UNITED STATES DEPARTMENT OF THE INTERIOR

GEOLOGICAL SURVEY

Bibliography and Brief History of Studies by the U.S. Geological Survey in Yellowstone National Park, Wyoming, Idaho and Montana: 1965-1986

by

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PREFACE

This report is intended to provide a convenient summary of research conducted by the U.S. Geological Survey (USGS) in Yellowstone National Park since the Survey began a comprehensive investigation of the geology of the park in 1965. USGS research at Yellowstone spans numerous scientific disciplines, involves scores of scientists in the field and in laboratories, and draws support from several congressional programs and other government agencies. Given the duration and complexity of the USGS research effort at Yellowstone and continued scientific and public interest in the park, the authors thought it would be useful to compile a bibliography of USGS publications dealing with Yellowstone and to summarize the evolution and current status of the USGS research effort in the park.

We have restricted our compilation to publications authored by USGS scientists and a few other studies carried out with USGS funding, with full knowledge that many others have contributed substantially to our understanding of the geology of Yellowstone Park. Indeed, collaboration between USGS researchers and others from universities and elsewhere has been particularly fruitful at Yellowstone, as evidenced by a vigorous program of grants and contracts to outside researchers funded by the USGS Geothermal Research Program since its inception in 1971.

The Geological Survey acknowledges the cooperation and support of the National Park Service, which is entrusted with preserving and managing the unique national treasure which is Yellowstone National Park.

HISTORY OF GEOLOGIC INVESTIGATIONS

EXPLORATION AND RECONNAISSANCE STUDIES

The area surrounding the headwaters of the Yellowstone River was one of the last areas to be explored in the continental United States. More than half a century of fantastic stories about Yellowstone's natural wonders led to the first organized expedition to the area in 1869; by 1871, three expeditions had explored the extraordinary geologic features of the Yellowstone area. The 1871 expedition, led by Ferdinand V. Hayden of the U.S. Geological and Geographical Survey of the Territories [a forerunner of the U.S. Geological Survey, which was formed in 1879], helped to advance the idea of creating a national park to protect this unique environment. Establishment of the Yellowstone area as the United States' first national park, by an act of Congress on March 1, 1872, was due in large part to Hayden's extensive scientific report and his enthusiastic support for passage of the Yellowstone National Park Congressional Bill.

Now, more than a century later, Yellowstone remains a subject of intense geologic interest and investigation. The park consists of approximately 9,000 km^2 of virgin forests, lakes, and meadows containing a myriad of hot springs, geysers, mudpots, and other thermal features, as well as deep canyons, rivers, waterfalls, and vast areas of volcanic terrane that have been extensively glaciated. It was recognized early that, with proper attention paid to conserving its precious natural resources, Yellowstone Park could provide a unique natural laboratory in which to conduct many kinds of scientific investigations. During the first three decades of the park's existence, numerous reconnaissance reports on the geology and thermal features of Yellowstone were published by the U.S. Geological Survey and its predecessor, the U.S. Geological and Geographical Survey of the Territories. However, in the first half of this century, USGS workers conducted relatively few investigations in Yellowstone National Park.

TOPOGRAPHIC MAPPING: 1955-1961

Topographic quadrangle maps (15-minute series) of the Yellowstone area were published by the USGS in the late 1950's, and a special topographic map of the park was released in 1961. These maps provided the necessary groundwork for detailed geologic and geophysical mapping in the 1960's.

GEOLOGIC MAPPING AND RELATED INVESTIGATIONS: 1965-1971

Starting in the summer of 1965, the USGS began comprehensive geologic investigation of Yellowstone in cooperation with the National Park Service and the National Aeronautics and Space Administration. This integrated study included surface and bedrock geologic mapping, regional geophysical investigations (including seismic, electrical resistivity, magnetic, and gravity surveys), chemical and isotopic studies of rocks and waters, and an extensive survey of the park's many thermal features (Campbell, 1969). Reconnaissance geologic maps of the entire Yellowstone National Park showing bedrock (mostly volcanic) and surficial (mostly glacial) geology were published in 1972 (U.S. Geological Survey, 1972). Synthesis of mapping results with geochemical, geophysical, and thermal studies provided the first integrated understanding of the geology of the Yellowstone region.

GEOTHERMAL INVESTIGATIONS: 1972-1982

Starting in 1972, many ongoing USGS investigations in Yellowstone were supported by the Geothermal Research Program of the USGS. The Geothermal Program also provided support to many non-USGS researchers through grants and contracts for geologic studies in the park. In 1980, projects funded by the Geothermal Program included studies of hot spring geochemistry, hydrothermal alteration, stable and radiogenic isotopes, ground deformation, petrology, volcanic geology, hydrology, geoelectric resistivity, heat flow, and seismicity (Duffield and Guffanti, 1982). Although no potential for exploitation of geothermal energy exists in the protected thermal areas of Yellowstone or its immediate surroundings, those areas provide a unique natural laboratory from which to gain an understanding of geothermal areas in general, and to test nondestructive methods that might be useful in evaluating geothermal energy resources elsewhere.

VOLCANIC HAZARDS INVESTIGATIONS: 1983-PRESENT

The focus of USGS research in Yellowstone National Park widened in 1983 to include an evaluation of potential volcanic hazards from the long-lived and currently active magmatic system beneath the area. Yellowstone has a long history of explosive volcanic activity, including three colossal caldera-forming eruptions in the past 2 million years and scores of smaller eruptions (still very large by human standards), some as recently as 75,000 years ago (Smith and Christiansen, 1980; Christiansen, 1984). Synthesis of geological and geophysical data for the Yellowstone region led Eaton and others (1975) to conclude that the Yellowstone caldera is underlain by a crustal reservoir of partly molten rhyolitic magma. Precise leveling surveys throughout the park have detected crustal uplift that might reflect recent intrusion of molten magma beneath Yellowstone caldera. Geologists and geophysicists who have studied Yellowstone agree that it is likely to erupt again, at some presently undetermined date.

SUMMARY OF ACCOMPLISHMENTS

GEOLOGIC MAPPING

One of the first tasks undertaken during the the comprehensive USGS study starting in 1965 was to prepare bedrock and surficial geologic maps of Yellowstone Park at a scale of 1:62,500. Ten U.S. Geological Survey Quadrangle (GQ) Maps and one Miscellaneous Geologic Investigations Map showing the bedrock geology of most of the park were published from the mapping studies of H. R. Blank Jr., R. L. Christiansen, W. R. Keefer, J. D. Love, W. H. Nelson, W. G. Pierce, H. J. Prostka, E. T. Ruppel, and H. W. Smedes. A 1:125,000-scale USGS Miscellaneous Geologic Investigations Map (I-711) combined the geologic mapping of these investigators to produce a single large-scale bedrock geologic map of Yellowstone National Park. The geology of pre-Tertiary metamorphic and sedimentary rocks in the northern part of the park, stratigraphy of Quaternary volcanic rocks and older Tertiary Absaroka volcanic rocks, and the geology of sedimentary rocks of the southern part of Yellowstone Park were described in a series of USGS Professional Papers (729A-D).

The surficial geology of Yellowstone Park was depicted in eighteen 15-minute U.S. Geological Survey Miscellaneous Geologic Investigations Maps (scale 1:62,500) covering nearly all of the park. In addition to their mapping, K. L. Pierce, G. M. Richmond, and H. A. Waldrop described the detailed effects of late Pleistocene glaciation in the Yellowstone region in numerous reports. A 1:125,000-scale USGS Miscellaneous Geologic Investigations Map (I-710), showing the surficial geology of the entire park, was synthesized from their work.

VOLCANIC HISTORY

Subsequent investigations have focused primarily on the Yellowstone Plateau's extensive Quaternary rhyolitic volcanism, associated tectonic activity, and consequent thermal features. The Yellowstone volcanic "hot spot" lies at the eastern terminus of the northeast-trending Snake River Plain, which has experienced widespread basaltic and rhyolitic volcanism, gradually migrating northeastward with respect to the westward moving North American plate, during the last 15 million years (Eaton and others, 1975). K-Ar age data of J. D. Obradovich and R. L. Christiansen show that silicic volcanism in the Yellowstone region began about 2.2 million years ago. Christiansen's field studies in Yellowstone Park and the adjacent Island Park area separated the products of three climactic caldera-forming ash-flow eruptions, which were dated at 2.0, 1.3, and 0.6 million years ago.

Detailed geologic mapping of the large (75 x 50 km) 600,000-year-old NE-SW trending Yellowstone caldera by R. L. Christiansen and H. R. Blank, Jr., provided an understanding of processes that led to the catastrophic formation of all three calderas. Extensive petrologic and geochemical studies, including oxygen and radiogenic isotopic studies and trace-element studies by R. L. Christensen, W. Hildreth, and coworkers, provide additional clues to the complex evolution of Yellowstone's magmatic system during the past 2 million years.

K-Ar age data of J. D. Obradovich indicate that extrusive volcanism has occurred within Yellowstone Park as recently as 75,000 years ago, and that the youngest caldera was largely filled by rhyolitic lava flows between 150,000 and 75,000 years ago. These voluminous, predominently rhyolitic lava flows and pyroclastic deposits blanket much of Yellowstone National Park and adjacent Island Park areas (Christiansen, 1984)

REGIONAL GEOPHYSICS

Extensive geophysical investigations have provided additional information on current conditions beneath the Yellowstone caldera, including its spectacular hydrothermal system and underlying magmatic system. Results suggest that magmatic processes remain active beneath the Yellowstone caldera and that the system may erupt again, although the time scale for future eruptions cannot be specified.

A complete Bouguer gravity map of Yellowstone Park by Blank and Gettings (1974) shows a large NE-SW-trending gravity low, interpreted as a shallow, partly solidified reservoir of rhyolite magma (Eaton and others, 1975).

Interpretation of teleseismic records from a USGS seismometer network operated at Yellowstone since 1963 suggested to H. M. Iyer and coworkers that a large body of low-velocity material underlies the caldera. Although the exact nature of the body cannot be determined by analyses of teleseisms alone, the teleseismic data are consistent with a magma reservoir that is at least partly molten. Analysis of local earthquake activity by A. M. Pitt shows that only shallow-focus earthquakes occur directly beneath Yellowstone caldera, suggesting that at depths greater than 5 km the crust is either partly molten or too hot for brittle fracture to occur and that regional tectonic stresses are accommodated mainly by aseismic, plastic deformation.

A U.S. Geological Survey (1973) aeromagnetic map of Yellowstone Park shows a broad magnetic low within the Yellowstone caldera, suggesting the possibility of hot rock at relatively shallow depth beneath the caldera and the presence of extensive near-surface hydrothermal alteration (Eaton and others, 1975). Magnetotelluric data of Stanley and others (1977) also indicate that partly molten rock exists at shallow depth beneath the caldera. Leveling surveys revealed that the caldera floor had risen by more than 72 cm beteeen 1923 and 1975-1977, possibly owing to inflation of the magma reservoir (Pelton and Smith, 1979). Annual ground deformation surveys since 1983 indicate that uplift of Yellowstone caldera has continued since the 1975-1977 survey at about the historical average rate of 1.5 cm/yr.

HYDROTHERMAL SYSTEM

Far greater than average heat flow from the Yellowstone caldera is evident from the abundance of geysers, hot springs, and other thermal features. According to work by D. E. White, R. O. Fournier, L. J. P. Muffler, and A. H. Truesdell, Yellowstone's thermal features are surface manifestations of a convection system in which meteoric water descends along numerous fractures to depths of 3 to 4 km, is heated by conduction to temperatures of 350^{o} to 450^{o} Celsius, and returns to the surface as hot springs and geysers. These investigators also published geologic maps of Upper and Lower Geyser Basins, showing the present and past extent of hydrothermal activity in two of the most prominent thermal areas of the park. The minimum rate at which heat is carried to the surface by the hydrothermal system was calculated using measurements made in 1967 and again in 1968 of rates of flow and chloride concentrations in the major rivers that drain the park. An inventory of siliceous sinter deposits in Upper and Lower Geyser Basins and information about the rate at which silica is carried away by river waters showed that hydrothermal activity at about its present rate has been active since the end of the Pinedale glacial period. Several hydrothermal explosion craters (Muffler and others, 1971) provide evidence that thermal activity also occurred in the area at least as early as the late Pinedale glaciation, about 45,000 to 14,000 years ago (Pierce and others, 1976).

During 1967 and 1968, the USGS drilled 13 research holes in Yellowstone Park to obtain detailed physical and chemical information on the shallow part of the Yellowstone geothermal system (White and others, 1975). Studies of the drilling data and hydrothermally altered drill core from these holes by D. E. White and coworkers provided important new information on self-sealing and other factors influencing hydrothermal alteration in geothermal areas. R. O. Fournier, A. H. Truesdell, and several coworkers conducted an extensive fluid collection and analysis program of the Yellowstone geothermal system and developed several chemical geothermometers of considerable value in evaluating geothermal areas worldwide.

Studies of the mechanisms of geyser activity by S. W. Kieffer have advanced our understanding of Yellowstone's contemporary "eruptions", and provided a basis for evaluating the possible impact of human activity or regional earthquakes on these delicate manifestations of the forces that continue to shape the park.

CHEMICAL MONITORING AND VOLCANIC HAZARDS

The USGS currently monitors several factors on a continuous or repeated basis in order to detect changes that might indicate changing volcanic hazards or human impact on Yellowstone's shallow hydrothermal system. Funded by the National Park Service, the USGS measures water flow in all major rivers draining the park and monitors the flux of chloride ions in those waters to estimate the total thermal output of the park's hydrothermal system. Seismic activity in the park and adjacent Hebgen Lake fault zone is monitored by a network of seismometers operated in collaboration with the University of Utah. Crustal deformation, monitored with annual level surveys across the caldera floor, indicates continued uplift. Finally, the Yellowstone caldera is included in an ongoing compilation of unrest at large volcanoes worldwide, which will provide a context for evaluating the near-term volcanic hazards at the park.

The studies mentioned above and many others listed in the following bibliography have contributed to our understanding of the wonderland known as Yellowstone National Park.

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