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Introduction to Grand Canyon geology

Karl E. Karlstrom
Department of Earth and Planetary Sciences, 1 University of New Mexico, MSC03 2040, Albuquerque, New Mexico 87131-0001, USA

J. Michael Timmons
New Mexico Bureau of Geology and Mineral Resources, New Mexico Tech, 801 Leroy Place, Socorro, New Mexico 87801, USA

Laura J. Crossey
Department of Earth and Planetary Sciences, 1 University of New Mexico, MSC03 2040, Albuquerque, New Mexico 87131-0001, USA

INTRODUCTION

Grand Canyon is one of the premier geologic landscapes in the world. It is a geologically young canyon, carved in the last 6 million years (6 Ma) by the Colorado River and its tributaries. These waters, primarily sourced by snow melt in the Rocky Mountains, have utilized their percussion tools of boulders, cobbles, and sand, acting for millions of years, to carve a canyon that is up to one mile (1 mi; 1.62 km) deep (Fig. 1). The canyon has widened to >10 mi (16.2 km) through the same processes acting in side streams, aided by additional processes of hillslope erosion. The formation of the canyon and sculpting of the present landscape by erosional forces can be thought of as the youngest chapter of the geologic evolution of the Grand Canyon region. This carving of the canyon has revealed three sets of rocks in the walls of the canyon that record progressively older chapters: (1) The horizontal sedimentary rock layers that make up the upper strata throughout Grand Canyon are Paleozoic rocks, deposited between ~525 and 270 million years (m.y.) ago (between 525 and 270 Ma). (2) The tilted rock layers, exposed selectively in fault blocks and exceptionally well preserved in the eastern Grand Canyon, are Meso-Neoproterozoic sedimentary rocks of the Grand Canyon Supergroup that were deposited between 1255 and 700 Ma. (3) In the depths of Grand Canyon, the oldest rocks are the igneous and metamorphic rocks we call the *Vishnu basement rocks* (Granite Gorge Metamorphic Suite plus the Zoroaster Plutonic Complex). These rocks record the formation and modification of the continental crust of the region in the Paleoproterozoic Era between 1840 and 1660 Ma. Throughout this monograph, readers need to be familiar with the geologic time scale, the larger subdivisions of which are listed in Table 1.

This monograph accompanies the detailed *Geologic Map of Eastern Grand Canyon, Arizona*[1] (previously published as *Geologic Map of the Butte Fault/East Kaibab Area* by the Grand Canyon Association). This part of the canyon is special because it contains nearly all the rock units of Grand Canyon. It is the only part of the canyon where the 800–742 Ma Chuar Group strata are found, and the only place where the Sixtymile Formation is found. It also provides excellent exposures of the Butte fault, a major fault line in the crust with an interesting history of multiple movements, including formation of the East Kaibab monocline. The eastern canyon also contains Marble Canyon, the confluence of the Little Colorado River with the Colorado River, and river gravel and travertine deposits that record how fast the river has been carving the canyon. The purpose of this volume is to present an up-to-date and easy-to-understand summary of the geologic history of Grand Canyon, with emphasis on the eastern Grand Canyon. Geology, like any science, has complicated concepts and a necessary vocabulary, but we try to present difficult concepts in a context of familiar ones, and new words with enough context to help in understanding the vocabulary.

Each of the rock sets is becoming increasingly well understood, and our goal is for this monograph and the new geologic map to help readers get to know all the rocks in Grand Canyon

[1]The map is available on inserts accompanying this volume and also as GSA Data Repository Item 2012287, online at www.geosociety.org/pubs/ft2012.htm, or on request from editing@geosociety.org or Documents Secretary, GSA, P.O. Box 9140, Boulder, CO 80301-9140, USA.

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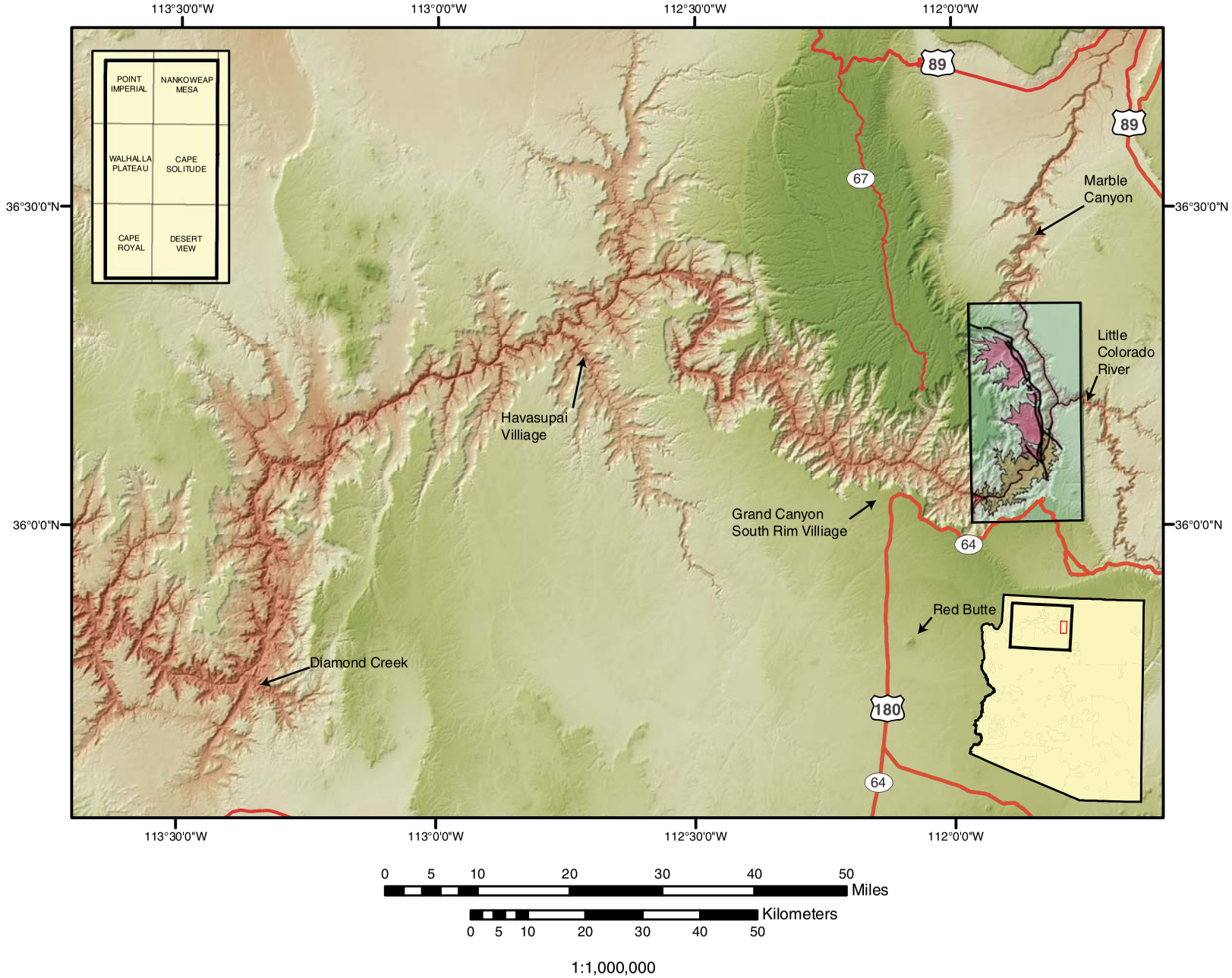

Figure 1. Digital elevation model (DEM) of Grand Canyon region, showing coverage of the new eastern Grand Canyon geologic map.

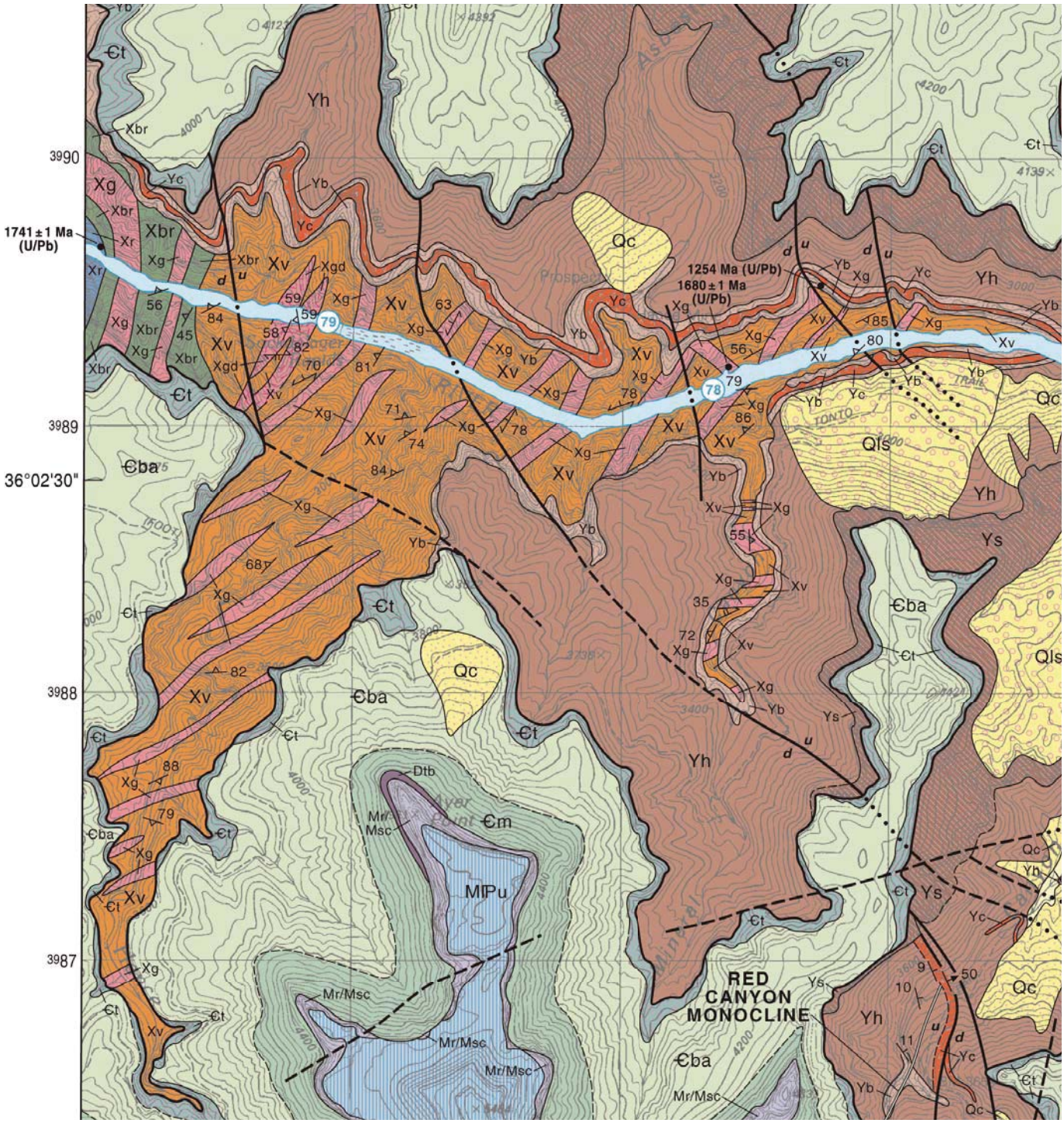

Figure 2. Part of the *Geologic Map of Eastern Grand Canyon* that contains the Vishnu basement rocks (see back pocket of book for complete map and explanation). For scale, the grid shows 1 km squares. Basement units are labeled with X for their Paleoproterozoic age. Units, from oldest to youngest: Xr—Rama Schist; Xb—Brahma Schist; Xv—Vishnu Schist; Xg—granite and pegmatite intrusions. Strike and dip symbols show orientation and steepness of tectonic layering of different ages, from oldest to youngest: S_1—strike line with triangle; S_2—barbed strike line with one tick; S_3—strike line with 2 ticks.

highs, wave processes were more dominant. Body fossils are rare in the Tapeats; however, trace fossils are more common upward in the formation in finer grained lithologies. Locally, deposits of braided streams occur near the base of the Tapeats and were deposited on floodplains that merged into the nearshore marine areas (Hereford, 1977). The finer grained *Bright Angel Shale* gradationally overlies and interfingers with the Tapeats Sandstone. The formation is composed of fine-grained sandstone, siltstone, and shale, the latter two being predominant. The Bright Angel Shale forms expansive slopes above the more cliff-forming Tapeats Sandstone. Deposition occurred for the most part in subtidal environments (Martin et al., 1986). Fair-weather processes influenced sedimentation, although the shelf was affected periodically by storms (Middleton, 1989; Rose et al., 1998; Middleton and Elliott, 2003). Trace fossils are abundant in the Bright Angel Shale and record a major proliferation of invertebrate fauna (Middleton and Elliott, 2003).

The youngest unit of the Tonto Group is the *Muav Limestone;* as its name suggests, it records the first widespread accumulation of carbonate sediments (limestone and dolostone) in the Paleozoic, and it also contains the first major occurrences of invertebrate fossils (McKee and Resser, 1945). Contacts with the Bright Angel Shale are gradational and reflect intertonguing of adjacent environments as well as repeated transgressions and regressions of the Cambrian seas. Deposition occurred in offshore areas apparently free of sandy and silty detritus. Several zones within the Muav preserve structures that are indicative of shallow-water sedimentation (Wanless *in* Middleton and Elliott, 2003) and likely indicate offshore buildups of carbonate sediments along localized shoaling zones (Fig. 5).

Ordovician and Silurian Systems

Ordovician and Silurian strata are absent in northern Arizona, although they do occur in southeastern Arizona (Middleton, 1989). It seems unlikely that strata of this age were not

Figure 3. Early Middle Cambrian paleogeography of southwestern North America during deposition of the Tapeats Sandstone and Bright Angel Shale. During the early transgression of shallow-marine environments across the Grand Canyon region, sandstone accumulated in high-energy shoreline (beach, barrier bar, shoal) settings, and mudstone formed in more protected (lagoonal, estuarine, high intertidal) and deeper water (offshore marine) settings. Minor fluctuations of local shorelines created complex interbedding of sand and mud. Today, similar settings are found along the Georgia-Carolina coast and on the margins of the North Sea.

Figure 4. Middle Cambrian paleogeography of southwestern North America. Environments were similar to those in Figure 3, but the shoreline had transgressed farther eastward.

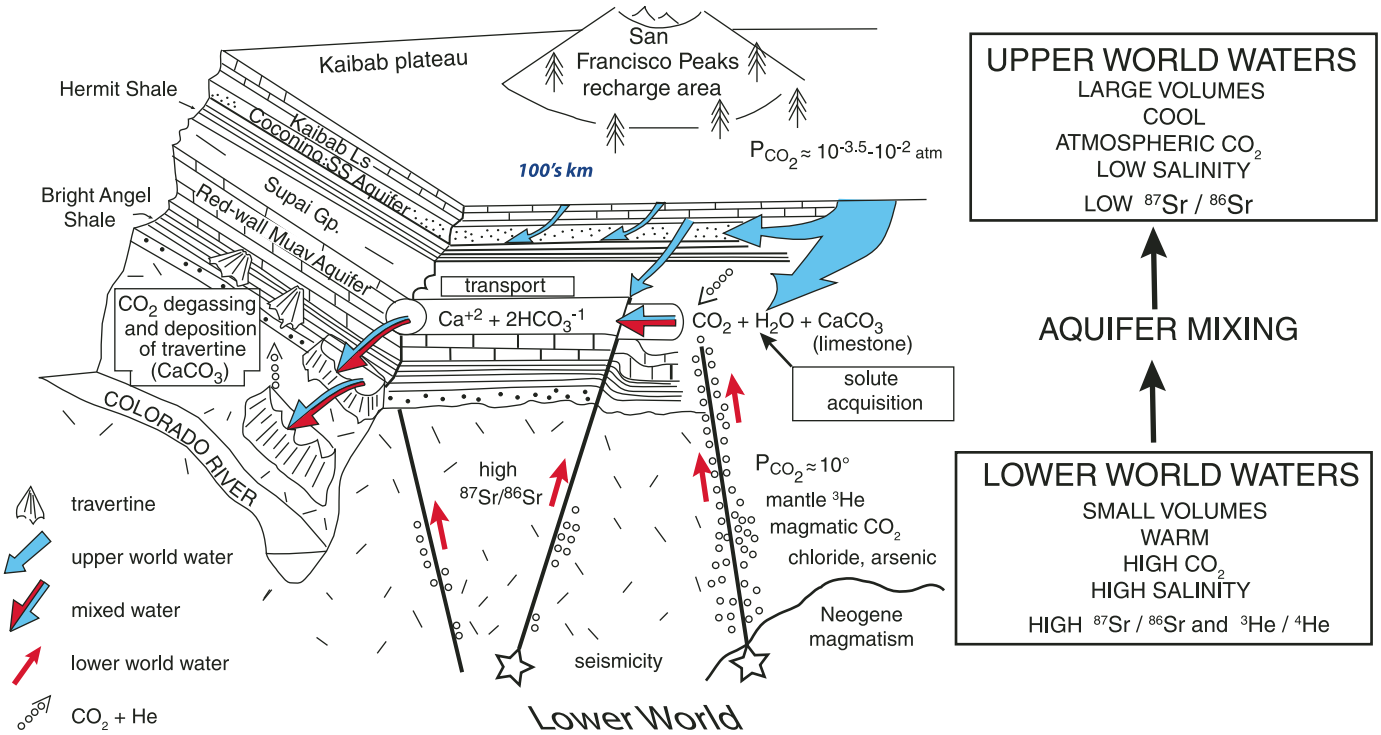

Figure 3. Schematic model for travertine formation on the Colorado Plateau. Blue arrows represent water recharged by precipitation on the Colorado Plateau and infiltrating to the Coconino and Redwall-Muav (R-M) aquifers. Red arrows represent deeply circulated waters and gases rising along faults and mingling with existing groundwaters. Large boxes highlight characteristics of "lower world" and "upper world" waters; small boxes along groundwater flow paths indicate regions of solute acquisition, transport, and deposition. Adapted from Crossey et al. (2006).

and geologic studies, can be used for a better understanding of both the incision of Grand Canyon by the Colorado River and of climatic variability. Pioneering work on dating Grand Canyon travertine deposits was done by Barney Szabo of the U.S. Geological Survey (Szabo, 1990), and we are expanding this work with recent, highly detailed studies of geologically well-constrained units throughout the Grand Canyon region. The new dates have implications for reconstructing climate (e.g., Pentecost, 1995), timing of local hydrologic changes, and past positions of the Colorado River as it has cut Grand Canyon (Pederson and Karlstrom, 2001; Pederson et al., 2002a, 2006; Karlstrom et al., 2007). Carbonates in subsurface cave deposits (speleothems and other karst formations) are the subsurface cousins to travertine deposits; these have also been used to produce excellent paleoclimate and landscape records in the region (e.g., Winograd et al., 1992; Polyak et al., 2008). However, travertines are only beginning to be used to provide datable continental records of changes in the landscape and hydrologic system through time. These deposits thus have rich potential to test evolving concepts of how desert environments reacted to glacial-interglacial climate changes farther north.

Grand Canyon has been deepening and widening throughout the last 6 million years (Ma) (Young and Spamer, 2001; Abbott, 2007). This well-exposed erosional landscape has been responsive to climate changes, but the record is hard to unravel because of the scarcity of datable deposits that can provide information for this erosional history. Travertine deposits in Grand Canyon are especially favorable for providing parts of this record; they are intimately associated with previous (higher level) positions of the Colorado River as it has incised Grand Canyon, and they are highly resistant to erosion. Past positions of the cliff walls can be seen where armored travertine-covered slopes protect past hillslopes in areas where the cliffs have retreated further, and where, in wetter past hydrologic conditions, springs gushed from vents that are now dry. Thus, travertines form a rare link between the paleoclimate record, a record of landscape change, and the modern groundwater system.

This chapter concentrates on key travertine localities in eastern Grand Canyon, mainly from Kwagunt Canyon to the Little Colorado River (Fig. 2). Other interesting occurrences in the Grand Canyon region, such as Elves Chasm, Havasu Canyon, and Travertine Grotto in western Grand Canyon, are also discussed briefly for comparison (Fig. 1). Here we summarize how these deposits form, what we know about when they formed on the basis of uranium-series dating, and how they can be used to understand both paleoclimate and paleolandscape evolution (canyon widening as well as canyon deepening). The research reported here is the result of our past decade of work on the travertines, but there is much more to be learned from these deposits about the Quaternary record in the Southwest.

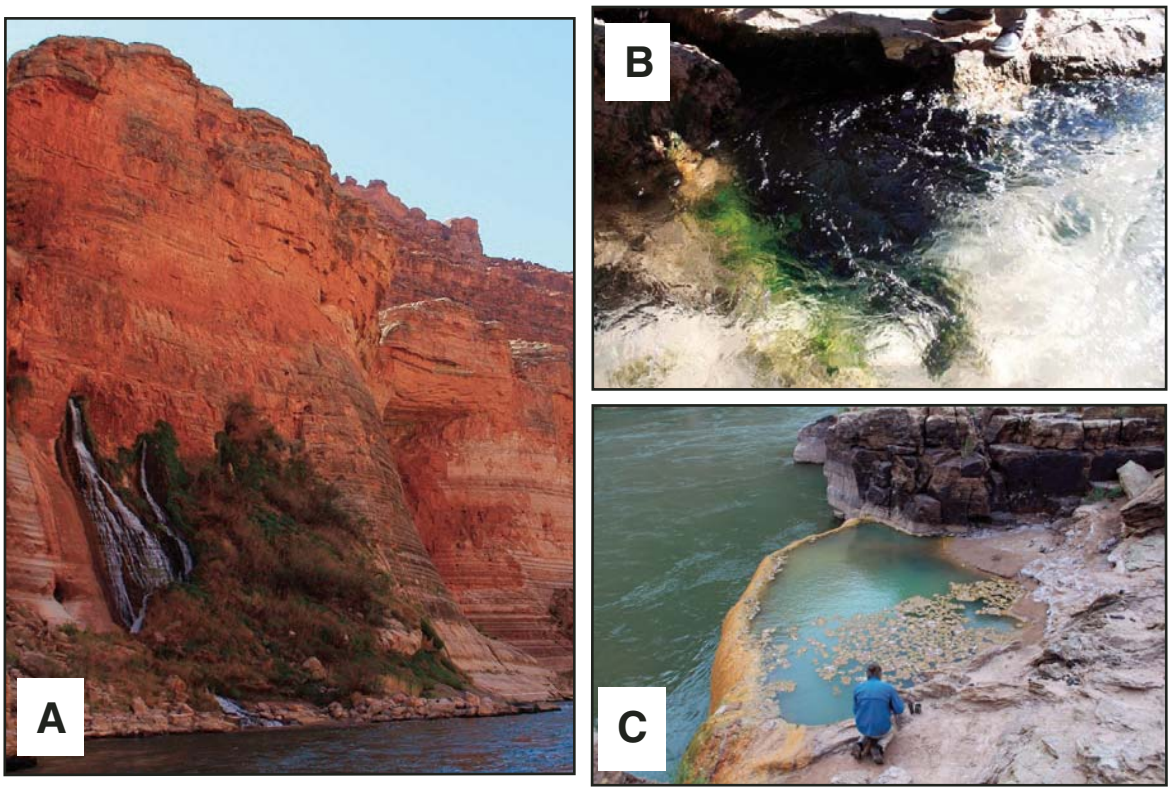

Figure 4. The truly indigenous waters of Grand Canyon are springs that emanate inside Grand Canyon. These springs are sourced in part by deeply circulated fluids we call *lower world waters* that mix with *upper world waters* that include (1) local aquifer waters recharged by precipitation in the Colorado Plateau region, and (2) the Colorado River water, sourced mainly by snowmelt and precipitation runoff originating from the high-elevation Rocky Mountains. (A) Vasey's Paradise at river mile 32 is dominated by upper world waters. (B) Fence Spring along Fence fault at river mile 30.5 discharges directly into the Colorado River and contains appreciable lower world fluids. (C) Pumpkin Spring (river mile 213) juxtaposes lower world spring waters and their associated travertine mound, directly on the banks of the Colorado River (left).

TRAVERTINE-DEPOSITING SPRINGS IN EASTERN GRAND CANYON

The Little Colorado River is the main tributary to the Colorado River in Grand Canyon (confluence at river mile 61). It floods heavily with spring runoff and during the summer monsoons, but its base flow emanates from Blue Spring, several kilometers above the confluence (Fig. 2). This spring has one of the highest discharges in the region (95 ft^3/s; Monroe et al., 2005) and emanates from caverns in the Redwall Limestone with outlets that are just a meter or two above the base of the Little Colorado River bed. Hence, given incision rates of 150–175 m/Ma over the last 380,000 years (380 ka; Karlstrom et al., 2007), these waters must have been groundwaters until as recently as tens of thousands of years ago. Interestingly, many of the more extensive travertine deposits in the eastern Canyon are on the east side of the Colorado River, north of the confluence (Fig. 2). These deposits have uranium-series ages of 380–100 ka, which provide important constraints on rates of river incision (Pederson et al., 2006; Karlstrom et al., 2007) and which also offer insights into hydrologic changes. We hypothesize that groundwater paleoflow through karst systems such as Blue Spring was carrying waters north (flowing north from recharge at high elevation in the San Francisco volcanic field) and that incision of the Little Colorado River to intersect the springs may have resulted in cessation of travertine deposition in the upstream Kwagunt reach ca. 100 ka. By this model, travertine-depositing springs and seeps along the east side of the Colorado River above the Little Colorado confluences became inactive once the Little Colorado River incised down to interrupt north-flowing groundwaters, and these now emerge at Blue Springs and related springs (Fig. 2).

The chemistries of spring waters and spring-fed side streams of Grand Canyon are reported in Crossey et al. (2006) and Monroe et al. (2005). The freshest and coldest springs (the upper world springs) are characterized by low total dissolved solids and contain mainly calcium and bicarbonate exactly in amounts predicted by a model in which waters recharge on the plateaus of the North and South Rims and infiltrate to the Redwall-Muav aquifer