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Paleozoic Stratigraphy of the Grand Canyon

The Paleozoic Era spans about 250 Myrs of Earth History from 541 Ma to 254 Ma (Figure 1). Within Grand Canyon National Park, there is a fragmented record of this time, which has undergone little to no deformation. These still relatively flat-lying, stratified layers, have been the focus of over 100 years of geologic studies. Much of what we know today began with the work of famed naturalist and geologist, Edwin Mckee (Beus and Middleton, 2003). His work, in addition to those before and after, have led to a greater understanding of sedimentation processes, fossil preservation, the evolution of life, and the drastic changes to Earth's climate during the Paleozoic. This paper seeks to summarize, generally, the Paleozoic strata, the environments in which they were deposited, and the sources from which the sediments were derived.

Tapeats Sandstone (~525 Ma – 515 Ma)

The Tapeats Sandstone is a buff colored, quartz-rich sandstone and conglomerate, deposited unconformably on the Grand Canyon Supergroup and Vishnu metamorphic basement (Middleton and Elliott, 2003). Thickness varies from ~100 m to ~350 m depending on the paleotopography of the basement rocks upon which the sandstone was deposited. The base of the unit contains the highest abundance of conglomerates. Cobbles and pebbles sourced from the underlying basement rocks are common in the basal unit. Grain size and bed thickness thins upwards (Middleton and Elliott, 2003). Common sedimentary structures include planar and trough cross-bedding, which both decrease in thickness up-sequence. Fossils are rare but within the upper part of the sequence, body fossils date to the early Cambrian (Middleton and Elliott, 2003).

As mentioned earlier, the basal unit of the Tapeats was deposited on a Precambrian surface with variable topography. Hereford (1977) determined the depositional environment as tidal flats, beaches, and braided river systems based on the sediment textures, structures, and fossil types preserved. Beach deposits are commonly observed around areas of paleotopographic highs (Hereford, 1977). As sea level rose, the high energy system fluvial system transitioned to shallow marine setting, which is observed in the fining grain size, reduction in bedding thickness, and reduction in magnitude of structures up-sequence.

The source region of the sediments in the Tapeats Sandstone has been refined using detrital zircons. Zircons are very resistant minerals which crystallize primarily in plutonic rocks. This mineral records the timing of crystallization and the chemical composition of the pluton. When a large amount of zircons collect into sediments, they can be traced back to their source using their age and chemical composition. Analysis of over 100 zircon grains from the Tapeats finds that the majority of sediments were sourced locally and a small percent from the south or east in the Grenville orogenic belt (Figure 2; Gehrels et al. 2011).

Bright Angel Formation (515 Ma – 505 Ma)

The Bright Angel Formation is made up of interbedded fine-grained sandstone, siltstone, and shale. This formation is dominated by a greenish shale, made up mainly by illitic clay with chlorite and kaolinite (Middleton and Elliott, 2003). Trace fossils of brachiopods, trilobites, and hyolithes are abundant in certain layers. Within the coarse-grained beds, sedimentary structures are visible, such as planar and trough cross-stratification, and wavy and lenticular bedding. The overall thickness of the formation varies laterally, thinning to the south and completely absent north of Prescott, AZ (Middleton and Elliott, 2003). The fossils recorded in the layers also record the time-transgressive nature of the formation. Fossils in the west are correlated to late Early Cambrian, whereas fossils to the east are Middle Cambrian.

The dominant environment of deposition of the Bright Angel Fm. is interpreted to be a calm continental shelf. Grain size and thin beds are reflective of a low energy marine environment (Middleton and Elliott, 2003). Later workers have also identified subtidal deposits, which were affected by tidal and storm processes (Martin, 1985), distinguished by fining upwards sequences overlying an erosive base with thin small-pebble conglomerates. From west to east beds thin and grain size reduces reflecting the continued transgression of the sea in Cambrian times.

The Bright Angel Shale has a similar sediment source as the underlying Tapeats. The dominant age signal points to a local source in southwestern North America with a slight increase in Mazatzal sediments (Figure 2), reflecting eastward transgression of the shoreline (Gehrels et al. 2011).

Muav Limestone (505 Ma)

The Muav Limestone is a cliff-forming limestone with minor interbeds of dolomite, siltstone, and mudstone. The contact between the Bright Angel Fm. and Muav Limestone is gradational (Middleton and Elliott, 2003). The degree of silty interbeds increases to the east and the limestone bed thickness increases west. Both of these observations are indicative of an eastward-advancing sea. This is further supported by the fossil record which dates the formation of the western Muav as Middle Cambrian and the eastern Muav as late Middle Cambrian (Middleton and Elliott, 2003).

Based on the faunal and textural evidence in the sediments, the Muav limestone is thought to be deposited at subtidal depths. Specifically open-marine fauna, fine-grained limestone and dolostone, and the grading of the formation eastward into the Bright Angel formation support subtidal deposition (Middleton and Elliott, 2003). Wanless (1973, 1975) also reported supratidal and intertidal facies in the western Grand Canyon. The sedimentary textures and structures suggest low-lying offshore islands far offshore where there were prolonged periods of deposition.

The Muav Limestone, which is primarily marine carbonate, does not contain significant detrital zircon and therefore no reconstructions of sediment source was appropriate.

Temple Butte Formation (385 Ma)

The Temple Butte Formation is primarily reddish purple color dolomite and sandy-dolomite composition. It has irregular bedding planes, indicative of channel-fill sediments. Upper layers contain greater amounts of detrital quartz, clay, and hematite. Conodonts fossils suggest a Late Devonian age for the Temple Butte Fm. (Beus, 2003).

Given the amount of dolomitization of limestone and rarity of fossils in the Temple Butte, it has been difficult to place good constraints on the depositional environment. Using the presence of carbonate facies and the few fossils such as crinoids, conodonts, and corals, the western and central Grand Canyon regions of the Temple Butte are inferred to represent nearshore, shallow, subtidal conditions (Beus, 2003). The eastern region of the Temple Butte preserves channel-fill deposits in an intertidal environment. Overall, the formation reflects deeper marine deposition to the east and shallow intertidal regions to the east.

The Temple Butte Formation was sourced from similar regions as the underlying Tapeats and Bright Angel. Significant zircon age peaks from the Paleo- and Mesoproterozoic point to a local source in southwestern North America and a lesser input from the midcontinent granite-rhyolite province in south-central North America (Figure 2; Gehrels et al. 2011).

Redwall Formation (~340 Ma-320 Ma)

The Redwall Limestone is made up of four members: the Whitmore Wash, Thunder Springs, Mooney Falls, and Horseshoe Mesa member (Beus, 2003). The Whitmore Wash member is a fine-grained dolomite in the eastern and central Grand Canyon and a fine-grained limestone in the western Grand Canyon. The limestone grades into dark, cherty beds of the Thunder Springs Member. This member is identified by alternating chert and carbonate layers (Beus, 2003). Similar to the Whitmore Wash, the Thunder Springs Member is primarily dolomite in the east and limestone to the west. Invertebrate fossils are common in the chert layers, such as corals, bryozoans, gastropods, and crinoids. The upper contact forms a low-angle unconformity with the Mooney Falls Member (Beus, 2003), suggesting tectonic activity and erosion prior to deposition. The Mooney Falls Member is a clean medium- to coarse-grained limestone with abundant marine fossils. The uppermost member, the Horseshoe Mesa Member, is a thin-bedded, fine, light-grey limestone and mudstone. Foraminifera fossils indicate a Late Mississippian depositional age (Skipp, 1979).

The four member of the formation represent two major transgression-regression sequences (McKee and Gutschick, 1969). All of the member were deposited in calm, submerged continental shelf-like environment at shallow depths.

Surprise Canyon Formation (~320 Ma-315 Ma)

The Surprise Canyon Formation is primarily observed as isolated, lens-shaped erosional valley and cave-fill deposits. It is made up of clastic and carbonate rocks with thicknesses depending on the depth of the paleovalley in which the layers were deposited.

A wide variety of depositional environments are represented in the formation. In the western and central sections, the basal layer is a conglomerate and sandstone of terrestrial origin, the middle layer is a limestone of marine origin, and the upper layer is marine siltstone and sandy limestone. In the eastern Grand Canyon, the three layers merge into one siliciclastic layer with no limestone. These layers represent a shift from estuary and dendritic stream to shallow marine settings. The fossils preserved in this formation are rich and diverse, including over 60 species of marine invertebrates (Beus, 1995). Evidence from fossil spores, foraminifera, and conodonts among others suggest a Late Mississippian deposition (Beus, 2003).

The Surprise Canyon Formation, which is the first terrestrial-derived sediments recorded in nearly 60 Myrs, contain a significant detrital zircon age peak at 1.3 Ga (Gehrels et al. 2011). This peak marks a shift in the sediment source from the earlier 140 Myrs of deposition. New sources at this time include the active Cordillera to the west, the Franklinian orogeny to the north, the Ouchita uplift to the south, and Appalachian orogeny to the east. The most compelling evidence points to a source in the east, the Appalachian orogeny, and locally from exposed Precambrian basement (Figure 2; Gehrels et al. 2011).

Supai Group (315 Ma-285 Ma)

The Supai Group is made up of four formations: the Watahomigi, Manakacha, Wescogame, and Esplanade Formations. From oldest to youngest, the formations grade from mudstone and siltstone, with minor limestone to predominantly sandstone. This marks a significant shift in depostional patterns in the Grand Canyon, since the last major sandstone deposits occurred in the Cambrian (Blakey, 2003). Trace fossils of burrows, resting marks, feeding marks, and trackways are well-preserved throughout the Supai Group (Blakey, 2003). Additionally, flora fossils are widespread and possibly represent broad floodplains and semi-arid environments.

The sandstone unit within the Supai Group suggest local eolian deposition. Sandstones in the Manakacha, Wescogame, and Esplanade Fms. have wind-ripple laminae and climbing cross-strata. Sedimentation appears to cycle through eolian, low-energy shoreline, and beach depositional environments (Blakey, 2003). Whether this cycle is taking place during transgression, regression, or completely on land is unclear. There is good control, however, that the carbonate layers are primarily of shallow-marine origin and lesser eolian origin.

The Supai Group yields detrital zircon ages similar to the underlying Surprise Canyon Formation. Younger grains are likely reflecting sedimentation sources in the Appalachian region, while older grains were shed from local basement uplifts and the ancestral Rocky Mountains (Figure 2; Gehrels et al. 2011).

Hermit Formation (280 Ma-275 Ma)

The Hermit Formation is poorly exposed and fine-grained throughout much of the Grand Canyon, which resulted in very little work being done on it (Blakey, 2003). However, the research that has been done suggests the Hermit Formation is comprised of easily eroded, reddish brown siltstone, mudstone, and very fine-grained sandstone. Silty sandstone layers preserve some ripple laminations and trough cross-stratification, but many layers are structureless (Blakey, 2003). In most locations, sandstone is most abundant at the base of the formation and mudstone increases in abundance upward. The upper contact is very sharp, with cracks up to 20 ft. deep in-filled with the overlying Coconino Sandstone. Fossils are sparse and sporadic within the Hermit formation but are overall similar to those found in the underlying Supai Group (Blakey, 2003). Evidence from the limited fossils suggest a middle Permian age (Blakey and Knepp, 1988).

The Hermit Formation cycles through layers of silty sandstone and mudstone. The sandstone tends to outcrop as ledges and the mudstone as slopes. The sandstone is interpreted to be shallow stream deposits, whereas the mudstone is interpreted to be overbank deposits. Sediments were likely laid down on found on a flat, broad, arid plain crisscrossed by streams, which were occasionally capable of carrying larger clasts such as pebbles.

Coconino Sandstone (275 Ma-273 Ma)

The Coconino Sandstone crops out as a thick, light-colored cliff overlying the slope-forming Hermit Formation. It is dominated by fine-grained, well sorted quartz and minor feldspar. Large-scale cross-stratification is readily observed in the cliff faces (Blakey and Middleton, 2012). Grain size and sorting indicate a very mature, well-traveled sandstone. The thickness of the Coconino Sandstone is variable, it thins to the north and west and is thickest in the central Grand Canyon (Middleton et al., 2003). Both vertebrate and invertebrate trace fossils are present, including fossil tracks of reptiles, arachnids, and other insects (Middleton et al., 2003).

The Coconino Sandstone represents a large eolian dune field. Geologists compare it to the modern day Sahara Desert (Blakey and Middleton, 2012). This interpretation is supported by the grain size and sorting, the sedimentary structures, and trace fossils. It is clear that this region was arid but likely had some water input, as evidenced by fossil rain drops (Middleton et al., 2003) and the fauna present.

Toroweap Formation (273 Ma- 270 Ma)

The Toroweap Formation was grouped together with the overlying Kaibab Formation for many decades due to similar composition until being Mckee split them into two formations in 1938 (Turner, 2003). The Toroweap forms slopes due to a high mud content in the limestone. The formation also contains minor sandstone layers. Thickness of the formation increases to the northwest and west as well as the purity and fineness of the limestone and mudstone. Common interbeds of gypsum and other evaporates suggest that a shallow sea retreated or was cut off from its source at various times during Toroweap deposition (Turner, 2003).

From the sedimentation style and open-marine flora and fauna, researchers conclude that the Toroweap was deposited in shallow sea, which was deeper and sourced to the west/northwest. This shallow sea would periodically dry up especially to the southeast and result in evaporite deposition (Turner, 2003).

Kaibab Formation (270 Ma)

The Kaibab Formation is very similar in composition to the underlying Toroweap (Turner, 2003). This layer is the uppermost unit in the Grand Canyon, easily seen as a cliff-forming, grey-to-white limestone. The uppermost layers of the Kaibab are not preserved in the Grand Canyon as they are less-resistant to erosion (Hopkins and Thompson, 2003). The thickness of the limestone increases to the northwest, where it reaches up to 500 ft. thick (Hopkins and Thompson 2003). The Kaibab Formation contains abundant marine-fauna such as brachiopods, bryozoans, crinoids, sponges, and corals (Hopkins and Thompson, 2003). Interbedded siliciclastics and carbonates point to a series of transgressions and regressions during the Late Permian deposition of the Kaibab (Hopkins and Thompson, 2003).

The Kaibab Formation is mostly carbonates and minor siliciclastics. These indicate deposition in a calm, shallow sea which occasionally received higher-energy inputs. The thickness of the carbonates increases to the west, suggesting that the siliciclastic source also was to the west, as it was through much of the Permian.

Permian Sediment Sources

The source of sediments from the time of the Hermit Formation until the Kaibab Formation does not significantly change. During deposition of the Hermit Formation however, there is a noticeable shift to younger zircons (270-380 Ma and 480-720 Ma). These younger inputs are likely from the southern Appalachians, where at this time the collision of terranes and docking of western Africa was ongoing (Figure 2; Dallmeyer 1989; Gehrels et al. 2011).

Conclusion

The Grand Canyon Paleozoic sequence dominates the landscape for any visitor. The nearly ~250 Myr record of Earth history found in the park preserves numerous transgressions and regressions. In addition, the flora and fauna fossils in the park give an intimate look into the evolution of life, starting with the Cambrian explosion, through to the end-Permian mass extinction.

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Figures

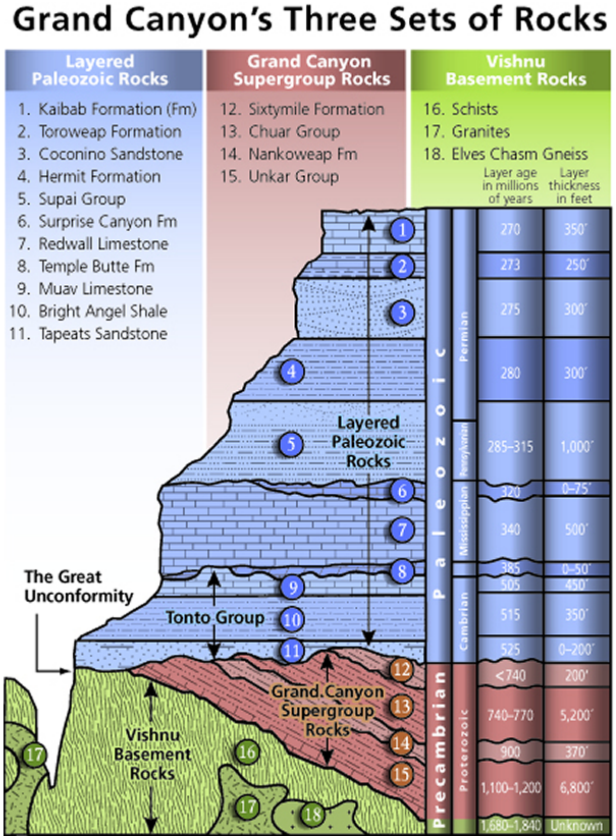

Figure 1: Stratagraphic Column of the Grand Canyon. This report focuses on the segment in blue, the layered Paleozoic rocks. Image modified from the National Park Service

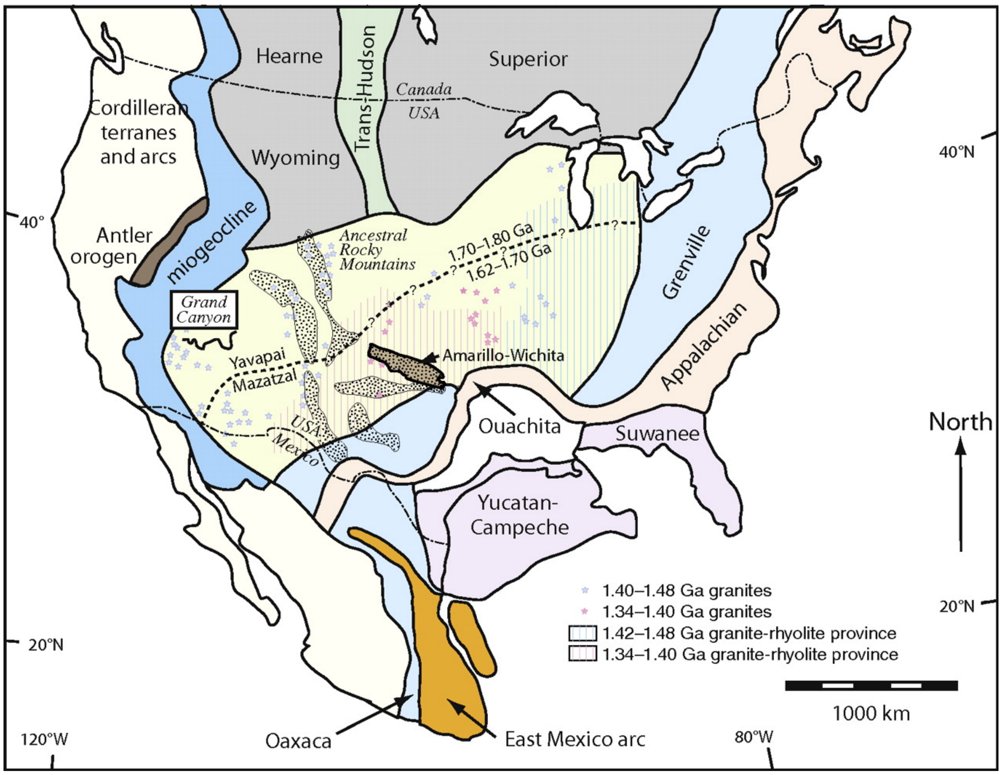

Figure 2: Age Province map of North America. Simplified to show regions of potential sediment sources for the Grand Canyon. Adapted from Gehrels et al. 2011