are being used for groundtruthing studies of ASTER and AVIRIS remote sensing data of this region. The site survey included non-invasive procedures such as land cover analysis, photography, Global Positioning Satellite (GPS) data collection, radiometric analysis (a non-contact thermometer), and field spectroscopy to aid in mapping of some of the sites. The samples are being analyzed with a laboratory spectrometer in visible to thermal infrared wavelengths and compared with the results of the remote sensing data. Through remote sensing and laboratory work, are characterizing the springs and their deposits from visible to thermal infrared wavelengths, especially focusing on the short-wave infrared and thermal regions. Comparisons of active, near-extinct, and extinct geysers are being determined. Because the hot springs of Yellowstone may be a planetary analogue, the results of this research will be applied to the detection of possible relict hydrothermal systems on Mars. The results of this study will form the basis of the Master's degree research for the PI.

Findings: AVIRIS and ASTER are powerful tools for the remote sensing of hot springs. AVIRIS, with its higher spectral resolution, allows for more detailed analyses than ASTER. ASTER is beneficial for regional and thermal characteristics of the basins, whereas AVIRIS can identify individual alteration minerals. Active and extinct springs have differences that are detectable through remote sensing and field spectroscopy. These differences are evident through various classification techniques, band ratioing, and spectral identification. Band ratios are useful for detecting hydrothermal alteration minerals, especially in the short-wave infrared wavelengths. However, unsupervised classifications cannot identify the entire extent of the thermally altered areas. Groundtruthing studies were necessary for truly accurate classifications. Comparison of field spectra from active geysers to extinct springs show significant variations and therefore should be easily mappable with AVIRIS. ASTER is proving beneficial for the mapping of the thermal areas. At the 90 m (TIR) resolution, the thermal areas can be distinguished, suggesting the potential success of THEMIS on Mars.

Status: For the samples collected, laboratory spectroscopy is ongoing and is being compared with the results of the remote sensing data and field spectral data. The Upper, Midway, and Lower Geyser Basins have distinct differences from each other that are detectable by ASTER and AVIRIS remote sensing. More extensive image processing and spectral studies are being done to map these areas and understand these differences. The results will explain the characteristics of the springs that are observed with the remote sensing data and lead to a greater comprehension of how to search for

similar features on Mars.

Project title: The Emergence of Scale-Invariant Architecture in Rimmed-Pool Carbonate Terraces: Abiotic Controls in Surface Hot Springs and Subsurface Cold Springs

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Objective: Similar morphological patterns are observed in modern calcium carbonate pond deposits precipitated from actively flowing spring systems in Yellowstone National Park, WY and in Fogelpole Cave, IL. These ponds and pools form terracettes, which are a series of pooled terraces deposited in a step-like pattern. On the front vertical face of the pond rims, there are microterracettes that are centimeter-sized terracettes. Hence, the two spring environments show similar patterns on the macro- and meso-scales. The Yellowstone terracettes are composed of travertine, a freshwater hydrothermal calcium carbonate deposit. The Fogelpole terracettes are composed of speleothem, a cave or cavity calcium carbonate deposit precipitated from cold water. Both environments have calcite ice sheets, thin rafts of carbonate that float on the water surface before eventually sinking to the bottom. It is an interesting paradox how surficial hydrothermal springs can precipitate carbonate minerals in patterns similar to those observed in cold subterranean springs. The macro-scale morphology, depositional patterns and crystalline architecture are similar. Yet all other fundamental environmental parameters are different, including water temperature, local climatic conditions, discharge and rate of carbonate precipitation.

Some of the possible physical and chemical controls on terrestrial carbonate precipitation include carbon dioxide degassing, temperature, calcite saturation states, evaporation and inhibitors to precipitation. Other potential influences on the observed patterns include flow, slope, surface tension and surface irregularities. This study focuses on the first four parameters above to determine their effect on carbonate deposition in the two environments. Saturation states with respect to calcite of both the travertine and speleothem waters are calculated with a geochemical modeling program. As an additional modeling experiment, the temperatures of the two waters are made equal and the saturation states compared. Analysis of the crystal fabrics in each study site is done on different scales (i.e. macro, meso and micro) to determine if morphological similarities still appear at smaller scales. In the process of addressing the different possible drivers for the similarities and differences, this study also details the physical and chemical environmental conditions present during precipitation. Similar analytical techniques are used for the Yellowstone travertine ponds as for the Fogelpole speleothem pools to facilitate the comparison.

Findings: Rimmed-pool deposits in surficial hot springs at Yellowstone National Park, WY, and cold springs in Fogelpole Cave, IL, are compared to evaluate the role of physical and chemical

parameters in controlling carbonate precipitation. Macroscale (>0.5mm) morphology and depositional patterns of carbonate precipitation in these hot and cold springs are independent of water temperature and calcite saturation states. Conversely, microscale (<0.5mm) crystal shape, mineralogy and chemistry directly reflect the dramatically different physical, chemical and biological environmental conditions in the hot and cold springs. Both Yellowstone and Fogelpole spring waters precipitate hemispherical carbonate ponds in a terrace pattern. Yellowstone carbonates, called the travertine terraced ponds, precipitate at rates of 0.4–0.8 mm/day from 38°C spring water that is about 48 times supersaturated with respect to calcite (IAP/K = 48). Fogelpole carbonates, called speleothem rimmed pools, precipitate from 16°C water with IAP/K = 2. The much higher IAP/K values at Yellowstone are probably related to very high concentrations of calcite precipitation inhibitors, S04 and Mg2 . Plane-light and cathodoluminescence petrographic analyses established very different paragenetic sequences for the two deposits. ESEM analysis indicates that the travertines are composed of a greater variety of crystal fabrics and have more euhedral forms than the speleothems. Size histograms show that the water Departmenth and pond length of the terracette and microterrace crystallization patterns may be scale invariant. Precipitation in both systems is driven mainly by C02 degassing and not evaporation. Differences in equilibrium and observed d13C values of calcite suggest microbial respiration may influence carbonate precipitation.

Project title: Study and Monitoring of Selected Geyser Activity

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Objective: Continue monitoring of selected geysers and hot springs to determine behavior of the features, especially as to frequency and duration of eruptions. Where possible, correlate the geyser and hot spring activity with activity of other hydrothermal features or external forces or conditions such as water table, lake level (for geysers at West Thumb Geyser Basin), weather (e.g., rainfall or wind), and earthquakes.

Monitoring under this permit began in 1997 with seven geysers. The objective of the continuing study is to extend the scope of the monitoring both in terms of the number of features covered and the timespan.

Findings: Several data loggers belonging to the NPS and the author were deployed over the winter of 2000–2001. When the summer field season began the total number of data loggers was increased to approximately 25 (the actual count varied with time as repairs were sometimes necessary). Data from the loggers was collected weekly and analyzed to determine geyser eruption times and, where possible, duration.

The data files from the loggers along with spread sheets containing the analysis of intervals are presently located in the Spatial Analysis Laboratory in the Yellowstone Center for Resources. No major earthquakes occurred during the study period, so no correlation with seismological events was performed. Work

is continuing on the effects of rainfall and water levels in adjacent bodies of water on the geyser activity.

Project title: The Search for Microbial Biomarkers in Terrestrial Deposits

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Objective: The primary purpose of this investigation is to evaluate the fossilization process and the potential for a long term record of the microbial life that exists associated with hot springs and their carbonate (travertine) and siliceous (siliceous sinter) deposits. Basically, we are looking for biomarkers, indicators that microbes once existed as part of the hot spring environment. This will allow us to determine the likelihood of finding fossilized microbes in extraterrestrial bodies, e.g., Mars, and what is the most likely preserved material. For example, will we have a better chance of finding body fossils or geochemical indicators of former organisms.

In order to carry out this investigation, we have and will continue to analyze the waters from which the mineral precipitates originate as well as the solid precipitates of carbonate (Mammoth Hot Springs) and siliceous sinter (Cistern Spring, Norris Geyser Basin). It is our intent to search for mineralogical (crystal habit, size, etc.) and geochemical (major, minor, and trace elements as well as isotopic) differences between biotically induced and abiotic precipitates as well as microbial remains (bacterial body fossils, biofilms, etc.).

Findings: Our work has demonstrated that the microbes readily decay in the rock. We have sampled from cores taken through the siliceous sinter and have compared these analyses with those of modern material forming on the surface of the hot springs. Within a few meters Departmenth, samples in which macroscopic forms clearly demonstrate that microbes were present in abundance (e.g., stromatolites), have no remnants of the biochemical materials that are present in the surface materials. That is, decay of the organics occurs very shortly after the rock is formed. This unexpected result is not surprising considering the porous nature of the sinter and the hot, acidic, oxygen-rich waters that are constantly coursing through these deposits. Additionally, siliceous preservation of the microbes as body fossils becomes obscured as additional silica is deposited around these tiny fossils. These results indicate that hot spring deposits on Mars may not be the ideal site to look for evidence of preexisting life.

Project title: Mapping, Chronology, and Geochemistry of Hydrothermal Explosion Deposits in YNP

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Objective: Hydrothermal explosion craters and associated breccia deposits are commonly observed features in Yellowstone National Park. Visitors to popular thermal areas like Upper and Lower Geyser Basin, Norris Geyser Basin, and West Thumb Geyser Basin often see deep conical pools of thermal water and large rock fragments of explosion breccia littering the landscape. Each of these pools is an explosion crater, and they occur throughout the Park at all scales from sub-meter to kilometer diameters. Because hydrothermal explosions can occur at any time, they constitute a potential hazard to visitors in the Park. Mary Bay, a 3-km-diameter embayment on the north shore of Yellowstone Lake, is a major hydrothermal explosion crater complex that erupted about 10,000 years B.P. and deposited an apron of explosion breccia for several kilometers around Mary Bay. Other major explosion craters in the Park include: Indian Pond, Turbid Lake, Duck Lake, Fern Lake, Pocket Basin, Roaring Mountain, and a newly discovered site in the Sulfur Hills. Smaller hydrothermal eruptions, at Biscuit Basin, Porkchop Geyser, Seismic Geyser and other localities have been observed in recent years. Our objective is to use geologic and stratigraphic studies, geochronology (principally 14°C analyses of carbon), the new high-resolution aeromagnetic data, seismic data from the monitoring network in the Park, sonar imaging in Yellowstone Lake and geochemical, mineralogical, fluid inclusion studies to understand better the mechanisms of hydrothermal eruptions, the causes of such events, regional seismicity, and possible relations to recently discovered regional inflation/deflation cycles ("heavy breathing") in the Yellowstone caldera.

Findings: To date, over 60 samples of hydrothermal explosion breccia have been collected for alteration mineralogy, oxygen isotope, rock magnetic measurements, geochronology, and geochemistry analyses and interpretation. We plan to continue to examine and analyze recent, post-glacial, hydrothermal explosion deposits identified in cores and exposed around Yellowstone Lake, in addition to examining other less studied hydrothermal explosion deposits in the Park. We will continue to examine and analyze geothermal vent locations, physical characteristics of the deposits and vents and their distribution and chronology, and analyze stable isotopes and fluid inclusions to determine the deposits' temperature of formation and composition of fluid. We will examine details of these hydrothermal systems and their relation to magmatic activity, faulting, and changes in post-glacial lake levels. We also will apply AVIRIS data in conjunction with the recently acquired aeromagnetic survey of YNP to examine areas in and north of Yellowstone Lake that may be future potential sites of hydrothermal explosions. Geothermal fluid changes that are potentially mineralizing within the

600,000-year-old caldera may reflect contrasting time scales: The inflation/deflation cycles occur on a millennial time scale whereas the hydrothermal explosions occur within minutes. Changes in pressure and flow rate would dramatically change as mineralized geothermal fluids are released and confining pressures drop, which may significantly contribute to mineralization. Finally, high-resolution sonar imaging, seismic reflection, and submersible surveys in the northern, West Thumb, and central basins in Yellowstone Lake have identified sublacustrine hydrothermal craters, vents, domal structures, and gas pockets.

Project title: Mapping the Floor of Yellowstone Lake Using High-Resolution Bathymetry, Seismic Reflection, and Submersible Remotely Operated Vehicle

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Objective: Our goal is to obtain a high-resolution bathymetric map of Yellowstone Lake and unequivocally characterize many lake bottom bathymetric features such as faults, fissures, slumps, hydrothermal deposits, explosion craters, submerged shorelines, and glacial deposits. Subbottom seismic reflection profiles, combined with towed magnetometer data obtained at about 200 m line spacing, may discern zones of active, present-day geothermal fluid migration through sediments or hydrothermally altered sediments.

Identification of submerged faults, explosion craters, hydrothermal vents, and slumped structures will improve understanding of the interrelationship of these features, their causes, and influences by deeply circulating hydrothermal fluids. These surveys will also contribute to identify locations of spawning sites for introduced lake trout. The surveys give an accurate picture of the geologic forces forming Yellowstone Lake and how geology affects the aquatic biosphere.

Recent studies show the Yellowstone caldera has cycles of inflation and deflation with an amplitude of 30 meters on a millennial time scale. To evaluate this, submerged and tilted shorelines and sites for sub-bottom profiling and coring must be mapped using modern sonar imaging. Samples obtained will be dated. The underwater geologic history integrated with the exposed shoreline history will help define the chronology and shape of cycles related to inflation and deflation of the Yellowstone caldera, and also how these cycles may contribute to hydrothermal explosions.

Findings: The 1999–2001 high-resolution bathymetric, seismic reflection, and submersible surveys of the northern, central, and West Thumb basins of Yellowstone Lake (65–70% of the total lake) revealed a spectacular landscape previously unknown to the world. Large siliceous spires and hydrothermal explosion craters protrude into and pockmark the floor of the lake, an area mostly within

the 640,000-year-old Yellowstone caldera. In addition to the abundant circular, steep-walled depressions interpreted as hydrothermal explosion craters and the siliceous spires, we identified domal features containing gas (steam?) pockets, deformed sediments, and hydrothermal vents, and recent, previously unmapped faults, fissures, slump structures, and submerged older lake shorelines. SEM images of the spires sampled indicate their composition to be predominantly diatomaceous with subordinate bacteria and amorphous silica. To complement this work, groundtruthing of the surveyed area, involving a submersible remotely operated vehicle (ROV) with sampling (for solids and fluids) and photographic capabilities is being conducted. This summer (2002), we plan to complete our mapping of the lake, finishing with the South and Southeast Arms and parts of Flat Mountain Arm.

Our intent is to produce the following: 1) A high-resolution bathymetric map of Yellowstone Lake. 2) A high-resolution magnetic map of Yellowstone Lake. 3) High-resolution seismic reflection profiles. 4) Geochemistry and stable isotopic studies of vent waters and deposits from hydrothermal vent sites. 5) Thermal probe measurements at thermal vent sites. 6) SEM images, mineralogical analyses, U-series dates of collected siliceous spire samples. 7) Mineralogical analyses, thin sections, lithologic studies of sublacustrine hydrothermal explosion craters and associated deposits. 8) Geochemical and isotopic analyses of lake biota. 9) Various analyses of core samples at selected sites. 10) Fly-throughs of the lake to be shown at geologic exhibits within Yellowstone National Park and on our website. 11) An improved geologic understanding of various features (eg. siliceous spires, submerged shorelines, hydrothermal explosion craters, domes, etc.) and timing of specific events. 12) 3–5 minute video describing the survey and discoveries to be shown at visitor centers at Yellowstone National Park. 13) All products from this study will be made available to the National Park Service (YNP) as a base in making decisions regarding resource management issues.