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Proterozoic history, rocks and tectonics of the Grand Canyon

Introduction

Deep within the Grand Canyon, below the generally horizontal Paleozoic strata and the "Great Unconformity", lie the Proterozoic rocks recording early North American (Laurentian) continent formation, supercontinent breakup, and extended periods of erosion. The Proterozoic rocks of the Grand Canyon are largely broken into two categories: the crystalline basement rocks and the Grand Canyon Supergroup. The crystalline basement rocks formed and metamorphosed as various volcanic arcs collided with the Laurentian continent approximately 1750 to 1650 million years ago (Ma) contributing to the formation and early assembly of the supercontinent Rodinia. As breakup of Rodinia began around 1.25-1100 Ma, the Grand Canyon Supergroup was deposited offshore western Laurentia and deposition continued through rift extension around 700-800 Ma (Karlstrom et al., 2000; Timmons et al., 2001). Approximately 200 million years (Myr) are missing between the top of the Grand Canyon Supergroup and the deposition of the Paleozoic Tonto Group, likely due to continued rifting, uplift and erosion.

For both the crystalline basement and G Grand Canyon Supergroup, we describe the various rock units and then offer some tectonic interpretations providing insight to the history of the North American continent throughout the Proterozoic.

Crystalline Basement

The crystalline basement rocks are exposed in three primary areas of the Grand Canyon: the Upper (river mile 77-118), Middle (river mile 127-137) and Lower (river mile 207-261) Granite Gorges. Crystalline basement rocks date from 1840-1350 Ma.

Elves Chasm Pluton

Dated at 1840 Ma (Hawkins et al., 1996), the Elves Chasm pluton is the oldest rock unit exposed in the southwestern United States (Karlstrom et al., 2003). The Elves Chasm pluton is composed mostly of hornblende-biotite tonalite, quartz diorite, and gneiss (Karlstrom et al., 2003). High Ca/K ratios in the Elves Chasm pluton distinguishes the unit from younger arc plutons (Karlstrom et al., 2003). The Vishnu Schist was deposited on top of the Elves Chasm Pluton.

Granite Gorge Metamorphic Suite

The Granite Gorge Metamorphic Suite consists of metasedimentary and metavolcanic rocks dated between 1750-1730 Ma. These rocks are further broken into the Rama, Brahma and Vishnu schists.

The Rama Schist is a quartzofelspathic schist and gneiss with phenocrysts of quartz and feldspar (Karlstrom et al., 2003). Relict lapilli observed in some units suggest a felsic to intermediate volcanic protolith. The Brahma schist is composed of hornblende-biotite schists and amphibolites, with orthoamphibole-bearing schists interbedded with amphibolites (Karlstrom et al., 2003). The tholeiitic character of the amphibolites suggest an island arc basalt protolith (Clark, 1979). Localities with pillow structures found within the amphibolites indicate that lava flows erupted underwater (Karlstrom et al., 2003), further indicating the Brahma Schist is metamorphosed seafloor basalt. The Rama and Brahma Schists are highly interlayered and are dated at 1742±1 Ma and 1750±2 Ma, respectively (Hawkins et al., 1996).

The Vishnu Schist is composed of quartz-mica schist and pelitic schists interpreted to be metamorphosed sandstones and mudstones eroded off the flanks of oceanic islands (Karlstrom et al., 2003). Rhythmic and graded bedding within the metamorphosed sandstones and mudstones suggest deposition as submarine turbidites (Ilg et al., 1996; Karlstrom et al., 2003).

Intrusive Rocks

The intrusive rocks within the crystalline basement have been variously named the Zoroaster Gneiss (Campbell and Maxson, 1933), Zoroaster Granite (Maxson, 1968), or Zoroaster Plutonic Complex (Babcock et al., 1979). However, new mapping and geochronology efforts (Ilg et al., 1996; Hawkins et al., 1996) show variations in crystallization age and types of intrusions. These intrusive rocks are now broken into four main categories: older basement (Elves Chasm pluton, above), arc-related plutons, syncollisional granites and post-orogenic granites (Karlstrom et al., 2003).

The arc-related plutons range in age from 1740-1710 Ma and include the Zoroaster, Trinity, Ruby, Diamond Creek, Pipe Creek, Horn Creek, Boucher and Crystal plutons. Compositions range from gabbro to granodiorite, and individual plutons have undergone varying degrees of deformation (Karlstrom et al., 2003). These plutons are inferred to have formed from melting above the subducting plate that fed the eruptions of the island arcs (Karlstrom et al., 2003).

The syncollisional granites, dated at 1698-1662 Ma (Hawkins et al., 1996), are generally comprised of granite and pegmatitic granite and include the Cottonwood, Cremation, Sapphire, Garnet Canyon complexes, Travertine Falls, Separation, Surprise and Phantom plutons. These granites are heavily stretched, folded and foliated suggesting intrusion during peak contractional deformation (Karlstrom et al., 2003).

Post-orogenic granites, consisting of the Quartermaster pluton and other related pegmatites, are dated around 1.35 Ga and are the youngest intrusive rocks in the Grand Canyon (Karlstrom et al., 2003). These are coarse-grained friable granites that intrude the Surprise Pluton within the Lower Granite Gorge (Karlstrom et al., 2003). Cross-cutting relationships indicate these rock postdate the peak contractional deformation event around 1660 Ma (Karlstrom et al., 2003).

Tectonic Interpretation of the Crystalline Basement

The Crystalline Basement rocks record the creation of an oceanic island arc complex, accretion of this arc to North America, and exhumation to the surface from the middle crust prior to Grand Canyon Supergroup deposition.

Around 1750 Ma, off the coast of Laurentia, arc-arc and arc-continent subduction created the protoliths of the Rama, Bhrama, and Vishnu Schists. The

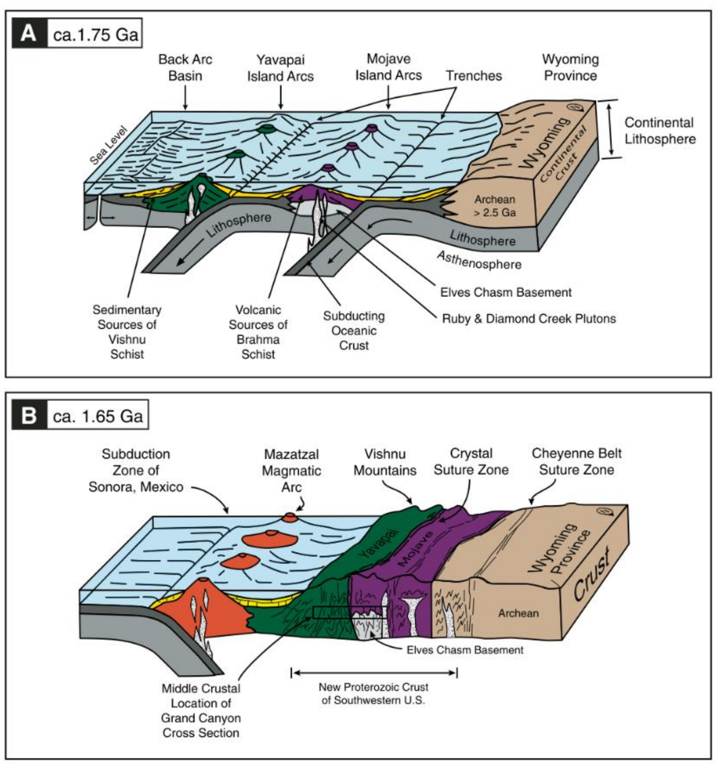

Figure 1: Plate tectonic model for crust formation in the Grand Canyon from 1.75-1.65 Ga (from Karlstrom et al., 2012).

1840 Ma Elves Chasm pluton served as a microcontinent on which the Mojave and Yavapai volcanic arcs were built (Karlstrom et al., 2012). The volcanic protoliths of the Rama and Bhrama Schists erupted synchronously around 1750 Ma, while Vishnu protolithic sediments were deposited on the volcanic flanks. The arc-related plutons also formed on the Mojave and Yavapai volcanic arcs. From 1710 Ma to 1660 Ma, Mojave and Yavapai volcanic arcs accreted to the edge of the North American Continent (figure 1) (Ilg et al., 1996; Karlstrom et al., 2012). The most intense deformation took place during the Yavapai orogeny, creating moderately high mountains similar to the modern day Alps (Karlstrom et al., 2012). This region was tectonically similar to modern day Indonesian region, with active tectonics, complex evolving subduction geometries, and volcanic peaks and thrust sheet well above sea level (Karlstrom et al., 2012). At this point, the Granite Gorge Metamorphic Suite was buried approximately 20-25 km below the surface (Karlstrom et al., 2003). Over the next 300 Myr until about 1300 Ma, exhumation and erosion brought these rocks to the surface at which point deposition of the Grand Canyon Supergroup would begin.

Grand Canyon Supergroup

The Grand Canyon Supergroup, accumulated between ~1250 - 742 Ma and is composed of gently tilted sedimentary and igneous rocks located in various localities throughout the Grand Canyon, with the largest outcrop around the "big bend" of the eastern Grand Canyon (approximately river miles 65-80). These rocks record a portion of the approximately 1,200 Myr time gap of the Great Unconformity. From oldest to youngest, the Grand Canyon Supergroup is broken into the Unkar Group, Nankoweap Formation, Chuar Group and Sixtymile Formation (figure 2). Today, the supergroup is preserved only in downdropped fault blocks.

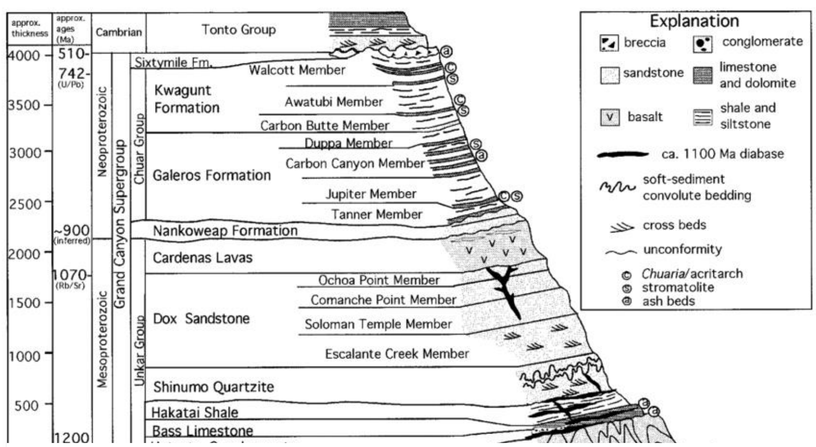

Figure 2: Stratigraphic column of the Grand Canyon Supergroup with approximate thicknesses and ages (from Timmons et al., 2001).

<u>Unkar Group</u>

The Unkar Group rests noncomformably on the crystalline basement rocks at the base of the Grand Canyon Supergroup. The 1770 m thick unit is broken into five formations: Bass Limestone, Hakatai Shale, Shinumo Quartzite, Dox Formation, and capped by the Cardenas lavas. Together, these units record a period of major west-to-east transgression of the Unkar Sea (Hendricks and Stevenson, 2003). The Unkar Group was deposited between ~1250-1070 Ma.

The Bass Limestone is primarily dolomite with smaller amounts of arkose, sandy dolomite with intercalated shale and argillite, breccias and conglomerates (Hendricks and Stevenson, 2003). Sedimentary structures include ripple marks, desiccation cracks, interformational breccias/conglomerates, and graded beds, suggesting a low-energy intertidal to supertidal environment depositional environment (Hendricks and Stevenson, 2003). Dated zircons from an ash layer within the Bass give an age of 1254.8±1.6 Ma (Timmons et al., 2005) providing an approximate age for the start of deposition of the Unkar Group. Conformably overlying the Bass Limestone is the iron-rich and colorful Hakatai Shale. The Hakatai Shale is composed of highly fractured argillaceous mudstones and shales overlain by a medium-grained quartz sandstone (Hendricks and Stevenson, 2003). Deposition of the Hakatai is inferred to be in a low-energy mudflat environment to a higher-energy, shallow marine environment based on mudcracks, ripple marks, and tabular-planar cross bedding (Hendricks and Stevenson, 2003). The contact between the Hakatai Shale and overlying Shinumo Quartzite is marked by an approximately 75 Myr disconformity (Hendricks and Stevenson, 2003; Timmons et al., 2005). The Shinumo Quartzite consists of a series of massive, cliff-forming sandstones and quartzites with abundant cross beds, mudcracks and clay galls (Hendricks and Stevenson, 2003). These structures suggest near-shore, shallow marine to fluvial and deltaic environment (Daneker, 1974; Hendricks and Stevenson, 2003). Conformably overlying the Shimuno Quartzite is the Dox Formation; the thickest unit of the Unkar Group. The Dox Formation is made up of sandstones, mudstones, siltstones, and shaley siltstones, indicating a transition in depositional environments from subaqueous delta, to floodplain, to tidal flat (Hendricks and Stevenson, 2003).

The Cardenas Lavas are comprised of a series of basalt and basaltic andesite flows with sandstone interbeds (Hendricks and Stevenson, 2003). The contact between the Cardenas and the underlying Dox is conformable with a thin basaltic flow through the upper portion of the Dox Formation and exhibits soft sediment deformation (Hendricks and Stevenson, 2003). Much attention has been given to the Cardenas Lavas because of the units geochronologic importance. Rb/Sr dating from McKee and Nobel (1976) and Elston and McKee (1982) dated the Cardenas at 1090±70 Ma and 1070±70 Ma, respectively, providing estimates on the completion of Unkar deposition. The entire Unkar Group, below the Cardenas, is intruded by diabase sills and dikes, however it remains unclear if these intrusions are related to the Cardenas Lavas (Hendricks and Stevenson, 2003).

Nankoweap Formation

Unconformably resting between the Cardenas Lavas (lower contact) and the Chuar Group (upper contact) is the Nankoweap Formation. The Nankoweap is comprised mostly of red-brown and tan sandstones with subordinate siltstones and mudcracks (Ford and Dehler, 2003). The lower portion contains lenses of volcanic detritus originating in the Cardenas (Ford and Dehler, 2003) and is interpreted to be deposited in the quiet shallow water of a structurally controlled lake (Elston and Scott, 1976). The upper portion contains many sedimentary structures within the sandstone including cross-beds, ripplemarks, mudcracks, soft-sediment deformation, and rare salt pseudomorphs (Ford and Dehler, 2003), interpreted to be deposited in a low-energy, shallow water, marine or lake environment (Elston and Scott, 1976).

Chuar Group

The Chuar Group is subdivided into two formations: the Galeros and Kwagunt Formations. These formations are further broken into the Tanner, Jupiter,Carbon Canyon and Duppa Members within the Galeros and the Carbon Butte, Awatubi and Walcott Members within the Kwagunt. The Chuar is approximately 1500 m thick, with thickness variations due to lateral facies changes and changes in accommodation space across the Chuar syncline (Ford and Dehler, 2003). Overall, the Chuar Group shows a pattern of repeating carbonate-shale cycles (Ford and Dehler, 2003) indicating a deep marine environment. Age of the Chuar is constrained between ~850-742 Ma. The basal Tanner Member is dated at 800 Ma from U-Pb analyses of diagenetic monazite (Williams et al., 2003). A small ash layer near the top of the Chuar Group yields a U-Pb zircon age of 742±6 (Karlstrom et al., 2000), recording the approximate completion of deposition within the Chuar Group.

The Galeros Formation is fairly uniform throughout, consisting of coarsely crystalline dolomite within the Tanner Member and mostly alternating limestones and shales throughout the remaining members (Ford and Dehler, 2003). At the top of the Galeros, lies the Duppa Member, consisting of mostly shale with layers of red mudstones, thinly bedded sandstones, and siltstones near the top (Ford and Dehler, 2003). The contact with the overlying Kwagunt Formation is gradational (Ford and Dehler, 2003). At the base of the Kwagunt is the Carbon Butte Member. This member contains the only thick (~76 m) sandstone deposit within the Chuar formation, with interbedded shales and siltstones (Ford and Dehler, 2003). The Awatubi Member consists of a stromatolitic carbonate unit at its base, overlain by shales and mudstones (Ford and Dehler, 2003). The Walcott Member is more diverse than the layers below it, containing a flaky dolomite at its base, black shales, silicified oolite beds and three distinctive carbonate beds (Ford and Dehler, 2003).

Sixtymile Formation

The 60 m thick Sixtymile Formation is mostly composed of breccias and sandstones with subordinate siltstones and mudstones (Ford and Dehler, 2003). Above the Sixtymile Formation is the Great Unconformity and the Cambrian Tapeats Sandstone. A significant change in depositional environment, from the Unkar and Chuar Groups, is observed in the Sixtymile Formation recording sea-level regression. Near the base of the formation, large boulders are interpreted as landslide blocks from the Chuar syncline (Ford and Dehler, 2003). Other coarse clastic sediments (debris-flow deposits) likely indicate a transition to a largely terrestrial environment from the mostly marine environments observed throughout the Unkar and Chuar Groups. The middle and top of the Sixtymile Formation transition between thinly bedded siltstones and sandstones, likely deposited in a low-energy fluvial environment (Elston, 1979). Locally derived breccias in the middle portion also suggest debris-flow deposition (Elston, 1979). The Sixtymile Formation was deposited 742 Ma following deposition of the ash layer at the top of the Kwagunt Formation (Timmons et al., 2001).

Tectonic Interpretation of the Grand Canyon Supergroup

Accreting terranes around the North American continent from ~1300-1000 Ma eventually resulted in the formation of supercontinent Rodinia (Timmons et al., 2005). Within the Unkar Group, are a number of contractional and extensional faults (Butte, Phantom, Crystal, Muav, and 137 Mile faults) that overlap in time with the collision of the Grenville terrane to the south of present-day Grand Canyon (Timmons et al., 2003). The accreting Grenville terrane produced NW-directed shortening, which resulted in intracratonic basin formation (NE-SW extension) in the area of the Grand Canyon (Timmons et al., 2005). Contraction occurred during early Unkar deposition, while extension occurred during the late Unkar and early Nankoweap deposition (Timmons et al., 2005). Deposition in these intracratonic basins is recorded by the Unkar Group between ~1250-1070 Ma. Extension within the Unkar is kinematically linked to Grenville orogenesis. Magma upwelling occurred near the end of Unkar deposition, associated with the Cardenas Lavas.

The Chuar Group also records extension, however in contrast to the Unkar, this E-W extension is interpreted to be linked to rifting of the Western Cordillera and continuing breakup of Rodinia around 800 Ma (Timmons et al., 2001; Timmons et al., 2005; Karlstrom et al., 2012; Dehler et al., 2012). Deposition of the Chuar Group and Sixtymile Formation show thickness variations consistent with synchronous deposition, fault movement, and synclinal development along the Butte Fault system and associated Chuar Syncline (Timmons et al., 2003).

Synthesis

The Proterozoic rocks of the Grand Canyon record a complex history of the early North American continent (figure 3). Metavolcanics and metasedimentary rocks of the Granite Gorge Metamorphic Suite record a period of island-arc formation off the coast of Laurentia, and subsequent continental collision and accretion between 1750 and 1650 Ma. Exhumation of the Granite Gorge Metamorphic Suite from 1650-1300 Ma occurred during the formation of supercontinent Rodinia, as rocks were brought to the surface from depths of ~20 km. The tilted strata of the Grand Canyon Supergroup, preserved today in downdropped fault blocks, began deposition around 1250 Ma during the final stages of Rodinia formation. This first pulse of extension in the Grand Canyon is associated with the Grenville orogeny and early Grand Canyon Supergroup. Deposition of the remaining Grand Canyon Supergroup occurred during a second pulse of extension around 800 Ma, associated with rift extension and break up of supercontinent Rodinia. After deposition of the Grand Canyon Supergroup, continued rifting, uplift and erosion occurred for the next ~200 Myr, until deposition of the Tapeats Sandstone around 530 Ma. Two unconformities exist directly below the Tapeats Sandstone. The first being where the Tapeats rests on the Grand Canyon Supergroup and the second being the Great Unconformity, spanning approximately 1.2 billion years, where the Tapeats Sandstone rests on the Granite Gorge Metamorphic Suite. The Grand Canyon Supergroup illuminates ~550 million years of this 1.2 billion year puzzle. Deposition of the iconic, flat-lying, Paleozoic sediments buried the Proterozoic rocks, until very recent incision (~6 Ma) exposed them at the bottom of the modern day Grand Canyon.

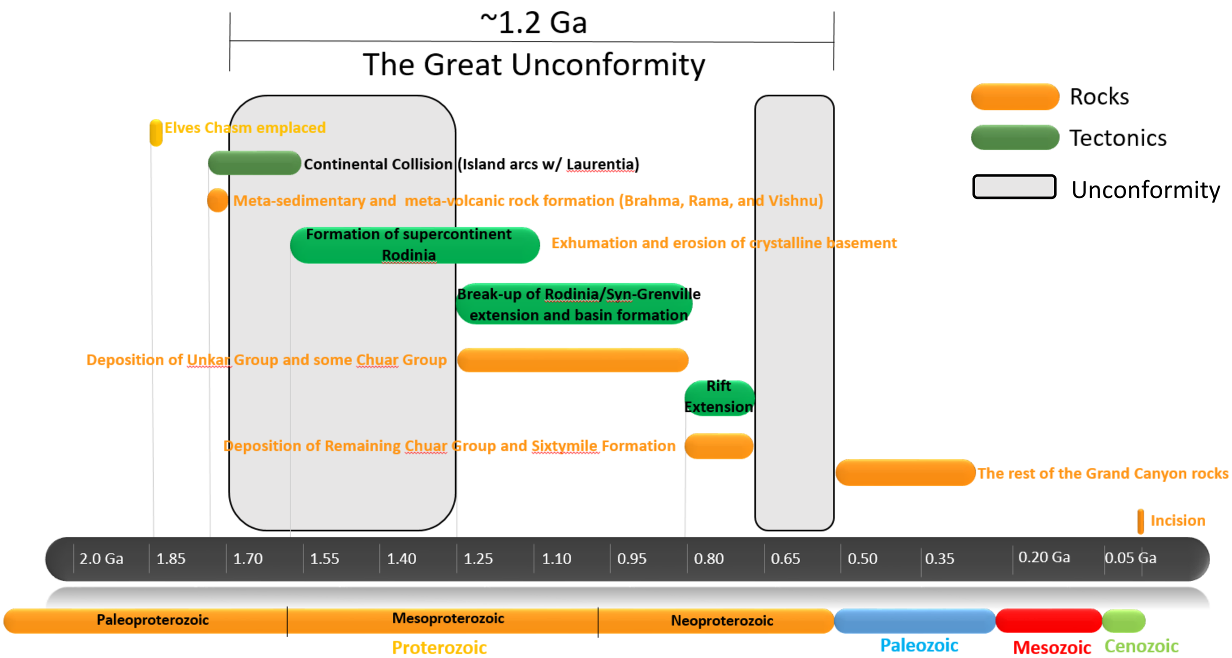

Figure 3: Approximate time line of events in the Grand Canyon.

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