

## New Insights on old rocks: an evolving story of ~two billion years of Earth history at Grand Canyon

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1840 ± 1 m.y. (m.y. = million years): The old time geologists (Noble and Hunter, 1916) were half right about the oldest rocks. The Elves Chasm gneiss is indeed the "basement" for the Granite Gorge Metamorphic Suite, but the Trinity gneiss, at 1730 ± 3 m.y., is not. (Ilg et al., 1996; Hawkins et al., 1996)

1760-1713 m.y.: Precambrian "mountains" (now eroded) were built in this region in a setting similar to the modern Philippians/Japan- type island arc subduction systems (not like the modern Himalayas). Rocks of the Granite Gorge Metamorphic Suite in the Upper Granite Gorge provide a trip to the ~ 20-km-deep roots of an ancient plate collision zone. The Vishnu, Brahma, and Rama schists are metavolcanic rocks from the arcs; the Crystal Creek shear zone is interpreted to be a suture between two colliding island arcs (Karlstrom et al., 2003).

1740 ± 2 m.y.: The Zoroaster granite is one of >23 granite intrusions that were injected into the collision zone before, during, and after the arcs collided. Each has its own age and story to tell (Karlstrom et al., 2003) but we can refer to them as the "Zoroaster plutonic suite".

The Grand Canyon Supergroup is actually much thicker (~ 4000 m) than the Paleozoic strata (~ 2000 m) but, because it is faulted and tilted, you never see it all stacked up together (Timmons et al., 2003).

1255- 1070 m.y.: Unkar Group (~ 2000 m thick) was deposited in fault-controlled basins; Dox Formation (1175-1100 m.y.) was deposited by rivers carrying sediment great distances (from the Texas area) where there was a high mountain range forming due continent-continent collisions related to the assembly of Rodinia supercontinent (Timmons et al., 2005).

~800 to 742 ± 6m.y.: Chuar Group (~ 2000 m thick) records extension within the continent related to rifting apart of Rodinia, ocean chemistry fluctuations in shallow seas are recorded in marine shales that just pre-date the global "snowball Earth" glaciations, and the appearance of diverse microfossils, including the first heterotrophic organisms on Earth (single-celled organisms that get their nourishment from eating other organisms rather than photosynthesis; Karlstrom et al., 2000; Dehler et al., 2001; 2005). The fossil *Chuaria* (Walcott, 1899) is now found worldwide.

Tilting of Grand Canyon Supergroup rocks: Elston and McKee (1882) named this the "Grand Canyon Disturbance" and thought of it as a single event, but we now know that tilting of strata took place both at Unkar and at Chuar time. The Butte fault is a N-S Chuar-age rift fault that helped control subsidence in the Chuar basin (Timmons et al., 2001).

1660 to 520 m.y.: The Great Unconformity (Powell, 1895) is a rock contact that represents several periods dominated by erosion; but we now know it is made up of at least 6 smaller unconformities (time gaps in the rock record). Even in well-exposed sections like Grand Canyon, there is more time missing than is recorded by rocks, so reconstructing the history of the Earth is a global project. Where Tapeats Formation rests on crystalline rocks (where Grand Canyon Supergroup is not preserved), there is ~1.1 billion years of the record missing.

520 to 253 m.y.: Paleozoic deposition of Grand Canyon's horizontal strata (~ 2000 m) took place as seas advanced and retreated many times. Species developed and became extinct as environments changed.

253 to ~70 m.y.: Early Mesozoic deposition was dominated by land environments during the time of the dinosaurs, switching to deposition of sand and mud in an inland seaway. These rocks are preserved in the Grand Staircase north towards Zion, but were mostly stripped away in the Grand Canyon region during the "Great Denudation" (Dutton, 1882).

80 to 50 m.y.: the western U.S. region was uplifted from near sea level to an elevation of 1-2 km during the Laramide orogeny, marking the change to the erosional landscape we see today. Monoclinical folds formed by new compressional movements on Unkar- and Chuar-age faults, for example (Timmons et al., 2001; Kelley et al., 2001).

25 m.y. to present: The Basin and Range province represents the extensional collapse of highlands in the western U.S.; this extension also has affected the edges of the Colorado Plateau region and reactivated older faults like the Hurricane and Toroweap fault of Grand Canyon, which are still active earthquake faults, slipping (west-side-moving-down) at an average rate of 0.07 mm/yr (Pederson et al., 2002).

5.5 m.y. to present: Carving of western Grand Canyon as we know it today began after deposition of the Hualapai Limestone of the Lake Mead area. Basins of the lower Colorado River became integrated with rivers on the Colorado Plateau to carve across Grand Wash cliffs.

719,000 years to present: Basalt flows and lava dams were formed as volcanoes exploded on the edge of Grand Canyon starting 719,000 years ago, damming the river intermittently in "leaky dams" that probably did not create as many or as large lakes as proposed by Hamblin (1994). Major episodes of volcanism built an edifice 700-500,000 years ago centered near Lava Falls, 300,000 years ago near Whitmore, and 200-100,000 years ago on the north rim upstream of Whitmore. One lava flow contains pieces of pottery indicating ongoing (< 1000 years) volcanic activity.

380,000 years to present: Travertines were deposited by CO<sub>2</sub>-rich lower-world springs. These preserve information on past climates, past river levels, and past landscapes (Crossey et al., 2006) and are an indication of leakage of mantle-derived fluids up faults (originating at surprising depths of >80 km) all across the western U.S. (Newell et al., 2005).

Incision rates in the last half million years: New dates on basalt and travertine that rest on elevated past river gravels indicate the Grand Canyon is deepening at a rate of 0.14 mm/yr in the eastern Grand Canyon and at an apparent rate of 0.08 mm/yr in the western Canyon. The upstream incision rate (0.14) is subequal to the downstream rate (0.08) plus the fault slip rate (0.07), indicating fault dampening of apparent incision of western blocks as they are lowered by faulting out of the way of the Colorado River "buzz saw" (Pederson et al., 2001; 2002) and hence an interaction of neotectonics and Canyon incision. Glacially-influenced climate cycles of filling and cutting are superimposed on this long-term bedrock incision (Anders et al., 2005, Pederson et al., 2006). These incision rates are not high enough to carve Grand Canyon in 5.5 m.y. probably indicating both faster rates in the early history of incision and re-use of older paleocanyons that got deepened and linked together into today's Grand Canyon.

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