One Hundred and Sixty Years of Grand Canyon Geological Mapping

By Karl Karlstrom, Laura Crossey, Peter Huntoon, George Billingsley, Michael Timmons, and Ryan Crow

Introduction

The railroad surveys and government-sponsored exploration of the West led to the first accurate geologic maps of the now-iconic landscapes of the Grand Canyon and Colorado Plateau region. Maps by John Newberry and Joseph Ives (1861), Clarence Dutton (1882), and Charles Walcott (1894) represent impressively accurate geologic maps of previously uncharted regions. Ever since the John Wesley Powell explorations of 1869 and 1871–72, gaining new knowledge via geologic mapping has been entwined with artist renditions of landscapes, and efforts to educate the American public about Grand Canyon and about science.[1] Maps by Levi Noble (1914) and

[1] John Wesley Powell, *Exploration of the Colorado River and Its Canyons* (New York, 1875). The authors would like to thank Grand Canyon National Park for permits that support

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John Maxson (1961) significantly refined and updated the paleontological ages and stratigraphic nomenclature for the rocks in Grand Canyon. Four editions of the Geologic Map of the Eastern Part of Grand Canyon National Park, popularly known as the "Blue Dragon," authored by Peter Huntoon, George Billingsley, and others (1976, 1980, 1986, 1996), provided the first modern compilation for the entire eastern Grand Canyon. Each succeeding edition incorporated the most current state-of-the-art structural geology and stratigraphy available. Western Grand Canyon geologic maps by Huntoon, Billingsley, and others (1981–2000) extended the mapping to the western edge of the Colorado Plateau, with the later work characterizing mineralized breccia pipes found on the Hualapai Reservation. Regional-scale mapping of the entire Grand Canyon region published between 2000 and 2013 by George Billingsley and others now comprises a digital geologic framework for Grand Canyon. Detailed mapping by Karl Karlstrom and his students Brad Ilg, Mike Timmons, Carol Dehler, Ryan Crow, and Jesse Robertson from 1990 to the present provides increasingly precise geochronology of rock units, refinement of stratigraphic nomenclature, improved mapping and dating of fault networks, and reconstruction of geologic history.

In looking forward to the next hundred years of geologic studies in Grand Canyon, we envision a Google Earth–type seamless zoomable digital map and accompanying databases that bridge between all scales of geology of this iconic region. Future efforts at mapping Grand Canyon geology can be nationally and globally trend-setting and are a fitting continuation of the past one hundred and sixty years of geologic-mapping innovations. This format will also allow better geoscience interpretation using digital map products and phone apps to continue Grand Canyon's role as a global front runner in informal geoscience education. All scales of geologic maps and a seamless merging from scale to scale are needed to examine geoscience problems and patterns and provide a framework for effective management of park resources such as water, threats and benefits from uranium mining, and sustainable

continued research and outreach. Research and outreach have been funded by the National Science Foundation. We thank Gordon Haxel and David Turpie for reviews that helped improve the paper.

land uses of all types. This paper shows how geologic maps of Grand Canyon National Park's rocks and landscapes have become more detailed and informative through time and have set high standards for innovation in geologic mapping and for providing advances in geoscience knowledge in general. Importantly, since Powell, the mapping process has involved an integration of science, art, science education, and outreach for the American public. The 160-year-long linkage among geology, art, resources, and science education forms one of Grand Canyon National Park's important (and continuing) legacies.

Background: Geologic Mapping

Geologic maps encode a full range of four-dimensional information about the Earth's structure and natural history. Obviously, some rock or deposit occupies every spot on Earth's surface. Geologic maps show what rocks are at each place and in so doing describe not only the rock type but also its age and history. The geologic map and the cross sections drawn from them by geologists show the three-dimensional geometries of different rock packages—whether of flat-lying layers, tilted strata, or complexly deformed basement rocks. Based on the sequence of layers, fossil forms within the layers, and radiometric dating, maps can also show rock ages. Relative dating of one rock to another describes which came first; and numerical ages tell how many years old a rock is. For example, the Elves Chasm Gneiss is found at the bottom of Grand Canyon so we know it is older than the layers that were deposited on top of it, and the U-Pb dating technique tells us that it is 1,840 million years old, plus or minus one million years of analytical uncertainty.[2] Modern maps benefit from steadily improving digital elevation models (DEMS) of the landscape and from increasingly precise and well-tested geochronology. Geologic maps are always progress reports because geologists steadily gain more knowledge about the ages of rock units and the geologic history of an area due to additional study and new techniques.

[2] D. P. Hawkins, S. A. Bowring, B. R. Ilg, K. E. Karlstrom, and M. L. Williams, "U-Pb Geochronologic Constraints on Proterozoic Crustal Evolution," *Geological Society of America Bulletin* 108 (1996): 1167–81.

Geologic maps are presented at different scales. Scales are expressed as the ratio of 1 unit on the map to xxxx units on the ground. Very detailed maps of small areas are sometimes used, for example 1:1 for a sketch of a complex outcrop, to 1:100 to 1:1000 for mine sites or for planning cities or structures. Intermediate scale maps of 1:12,000 to 1:24,000 (1 inch = 1,000 to 2,000 feet) are now the standard scales for detailed mapping of the United States (for example, ~25 percent of Arizona is now mapped at 1:24,000). More regional and generalized maps are useful for presenting regional overviews, for example 1:1 million for the state of Arizona and 1:2,500,000 for the conterminous United States. Currently the most complete geologic mapping covering the entire Grand Canyon region is a series of 1:100,000 maps. More detailed geologic mapping is only available for portions of the Grand Canyon region.

For Grand Canyon, geologic maps evolved along with visual depictions of the geology in the form of rock columns and drawings, and with art created by painters like Thomas Moran and lithographers like Oliver Wendall Holmes. These and other famous nineteenth-century landscape painters and lithographers worked with geologists to depict the landscapes of the western United States. The combination of mapping, writing, and art have been immensely successful at advancing the science of geology globally, at making direct connections between scientific exploration and policy, and at providing science education for the American public.[3]

What follows is a summary of the history of geologic mapping at Grand Canyon and the geologists that made them over the past 160 years. We also try to envision the next hundred years of geologic mapping and what it can lead to in the realms of science and science education. Grand Canyon National Park gets more than six million annual visitors and provides one of the best venues for informal geoscience education and interpretation in the world.

Landmark Grand Canyon Geologic Maps before 1900

The first geologic maps of the western United States were created as a result of the transcontinental railroad surveys that documented

[3] Stephen J. Pyne, *How the Canyon Became Grand: A Short History* (New York, 1998).

uncharted territories. Joseph Christmas Ives was a New York–born and West Point–trained engineer who was the commander of the 1857–1858 expedition to explore the navigability of the Colorado River from its delta northwards. The expedition included Connecticut-born John Strong Newberry, with college training from Western Reserve College in both natural science and medicine, and German-born Frederick W. von Egloffstein who acted as topographer and artist. The Ives expedition report included a geologic map of the western Grand Canyon region (Figure 1) that was prepared by Newberry and engraved and produced by von Egloffstein using a shaded-relief technique of his own design for depicting topography. The maps are accurate as far north as Black Canyon where the steamboat *Explorer* ran aground as it attempted to up-navigate the lower Colorado River. Newberry's party then made it on overland to Diamond Creek and later to Havasu Canyon and Fort Defiance, then part of New Mexico. The path of the Colorado River from the northeast was not yet known and the map mistakenly showed the Little Colorado River as the headwaters of the Colorado River. But the depiction of geologic units was remarkably good for its time, ten years before John Wesley Powell's 1869 river trip, and was based in part on fossil identifications made by Newberry.[4]

John Wesley Powell completed the first scientific exploration of unmapped segments of the Green and Colorado Rivers in 1869, and he repeated most of the trip again in 1871–1872. Starting in 1875 and continuing while he was director of the newly formed U.S. Geological Survey (USGS), Powell was in charge of the Geographical and Geological Survey of the Rocky Mountain Region. He formed a team of geologists that included Grove Karl Gilbert, Clarence Dutton, and Charles Doolittle Walcott, as well as artists including Jack Hillers, Thomas Moran, and William Henry Holmes. They dramatically advanced the field of geology of the Colorado Plateau and globally, and they generated public appreciation for Grand Canyon and other western landscapes, as well as for scientific exploration generally.

Clarence Dutton was Yale-trained but was largely self-educated in geology following his Civil War service. His 1882 report and monograph brought together the geologic understanding of the Colorado Plateau region from the Powell-USGS team with engaging

[4] Joseph C. Ives, *Report upon the Colorado Rver of the West* (Washington, D.C., 1861).

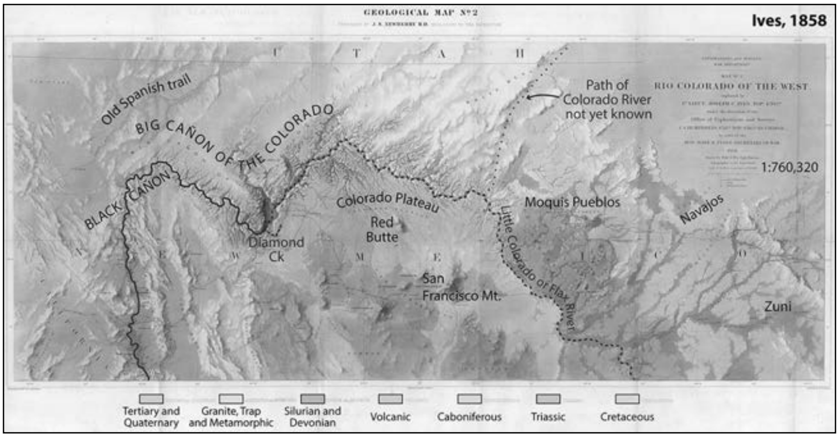

Figure 1: Geologic Map # 2 from the Ives (1861) report. Ives's map referred to Grand Canyon as the "Big Canon of the Colorado." In addition, Ives denoted the locations of Native American tribes and the old Spanish trail from Santa Fe to Los Angeles. Scale 1:760,320. Joseph C. Ives, Report Upon the Colorado River of the West (Washington, D.C., 1861).

scientific writing and inspirational images.[5] The geologic map was drawn on an artistically stylized topographic base published in the same folio. It was a geologic masterpiece. The map showed: 1) the Colorado River's path through Grand Canyon; 2) the igneous and metamorphic basement rocks, then called Archean, now known to be Paleoproterozoic, in age; 3) the tilted rocks, then called Silurian, now the Neoproterozoic Grand Canyon Supergroup; 4) Paleozoic flat-lying rocks, then called Permian and Carboniferous, now known to extend downward to include Cambrian strata; 5) the Grand Staircase of Mesozoic and Tertiary strata that were stripped back from the Grand Canyon during what Dutton called "The Great Denudation"; and 6) Cenozoic volcanic fields of varying composition built on the stratified rocks. This monograph remained the best geologic map and overall understanding of the Grand Canyon region for many decades.

Next came Charles Doolittle Walcott who was hired in 1879 to work for the U.S. Geological Survey. He soon joined Dutton for

[5] Clarence E. Dutton, *The Physical Geology of the Grand Cañon District: Second Annual Report of the United States Geological Survey, 1880–1881* (Washington, D.C., 1882); Clarence E. Dutton, *Tertiary History of the Grand Cañon District* (Washington, D.C., 1882).

work on the high plateaus of Utah, then spent numerous field seasons in eastern Grand Canyon. He and Powell forged a horse-trail from the north rim called the Nankoweap Trail to access remote areas of eastern Grand Canyon's Chuar Valley. Walcott spent many seasons unraveling the stratigraphy of Proterozoic and Paleozoic layers and published numerous papers between 1880 and 1920. His work was focused on paleontology but also resulted in the first detailed geologic map of the Chuar Group of what he named the Grand Canyon Series, later to become Grand Canyon Supergroup. He recognized these strata to be from the Proterozoic Era. He also described Cambrian fossils in the Tonto Group and discovered in the Chuar Group a sub-millimeter single-celled fossil that he named *Chuaria.* Walcott's geologic map (Figure 2) appeared on one of the first topographic contour maps (two-hundred-foot elevation contours), surveyed during the same expeditions that mapped the geology. As usual, new mapping led to numerous scientific advances: Walcott described the Proterozoic lava flows now known as the Cardenas Basalts, made important paleontology collections, and refined Grand Canyon's stratigraphy.[6]

Levi Noble's 1914 Geologic Map

Levi Fatzinge Noble was born in New York in 1882, the same year Clarence Dutton's *Tertiary History* was published. In 1908, at age twenty-six, while working on his PhD at Yale, he first visited Grand Canyon and hiked down the South Bass Trail and crossed the river on John Bass's cable car. He hiked through the full section of Paleozoic strata and, near the river, saw tilted rocks of Grand Canyon Supergoup. Many of these layers had not been examined in detail and many were unnamed. Looking back a few years later, he described this experience as "casting a spell from which the observer is never entirely free."[7] Noble's *Geologic Map of the Shinumo Quadrangle* (1914) used the emerging Matthes-Evans topographic maps of Grand Canyon National Park (cartography from 1902 to

[6] C. D. Walcott, "Precambrian Igneous Rocks of the Unkar Terrane, Grand Canyon of the Colorado" in *Fourteenth Annual Report of the United States Geological Survey to the Secretary of the Interior, 1892–1893*, Part 2, p. 497–519.

[7] Lauren A. Wright and Bennie W. Troxel, "Levi Noble: Geologist; His Life and Contributions to Understanding the Geology of Death Valley, the Grand Canyon, and the San Andreas Fault" (U.S. Geological Survey Report, 2002).

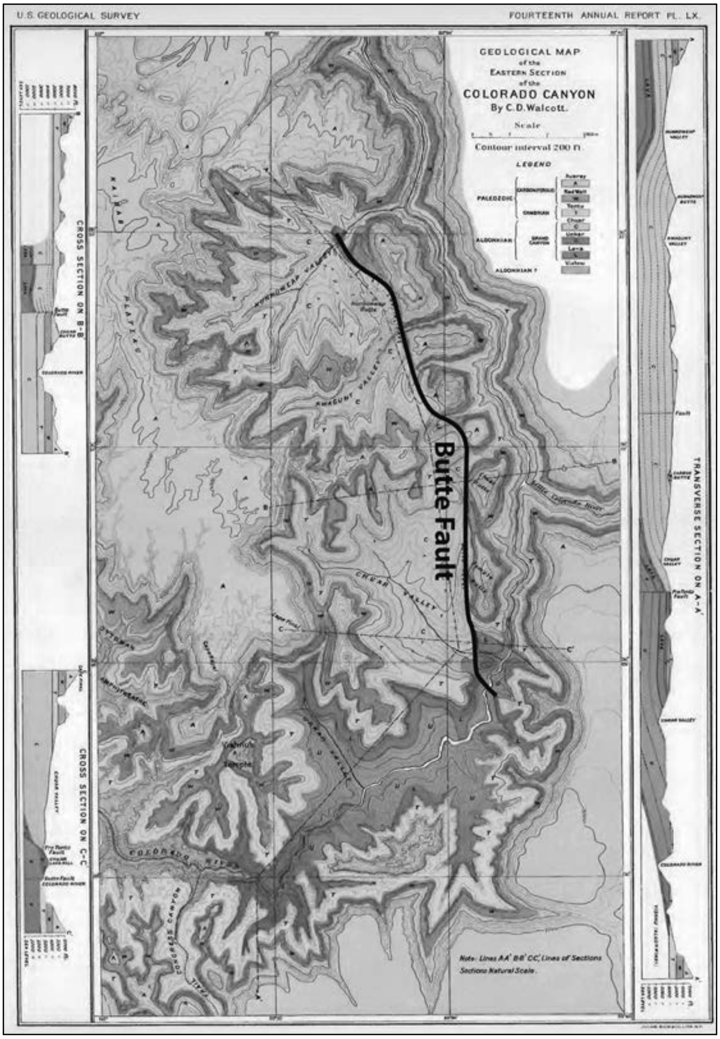

Figure 2: Charles Walcott's "Geologic map of the Eastern Section of the Colorado Canyon" (1894) identified the "Algonkian" (Proterozoic) Unkar and Chuar "terranes" (now groups) within the Grand Canyon "Series" (now Supergroup) and the Cambrian Tonto Group. C. D. Walcott, "Precambrian Igneous Rocks of the Unkar Terrane, Grand Canyon of the Colorado" in Fourteenth Annual Report of the United States Geological Survey to the Secretary of the Interior, 1892–1893.

1923; published in 1927).[8] Noble's PhD mapping concentrated on the areas reachable from the South and North Bass trails. His map made numerous advances in the geologic study of Grand Canyon. It resulted in the formal definition (generally still used) of most of the Paleozoic and Unkar Group stratigraphic units. This was the first map to begin to differentiate the basement rocks (still labeled Archean); he used the name quartz diorite for the unit now known as the Ruby pluton.[9] He retained the term Aubrey Group for the Carboniferous rocks and subdivided the Tonto Group into Tapeats sandstone, Bright Angel shale, and Muav limestone, leading to today's formational nomenclature. Noble continued to work on Grand Canyon geology until about 1930 and contributed equally impactful geologic studies of the San Andres fault, Death Valley, and other areas.[10]

John Merriam and the 1937 Colorado River Expedition

In the two decades following Noble's 1914 map, Grand Canyon geologic work saw dramatic advances in the areas of Paleozoic and Protorozoic stratigraphy, but few geologic maps were published.[11] In 1937, John C. Merriam, a University of California–Berkeley paleontologist and then-director of the Carnegie Institution, organized a 1937 Colorado River trip. According to Robert P. Sharp, a junior scientist on the trip:

> Solomon-like, Merriam apportioned the Paleozoic section to E. D. McKee, then ranger naturalist of the National Park Service, later of the US Geological Survey; the Proterozoic sedimentary and volcanic rocks to N. E. A. Hinds of the University of California (Berkeley); and the Archean complex to Ian Campbell and John H. Maxson of Caltech. Merriam supported these investigators with financial grants and facilitated publication of results in Carnegie Institution monographs.

[8] Levi F. Noble, *The Shinumo Quadrangle: Grand Canyon District, Arizona,* U.S. Geological Survey Bulletin 549 (Washington, D.C., 1914).

[9] B. Ilg, K. E. Karlstrom, D. Hawkins, and M. L. Williams, "Tectonic Evolution of Paleoproterozoic Rocks in Grand Canyon, Insights into Middle Crustal Processes," *Geological Society of America Bulletin* 108 (1996): 1149–66.

[10] Wright and Troxel, "Levi Noble."

[11] Summarized in Edwin D. McKee, "Stratified Rocks of the Grand Canyon," in *The Colorado River Region and John Wesley Powell* (Washington, D.C., 1969), 23–58.

Thus, I found myself in earliest October 1937 at Lee's Ferry on the Colorado River in the company of three experienced boatmen and three senior geologists—Campbell, Maxson, and J. T. Stark of Northwestern University. We were to board three wooden Stone-Galloway river boats for a two-month voyage of 280 miles through the Grand Canyon into Lake Mead, then filling behind Boulder (Hoover) Dam. McKee later joined the party at the foot of the old Bass Trail, partway along our route.

In 1937, the Colorado River was not a tourist's run; probably less than 100 people had made the trip through the canyon. Only one professional geologist other than Powell was known to have preceded us on such a voyage: Raymond C. Moore (1925), Professor of Geology at the University of Kansas and Kansas State Geologist, was a member of the 1923 Birdseye expedition sponsored by the US Geological Survey to locate and evaluate dam sites. . . .

I asked Campbell if he had any specific geological chores in mind for me, and he decided I should keep track of pegmatite bodies in the Archean terrane. This and other activities did not fully occupy my time, so I cast around for something to do on my own. The Paleozoic belonged to McKee, the Proterozoic to Hinds, and the Archean to Campbell and Maxson, so I had to find something in between to avoid stepping on toes. Two great unconformities are spectacularly exposed in the canyon walls: the younger one at the base of the Paleozoic beds where they rest upon truncated Proterozoic strata or the Archean complex, and the older one separating Proterozoic beds from truncated Archean rocks.[12]

John Maxson: Mapping Eastern Grand Canyon after World War II

John Maxson was born in Chicago in 1906. He studied geology at the California Institute of Technology, earning a PhD in 1931. He was one of the geologists on Merriam's 1937 geologic trip and, shortly after, was on the first motor-boat traverse of Grand Canyon. He collaborated with Ian Campbell, Carnegie Institution geologist, on Proterozoic basement rocks.[13] Following his work in World War II as an intelligence officer, he formed his own petroleum-exploration company, Aerial Exploration Company. His mapping of Grand Canyon National Park focused on the Bright Angel Quadrangle at a scale of 1:48,000 using the Matthes-Evans topographic base.

[12] Robert P. Sharp, "Earth Science Field Work: Role and Status," *Annual Reviews of Earth and Planetary Science* 16 (1988): 1–19.

[13] Maxson and Campbell subdivided the Proterozoic basement rocks (still called Archean) into Vishnu and Brahma schists and intrusive Zoroaster Granite. See Ian Campbell and John H. Maxson, "Geological Studies of the Archean Rocks at Grand Canyon," in *Carnegie Institution of Washington: Year Book No. 32* (Washington, D.C., 1933), 305–6. See also Bradley R. Ilg, "Tectonic Evolution of Paleoproterozoic Rocks in the Grand Canyon: Insights into Middle Crustal Processes" (PhD diss., University of New Mexico, 1996).

His map was first published by the Grand Canyon Natural History Association in 1961, followed by reprints in 1966 and 1968. Maxson's collaboration with Edwin D. McKee on the Paleozoic stratigraphy led us very close to modern stratigraphic nomenclature.[14] His mapping of the intersecting northeastern- and northwestern-trending orthogonal fault networks near Phantom Ranch and description on the back of the map sheet of the sequence of development of these structures were important contributions.

Maxson went on to begin mapping the entire eastern Grand Canyon using as his topographic base the 1:62,500 USGS photogrammetric topographic quadrangle maps for the eastern Grand Canyon that became available in 1962. In recognition of his Grand Canyon contibutions, he was named collaborator of Grand Canyon National Park in 1961 and collaborator-at-large of the National Park Service in 1962. He died in 1966 at age sixty before this work was completed, so the Grand Canyon Natural History Association published his work posthumously as "Preliminary Geologic Map of the Grand Canyon and Vicinity, Arizona," in three sheets. These were respectively an eastern sheet in color (1967) and central and western sheets with black lines on brown topography (1969).[15]

The Blue Dragon Maps, 1976–1996

In 1969, Park Superintendent Richard Lovegren and Chief of Environmental Activities and Systems David Ochsner approached Peter Huntoon immediately following a presentation at the Museum of Northern Arizona's Annual Symposium on Northern Arizona Geology about the park's desire to have a completed geologic map of the entire park on one sheet, as its boundaries were then defined. Huntoon had recently finished his master of science degree and was completing his PhD degree at the University of Arizona on Grand Canyon structural geology and karst hydrology.[16] By 1970, George Billingsley, who became a principal in the project, also had recently

[14] His rock column depiction of the three sets of rocks in Grand Canyon showed vertically foliated basement rocks and plutons, tilted Unkar Group, and 1200-m-thick (3,900 feet) section of Paleozoic strata.

[15] "John Haviland Maxson (1906–1966)," *American Association of Petroleum Geologists Bulletin* 50 (Nov. 1966): 2483.

[16] P. W. Huntoon, "Hydrology of the Tapeats Amphitheater and Deer Basin, Grand Canyon, Arizona" (MS thesis, University of Arizona, 1968); Peter Wesley Huntoon, "The Hydro-Mechanics of the Ground Water System in the Southern Portion of the Kaibab Plateau, Arizona" (PhD diss., University of Arizona, 1970).

completed his master's thesis at Northern Arizona University.[17] The timing of the park's request was fortuitous because the USGS had in 1962 assembled a 1:62,500 scale topographic map for Grand Canyon National Park and vicinity on one sheet. This topographic base was made photogrammetrically from 1951–1960 aerial photography. The project was launched in 1970. Publication of the four editions of the Huntoon et al. (1976, 1980, 1986, and 1996) "Geologic Map of the Grand Canyon National Park, Arizona" was carried out under the auspices of William Breed of the Museum of Northern Arizona who secured funds for the project from the Grand Canyon Natural History Association and who coordinated the participation of the several other specialists who contributed to the effort. "Eastern Part of" was added to the title beginning with the 1980 edition after the park was enlarged.

The map became known as the "Blue Dragon" because of the dominance of blue colors for the Paleozoic strata and because of the Chinese-dragon-like shape made by the Grand Canyon and its tributaries. It was a state-of-the-art collaborative mapping effort that made available, for the first time, a comprehensive geologic map of the eastern part of the Grand Canyon National Park on one sheet. The presentation included estimates of offsets along faults and monoclines based on field, aerial photo and map assessments, and refined stratigraphy. The map was dynamic in that Huntoon's and Billingsley's succeeding editions incorporated corrections and revisions, and new collaborators were brought in to incorporate fresh insights and mapping.[18] Together these editions became the best-selling and most widely distributed geologic map of all time, owing to sales by the Grand Canyon Natural History Association to an international public. Total grant funds for all the Blue Dragon geologic map editions totaled about $100,000, one of the most cost-effective geologic mapping projects of its scope in history. The

[17] George H. Billingsley Jr., "General Geology of the Tuckup Canyon, Central Grand Canyon, Mohave County, Arizona" (MS thesis, Northern Arizona University, 1970).

[18] The 1976 edition utilized mapping of the Precambrian metamorphic basement by Scott Babcock, Edwin H. Brown, and Malcome D. Clark (Babcock et al., 1979); Precambrian Supergroup by William J. Breed, James W. Sears, and Trevor D. Ford (Ford and Breed, 1973; Sears, 1973); Paleozoic stratigraphy by George H. Billingsley, and post-Precambrian structural geology by Peter W. Huntoon. The 1996 edition incorporated new mapping of the Precambrian metamorphic basement by Brad Ilg and Karl Karlstrom derived from Ilg et al. (1996), metamorphic pressure-temperature data by Michael Williams later published by Dumond et al. (2007), and remapping of the Precambrian Supergroup in eastern Grand Canyon by Huntoon.

authors ceded royalties to the benefit of the Museum of Northern Arizona and Grand Canyon Natural History Association. Sadly, the map is now out of print.

Western Grand Canyon Maps, 1981–1999

Huntoon and Billingsley, with contributions by Malcome Clark on the Precambrian basement, went on to map the geology in the western Grand Canyon between 1971 and 1980. They produced three 1:48,000 sheets using a black-line geologic overlay on a brown topographic base reduced from then newly published 1:24,000 scale USGS quadrangle topographic maps with forty-foot contours.[19] These maps also were published by the Grand Canyon Natural History Association.

The geologic data from the three western Grand Canyon maps, fitted and extended as necessary, served as the geologic base for four full-color 1:48,000 USGS maps summarizing the characteristics of breccia pipes on the Hualapai Indian Reservation produced by a team led by Karen Wenrich.[20]

Kenneth Hamblin's 1994 Lava Dam Map

Kenneth Hamblin, geologist from Brigham Young University, spent many years mapping the lavas flows of the Uinkaret volcanic field and especially the basalt flow remnants that flowed over the edges of Grand Canyon (Figure 3). This type of "topical map," where only the type of rock is depicted, is effective for discussion of a particular theme. Hamblin relied primarily on detailed descriptions of field relationships to map to better understand the lava dams.

Ryan Crow, a PhD student at the University of New Mexico, and his colleagues added new geochronology and geochemistry and showed that there were about seventeen river-damming events between 850 and 100 thousand years ago, rather than over the past

[19] The sheets from east to west were Vulcan's Throne (Billingsley and Huntoon, 1983), Hurricane fault zone (Huntoon, Billingsley, and Clark, 1981) and Lower Granite Gorge (Huntoon, Billingsley, and Clark, 1982).

[20] Those sheets were respectively northeast (Wenrich, Billingsley, and Huntoon, 1997), northwest (Wenrich, Billingsley, and Huntoon, 1996), southeast (Billingsley, Wenrich, and Huntoon, 2000) and southwest (Wenrich, Billingsley, Huntoon, and Young, 1999).

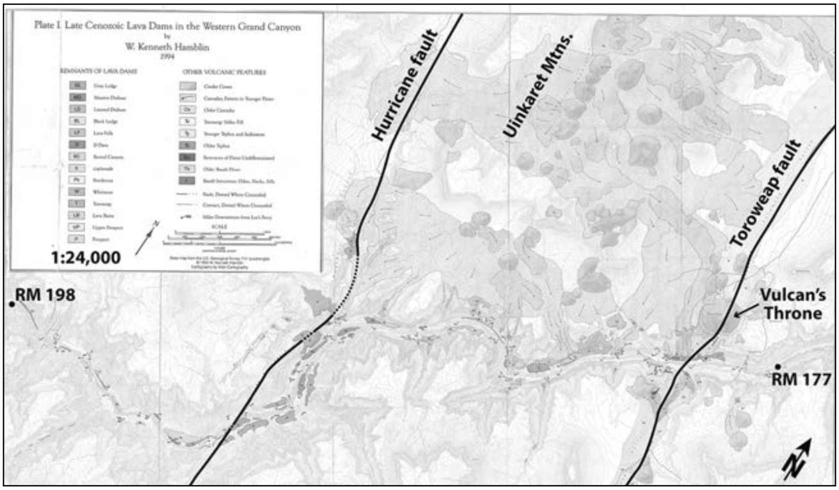

Figure 3: Kenneth Hamblin's 1994 geologic map of the lava dams in western Grand Canyon is an example of a map in which just a single rock type or set of rocks is depicted, in this case the basalts flows that erupted into western Grand Canyon. These basalts range in age from about 800,000 to 100,000 years old, their vents are located between the Hurricane and Toroweap faults, including Vulcan's Throne conder cone perched on the canyon's rim. Places where the fault trace is dotted "beneath" a lava flow indicate the flow is younger than the most recent fault slip, but places where the line is solid indicate that fault slip is younger than and hence offsets the flow. This region is a young and highly tectonically active region of the Colorado Plateau and displays the interaction of rivers, canyon carving, and volcanism. From W. Kenneth Hamblin, Lake Cenozoic Lava Dams in the Western Grand Canyon *(Boulder, Colo., 1994). Courtesy of the Geological Society of America.*

1.5 million years as previously thought.[21] New insights from field observations, three-dimensional analysis of flow remnants, and analytical study (e.g., geochronology) allowed for significant refinements to Hamblin's original mapping and increased our understanding of how lava flows and continental-scale rivers interact.[22]

[21] Older ages were from Dalrymple and Hamblin, *Proceedings of the National Academy of Sciences* 95 (1998): 9744–49.

[22] A newer map was published as a data repository item in Ryan S. Crow et al., "A New Model for Quarternary Lava Dams in Grand Canyon," *Geosphere* 11 (Oct. 2015): 1305–42. Dating and measurement of flows that overly ancestral Colorado River gravels were also used to calculate river incision rates over the past six-hundred-thousand years Ryan S. Crow et al., "Steady Incision of Grand Canyon at the Million Year Timeframe: A case for Mantle-Driven Differential Uplift," *Earth and Planetary Science Letters* 397 (July 2014): 159–73.

1990 Onward: University of New Mexico (UNM) Mapping

Many geologic questions such as those involving history and process require more detailed sampling, description, and mapping than is usually possible during small-scale mapping of large regions. Karl Karlstrom and his students and collaborators from several universities mapped rocks in the inner Grand Canyon at a scale of 1:12,000 with the ultimate goal of compiling the detailed mapping at a scale of 1:24,000. Grand Canyon exposes Proterozoic basement rocks near its bottom and is hence a window through the layered Paleozoic rocks of the Colorado Plateau. Basement rocks record the history of the assembly of the southern portion of the North American continent as well as the structural architecture (early faults and folds) that have had persistent influence on subsequent geologic history.

In the mid-1980s, while at Northern Arizona University (NAU), Karlstrom and his students and collaborators began mapping the Lower Granite Gorge of Grand Canyon at 1:24,000. Further mapping developments came in the 1990s. Brad Ilg, a graduate student at NAU and later a PhD student at UNM, mapped the Upper and Middle Granite Gorges at 1:12,000.[23] Results included discovery of the oldest rocks in the Southwest (the 1.84-billion-year-old Elves Chasm Gneiss), subdivision of three schist units that comprise the Granite Gorge Metamorphic Suite, and precise dating and characterization of about fifteen different granite plutons that intrude the schists.[24] Collectively, these are called the Vishnu Basement rocks. These rocks formed when volcanic microplates collided to form the Vishnu Mountains about 1.7 billion years ago. These discoveries led to new U-Pb dates, which were reported in journal articles.[25] New mapping was documented in generalized maps in peer-reviewed publications and in detailed basement maps in thesis format.

Mapping efforts in the 1990s also involved the Grand Canyon Supergroup. Mapping by J. Michael Timmons, UNM master's student, and colleagues greatly refined mapping of the structural geology of eastern Grand Canyon. This was followed by PhD theses at

[23] Bradley R. Ilg, "Early Proterozic Structural Geology of Upper Granite Gorge, Grand Canyon, Arizona" (MS thesis, Northern Arizona University, 1992); Bradley R. Ilg, "Tectonic Evolution of Paleoproterozoic Rocks in the Grand Canyon: Insights into Middle Crustal Processes" (PhD diss., University of New Mexico, 1996).

[24] Summarized by K. E. Karlstrom et al., "Paleoproterozoic Rocks of the Granite Gorges," in *Grand Canyon Geology*, ed. Stanley S. Beus and Michael Morales (New York, 2003), 9–38.

[25] U-Pb zircon geochronology was reported by Hawkins et al., "U-Pb Geochronologic Constraints on Proterozoic Crustal Evolution," 1167–81.

UNM by graduate students Mike Timmons (on the Unkar Group) and Carol Dehler (on the Chuar Group), which resulted in redefinition of these successions and interpretion of the sedimentary record of assembly and break-up of the supercontinent Rodinia.[26] The Timmons and Karlstrom "Geologic Map of Eastern Grand Canyon" (2013) is the first of a series of 1:24,000 map sheets planned to cover the Colorado River corridor. Cross sections and refined stratigraphic and time columns depict new dating. Accompanying scientific papers in a Geological Society of America (GSA) Special Paper help explain geologic progress made while making this map.[27] The map also includes mapping of surficial deposits that record the rates of carving of Grand Canyon by the Colorado River.[28] It shows the distribution of travertine deposits, the youngest rocks in Grand Canyon, which record groundwater flow in the past million years including degassing of mantle–derived CO_2 and ^3He.[29]

1:100,000 Mapping of the Grand Canyon Region, 2000–2013

George Billingsley of the U.S. Geological Survey undertook a 1:100,000 compilation of the nine 30 by 60 minute quadrangle sheets centered on the Blue Dragon map. The first, the Grand Canyon sheet, was released as an Open-File Report in 2000; the last, Glen Canyon Dam sheet, was released in 2013 and published at 1:50,000 (Figure 4). These maps integrate Billingsley's extensive new mapping with digital compilation of all previous mapping. They include reports that summarize the geology of each sheet and collectively form a comprehensive geologic map of the "new" Grand Canyon National Park that extends from Lake Powell to Lake Mead. This decades-long mapping effort also includes collaboration of

[26] A recent paper that cites older work is C. Dehler, G. Gehrels, S. Porter, M. Heizler, K. E. Karlstrom, G. Cox, L. C. Crossey, and J. M. Timmons, "Synthesis of the 780–740 Ma Chuar, Uinta Mountain, and Pahrump Groups (ChUMP), Western USA: Implications for Laurentia-wide Cratonic Marine Basins," *Geological Society of America Bulletin* 129 (2017): 607–24.

[27] J. Michael Timmons and Karl E. Karlstrom, eds., *Grand Canyon Geology: Two Billion Years of Earth History*, rev. ed. (Boulder, Colo, 2013).

[28] A recent summary of incision rates is in R. Crow, K. E. Karlstrom, A. Darling, L. J. Crossey, V. Polyak, D. Granger, Y. Asmerom, and B. Schmandt, "Steady Incision of Grand Canyon at the Million Year Timeframe: A Case for Mantle-driven Differential Uplift," *Earth and Planetary Science Letters* 397 (2014): 159–73.

[29] Travertines are discussed by L. J. Crossey and K. E. Karlstrom, "Travertines and Travertine Springs in Eastern Grand Canyon: What They Tell Us About Groundwater, Paleoclimate, and Incision of Grand Canyon," in Timmons and Karlstrom, eds., *Grand Canyon Geology*, 131–44.

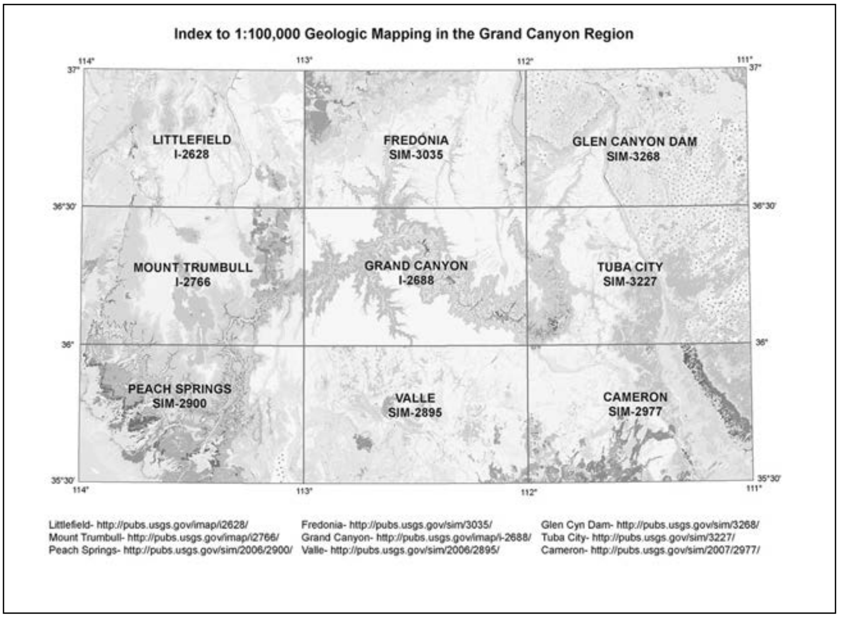

Figure 4: George Billingsley's 1:100,000 digital maps of the Grand Canyon region, with names for the nine map sheets and online locations listed.

numerous coauthors. Mapping by U.S. Geological Survey geologist L. Sue Beard of the Lake Mead Quadrangle extended this coverage to the west.[30] As discussed below, these digital maps provide the essential foundation for future generations of digital geology of the Grand Canyon region.

Summary

Figure 5 shows the area that we consider the "new" Grand Canyon National Park, slightly expanded from Billingsley's compilation. It also summarizes the areas of all previously published geologic maps discussed above. The rocks are extremely old; they span almost

[30] L. S. Beard et al., "Preliminary Geologic Map of the Lake Mead 30' X 60' Quadrangle, Clark County, Nevada, and Mohave County, Arizona" (2007), available online at https://pubs.usgs.gov/of/2007/1010/.

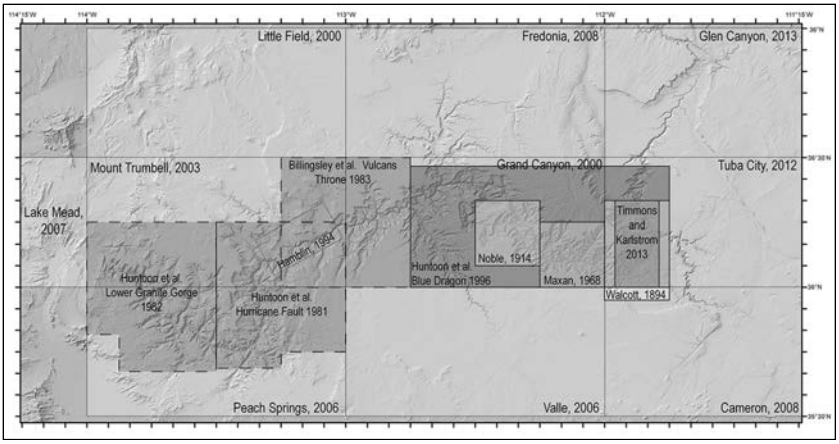

Figure 5: Index map showing locations of geologic maps of the Grand Canyon. Grand Canyon National Park is in need of a seamless geologic map covering the area from Lake Powell to Lake Mead.

two billion years or about 40 percent of Earth history. But the landscapes of this region are geologically young, having formed in the past seventy million years. A digital elevation model of the modern landscape is shown in Figure 5 with labels for important landscape features and deposits. This is not a geologic map in the strict sense, but it shows key locations that scientists and visitors alike need to know about in order to understand the century-long debate about the age and carving of Grand Canyon.[31] These include the following: A) The Lees Ferry area is where presently exposed Paleozoic rocks were buried beneath about three kilometers of Mesozoic strata and no Colorado River was present until after six million years ago. B) Vermillion cliffs is the southernmost of a series of steps (cliffs) and treads (benches) that extend northwards to make the Grand Staircase. C) Marble Canyon is a narrow segment of Grand Canyon, also less than six million years old. D) Little Colorado River's confluence historically marked the start of Grand Canyon. E) Upper Granite Gorge is the deepest

[31] A recent paper on the age and carving of Grand Canyon is K. E. Karlstrom, J. Lee, S. Kelley, R. Crow, L. J. Crossey, R. Young, G. Lazear, L. S. Beard, J. Ricketts, M. Fox, and D. Shuster, "Formation of the Grand Canyon 5 to 6 Million Years Ago through Integration of Older Palaeocanyons," *Nature Geoscience* 7 (Jan. 2014): 239–44.

and widest part of Grand Canyon and where an earlier paleocanyon cut across the Kaibab uplift twenty-five to fifteen million years ago. F) Hurricane fault zone segment is where the Colorado River has re-occupied the path of an older, sixty-five to fifty-five million year old, N-flowing "Music Mountain" paleoriver. G) Hindu paleocanyon is a landscape remnant of a paleocanyon that still contains gravels of the sixty-five to fifty-five million year old Music Mountain Formation. H) Westernmost Grand Canyon is also a young segment, cut in the past six million years.[32] I) Grand Wash cliffs form the abrupt end of Grand Canyon. J) Muddy Creek Formation and Hualapai Limestone provide evidence that the Colorado River did not enter Grand Wash trough until after six million years ago.

The Future of Geologic Mapping of Grand Canyon

New cartographic maps led to improved geologic maps throughout the history of Grand Canyon mapping. Similarly, modern high-resolution aerial photography, digital elevation data, and digital tools should provide near limitless abilities to portray park geology and resources in layered relational datasets and geographic information system (GIS) formats. Future geologic maps will probably be visualized with three-dimensional technology similar to Google Earth. Several next steps are planned. The Billingsley 1:100,000 regional framework can be upgraded into a seamless format with unified bedrock and surficial geology units, colors, and nomenclature. Detailed mapping at 1:24,000 of the river corridor needs standardization and publication in seamless format based on existing theses and new mapping. Innovative ways should be developed to depict geologic map data in an accessible format for park visitors, for example in visitor centers and as trail and river guides. One can envision a "streetview" type approach for higher resolution of outcrop and thin section scale relationships, similar to the Arizona State University virtual Grand Canyon fieldtrips (https://vft.asu.edu/). This seamless and multi-scale

[32] C. Winn, K. E. Karlstrom, D. K. Shuster, S. Kelley, and M. Fox, "6 Ma Age of Carving Westernmost Grand Canyon: Reconciling Geologic Data with Combined AFT, (U-Th)/He, and 4He/3He thermochronologic data," *Earth and Planetary Science Letters* 474 (2017): 257–71.

mapping initiative for Grand Canyon over the next decade will be a fitting continuation of over 150 years of geologic-mapping innovations. This format will also allow better geoscience interpretation using electronic maps, phone apps, and digital-maps displays to continue Grand Canyon's status as global front runner in informal geoscience education for people from all knowledge levels.[33]

Multiple scales of geologic maps and seamless merging from scale to scale are also needed for effective management of park resources. For example, one of many pressing problems for the park is how to provide a sustainable water supply for its six million annual visitors. There is no reliable surface water and no perennial rivers on the south rim, and the water table is very deep, so springs and groundwater on the north rim are currently relied on. Water delivery is currently being addressed by plans for a renovated pipeline system that carries water from the north rim to the south rim. Groundwater quality is being addressed by geochemical studies. But future groundwater quantity is potentially a major problem and it is likely to be negatively impacted by climate change ,which is reducing the snowpack recharge on the north rim. Hence future planners will need to have better information on sandstone and limestone aquifers, and fault pathways, as informed by geologic maps. The northwestern- and northeastern-trending orthogonal fault networks mapped by Noble and Maxson and Huntoon now need more detailed mapping to evaluate interconnected fast-pathways for groundwater flow. Management challenges also surround uranium deposits, archaeological sites, caves, ecosystems, wildlife corridors, and the river itself. Not least is the challenge to enhance public science literacy by effectively interpreting Grand Canyon's fundamental resources—it rocks, landscapes, and the time encoded by them.

[Editor's Note: For more maps and an appendix, please visit Karl Karlstrom's website, http://eps.unm.edu/people/faculty/profile/karl-karlstrom.html]

[33] The Trail of Time exhibit at the south rim, developed by the authors from 1995 to 2010, provides informal geoscience education for many of the park's six million visitors. The "Trail of Time Companion" by Karl Karlstrom and Laura Crossey (2010) guidebook is available at the park and can enhance that experience.