PROTEROZOIC ROCKS, TECTONICS AND STRUCTURES IN THE GRAND CANYON

Rocks exposed in the Grand Canyon below the '*Great Unconformity'* record a protracted period of continental collision, subsequent extension (rifting) and erosion. Crystalline basement rocks underlying sedimentary and volcanic strata of the Grand Canyon Supergroup are highly deformed and metamorphosed, owing to Meso-Neoproterozoic assembly of the supercontinent Rodinia. Breakup of Rodinia initiated approximately 1.1 billion years ago (Ga) and was well underway by approximately 800 million years ago (Ma). During disaggregation of Rodinia, parts of Australia and/or Antarctica (Moores, 1991; Karlstrom et al., 2012) were rifted from the western (modern coordinates) margin of Laurentia (North America). Sedimentation offshore of western Laurentia at this time is preserved as the Grand Canyon Supergroup. After an ~250 myr period of erosion, probably related to continued rifting, deposition of the Tonto group initiated in the early Cambrian and the Great Unconformity was formed.

Continental collision: 1.75-1.68 Ga

Paleoproterzoic basement rocks exposed deep in the Grand Canyon are referred to as the Granite Gorge metamorphic suite (Ilg et al., 1996) and consist of meta-volcanic, meta-sediment, and meta-plutonic rocks. Well-preserved primary sedimentary and volcanic features in the metamorphic rocks strongly suggest that these rocks record deposition in a marine environment adjacent to an island arc complex. Meta-volcanic units include the Brahma and Rama schists. The Vishnu schist is the meta-sedimentary unit. Arc- and collision-relate magmatism producing the meta-plutonic rocks occurred episodically from ~1.8-1.66 Ga.

<u>Elves Chasm Pluton:</u> The Elves Chasm pluton is dated at 1840±1 Ma (Hawkins et al., 1996). The margins of the Elves Chasm pluton are generally shear zones with younger metamorphic and igneous rocks. The Elves Chasm pluton appears to be the oldest rock unit exposed in southwestern North America.

<u>Brahma Schist:</u> The Brahma schist consists of amphibolite, amphibole-plagioclase schists, and amphibole gneiss. Due to the abundant mafic minerals in the Brahma schist, it is interpreted to be the metamorphosed mafic volcanic rocks (Ilg et al., 1996). Relict pillow structures in the Brahma schist are found throughout the Grand Canyon (Campbell and Maxson, 1933), supporting the interpretation that the Brahma schist is metamorphosed seafloor basalts. Felsic lenses in the Brahma schist yield U/Pb zircon ages of 1750±2 Ma (Hawkins et al., 1996).

<u>Rama Schist:</u> The Rama schist is comprised of quartzofeldspathic schist that locally grades to gneiss. In some lower-grade locales, these schists preserve euhedral plagioclase and quartz phenocrysts, suggestive of a felsic volcanic protolith. In higher-grade locales, the Rama schist contains leucocratic layers interpreted to reflect partial melting (Ilg et al., 1996). A gneissic section of the Rama schist yields a U/Pb zircon age of 1742±1 Ma (Hawkins et al., 1996).

<u>Vishnu Schist:</u> The Vishnu schist consists of pelitic schists, and quartz-mica schists. These rocks are interpreted to be metamorphosed equivalents of lithic-rich marine sedimentary strata (Ilg et al., 1996). Lower grade exposures of the Vishnu schist exhibit relict rhythmically banded and graded compositional layering interpreted as sedimentary bedding (Walcott, 1894; Clark, 1976),

possibly turbidite deposits (Ilg et al., 1996). Relict sedimentary bedding in the Vishnu schist appears to be conformable with the Brahma schist.

1.74-1.71 Ga Arc-Related Plutons: This suite of rocks includes the Zoroaster, Pipe Creek, Horn Creek, Trinity, Boucher, Crystal, and Ruby plutons, which range in composition from gabbro to granodiorite (Noble and Hunter, 1916; Ilg et al., 1996). Generally, these plutonic rocks intrude the Brahma, Rama, and Vishnu schists, but local shear zones are also common between these units. Sr isotope ratios, major element, and trace element data suggest these plutons represent the plumbing system to an island arc (Clark, 1976; Babcock, 1990).

1.70-1.66 Ga Collisional Intrusive Rocks: These felsic intrusive pegmatitic rocks occur in smaller volumes than the older suite of plutonic rocks. These rocks generally intrude along, but locally cross-cut, the metamorphic foliation (Ilg et al., 1996). U/Pb zircon ages for this suite of rocks range from 1698-1662 Ma (Hawkins et al., 1996).

Tectonic Interpretations: The tectonic events recorded by this suite of Paleoproterozoic rocks include 1) development of an oceanic arc complex, 2) closure of an ocean basin as this arc complex was accreted to North America, and 3) erosion to mid-crustal level prior to deposition of the Grand Canyon Supergroup.

The Brahma, Rama, and Vishnu schists and the 1.74-1.71 Ga plutonic suite comprised a Paleoproterozoic island arc complex. The volcanic protoliths for the Brahma and Rama schists appear to have been deposited in a submarine environment. Radiometric U/Pb ages and compositional interlayering between the Brahma and Rama schists indicate that the volcanic protoliths were erupted synchronously ca. 1.75-1.74 Ga. Coeval with deposition of these volcanic strata, the 1.74-1.71 Ga plutonic suite intruded at lower levels of this arc complex. Sediments shed from the volcanic islands were deposited offshore along with volcanic strata. The metamorphic equivalent of these sedimentary strata is the Vishnu schist. This volcanic arc appears to have been built on top of the ~1.84 Ga Elves Chasm pluton.

This arc complex underwent a period of NW-SE convergent deformation initiating as early as 1.71 Ga and continuing until ca. 1.66 Ga (Ilg et al., 1996). During this time, felsic dikes, sills, and stocks intruded along and across shear zones. Convergence recorded in the shear zones and high temperature flux suggest that this deformation is related to collision this island arc with North America (Karlstrom et al., 2012). Following this collisional event, the granite Gorge metamorphic suite appears to have remained deep in the crust until these rocks were exhumed to the surface by ~1.3 Ga (Elston, 1989).

Syn-Grenville extension: 1.25-0.8 Ga

The base of the Grand Canyon Supergroup is the Unkar Group, which consists of ~1800 m of sedimentary and volcanic strata deposited nonconformably on top of the Granite gorge metamorphic suite (Figure 1). The Unkar Group is divided into five formations: Bass limestone, Hakatai shale, Shinumo sandstone, Dox sandstone, and Cardenas lavas (Hendricks and Stevenson, 1990). While the contact between the Hakatai shale and Shinumo sandstone is an ~75 Myr disconformity, the section appears to be conformable above the Shinumo sandstone (Daneker 1975; Timmons et al., 2005). Strata of the Unkar Group typically dip ~10-30ºNE and are offset by ~60ºSW dipping normal faults (Sears, 1990). Sedimentary facies shifts between limestone, shale, and sandstone indicates significant variation in sea level during the time these strata were deposited. Vesicles and weathered flow tops in the Cardenas lavas indicate that these flows were erupted subaerially during a time of relatively low sea level (Elston and Scott, 1976).

Angular unconformities and mutually cross-cutting relationships between ~1.1 Ga mafic dikes and NW-striking normal faults in the Unkar Group indicate that these strata were deposited synchronously with NE-SW directed extension (Timmons et al., 2001). A radiometric U/Pb zircon age from an ash layer in the Bass limestone gives an age of 1254.8 ± 1.6 Ma (Timmons et al., 2005). The Cardenas lavas yield a Rb/Sr whole-rock age of 1070 ±70 Ma (Elston and Mckee, 1982). Together, these dates indicate that the Unkar group was deposited between ~1.25-1.0 Ga, consistent with the age of extension determined from intrusive dikes.

Tectonic Interpretations: The Mesoproterozoic (1.6-1.0 Ga) was a time of continental accretion resulting in development of a super-continent known as Rodinia (Li et al., 2008). The geologic record of Rodinia in North America is a NW-SE trending belt of convergent deformation dated ca. 1.25-0.98 Ga known as the Grenville orogeny (Tollo et al., 2004). Strata of the Unkar Group overlap in time with the Grenville orogeny, but differ in structural style. One interpretation of the NE-SW extension recorded in the Unkar Group is that it represents initial intra-cratonic rifting in the waning stages of the Grenville orogeny (Timmons et al., 2001). This extension may have been accompanied by mantle upwelling (Hoffman, 1989), as evidenced by 1.1 Ga magmatism (Cardenas lavas and associated intrusions). There may be a kinematic link between this NE-SW directed extension and NW-SE oriented Grenville contraction (Lambeck, 1983; DeRito et al., 1983; Karlstrom and Humphreys, 1998).

Despite an ~3-5º unconformity between the Cardenas lavas and overlying Nankoweap Formation, NW-striking normal faults continue in the lower Nankoweap formation (Gebel, 1978; Elston, 1979), suggesting NE-SW extension continued until an intraformational unconformity between the lower and upper Nankoweap Formation. Detrital U/Pb zircon ages from the Nankoweap Formation suggest NE-SW directed extension lasted until ca. 770-800 Ma (Dehler et al., 2012). These detrital U/Pb zircon data further imply that the unconformity between the Unkar Group and Nankoweap Formation represents a 300 Myr depositional hiatus.

Rift extension: 800-700 Ma

Above the Cardenas lavas, the Nankoweap sandstone, Galeros, and Kwagunt formations comprise the ~2500 m thick Chuar Group. Abundant shale beds in the Galeros and Kwagunt formations indicate a relatively deep marine environment at this time. Thin carbonate beds are intercalated with the deep marine shale, suggesting that sea level periodically lowered for short intervals before rising to resume deep marine deposition. An angular unconformity separates the upper Nankoweap Formation from the Chuar Group (Timmons et al., 2001). Detrital U/Pb zircon ages from the Nankoweap give a maximum depositional age of 800-770 Ma (Dehler et al., 2012), while deposition of the overlying Galeros Formation is suspected to have started ca. 770 Ma (Timmons et al., 2005). These age relationships suggest that relatively little time is missing across this unconformity.

Above the Tanner member of the Galeros formation, a series of angular unconformities are present in the Chuar Group (Timmons et al., 2001). These unconformities are interpreted to record development of the Chuar syncline, a growth syncline parallel to and within the hanging wall of the Butte fault. The Butte fault is a N-striking normal fault suspected to be the key structure causing the tilt of the Chuar Group (Timmons et al., 2001; 2005). Strata in the Chuar syncline thicken in the core of the fold and thin toward the Butte fault, indicating syn-depositional development of the syncline (Timmons et al., 2001). Tighter folding in stratigraphically lower (older) beds than in higher (younger) beds further supports this interpretation. Strata of the Chuar Group above the Tanner member of the Galeros formation are only found in the hanging wall of the Butte fault, suggesting that topography related to slip on the fault served as a buttress against which strata in the Chuar syncline were deposited. Paleozoic strata above the Great Unconformity are not deformed by this syncline, indicating that the folding occurred in the Proterozoic (Timmons et al., 2001).

The Sixtymile Formation overlies the Chuar Group across an angular unconformity. The original thickness of the Sixtymile Formation is unknown because the top is truncated by the Middle Cambrian Tapeats sandstone, however, up to 60 m is preserved below the Great Unconformity. An ash layer at the top of the underlying Kwagunt Formation places the initial deposition of the Sixtymile formation at ca. 742 Ma (Timmons et al., 2001). The lower Sixtymile Formation consists of slumped dolomite blocks and associated soft sediment deformation local to the Butte fault. The middle siltstone member displays some soft sediment deformation and contains siliceous horizons. The upper member consists of channel fill sandstone and conglomerate that scour the top of the middle member. Transition from deep marine depositional facies in the middle Sixtymile Formation to shallow marine or terrestrial facies in the upper part of the formation is suggestive of a drop in local (or global) sea level at this time.

<u>Tectonic Interpretations:</u> Normal slip on the Butte fault is interpreted to reflect regional E-W extension at the western margin of North America during the Neoproterozoic (Timmons et al., 2001; Karlstrom et al., 2012). The exact timing of transition between earlier NE-SW extension and later E-W extension is not known. However, since NE-SW syn-Grenville extension is interpreted to have persisted during deposition of the lower Nankoweap Formation (Gebel, 1978; Elston, 1979). The transition likely occurred after 800 Ma (Dehler et al., 2012), or more likely closer to 780-680 Ma (Whitmeyer and Karlstrom, 2007). Fault systems that facilitated E-W extension in western North America likely represent the initial rifting process. Development of oceanic crust outboard (west) of the continental normal fault system would have transferred extension to a mid-ocean ridge system separating western continents from North America at this time. No record of this oceanic crust is preserved in the Grand Canyon Supergroup.

Regional Correlations

Strata of the Grand Canyon Supergroup overlap in time with a number of other sedimentary sequences in North America. Linking the Unkar and Chuar groups to coeval sedimentary sequences in western North America can reveal how these basins formed and yield a more complete record of the tectonic processes occurring in western North America in the Neoproterozoic.

<u>Unkar Group:</u> The Unkar Group is interpreted to be deposited in an intracratonic basin near the center of Rodinia. The Apache Group and Troy quartzite of central Arizona are correlated with the Dox Formation based on age, lithology and paleomagnetic data (Elston 1986). More regionally, Mesoproterozoic sequences including the Unita Mountain Group, Sibley Series, and Keweenawan Supergroup are also correlated with the Unkar Group (Bues and Morales, 2003; Timmons et al., 2005). An early model for the Meso-Neoproterozoic sedimentary sequences in

North America was deposition into aulacogens (failed rift arms) that formed during the waning stages of the Grenville orogeny (e.g., Harrison et al., 1974). Although more recent data suggest this is an oversimplification (see Timmons et al., 2001). While the Unkar Group is not interpreted to have been deposited into an aulacogen, synchronous development of the Keweenawan Group in the mid-continental rift system further supports the interpretation that incipient breakup of the Grenville orogen created basins across Rodinia.

Chuar Group: Although there appear to be no obviously correlative strata near the Grand Canyon, the Beck Springs dolomite in the Death Valley area appears to have similar features to the Chuar Group. The Hector formation and Little Dal Group in northern Canada may also correlate with the Chuar Group based on the ages of cross-cutting intrusive rocks and microplankton fossils (Ford and Breed, 1973; Hoffman and Aitken, 1979; Link et al., 1993). These correlations and the tectonic setting of the Chuar Group suggest that E-W extension occurred along the entire western margin of North America during the Neoproterozoic.

Miogeocline development and the Cambrian explosion of life

A transition from deep marine depositional facies to shallow marine or terrestrial facies is the last record available in the Grand Canyon Supergroup. Any stratigraphy above the upper Sixtymile Formation has been eroded, possibly related to the drop in sea level recorded in the Sixtymile Formation. The ~250 Myr depositional hiatus represented by the Great Unconformity leaves many questions about what happened during this time. Presumably E-W rifting persisted for some time, local basins likely formed and were eroded away, and sediment was shed from the continent to depocenters offshore. However, one thing is certain: by the early Cambrian, western North America was a passive margin, as recorded in the Tonto Group and other Paleozoic strata. During the depositional hiatus represented by the Great Unconformity, the earth's biosphere underwent a major transformation. The Cambrian explosion of life is documented worldwide as a major change in biodiversity (Marshall, 2006). This change occurs in the stratigraphic record across the Great Unconformity. Aside from stromatolite-bearing horizons (e.g. Timmons et al., 2005), the sedimentary strata below the unconformity show little evidence of life in the Proterozoic seas, while Paleozoic rocks above the unconformity contain abundant trace fossils, body fossils, and other indicators of a biological diversity in the Cambrian seas.

Summary:

Igneous, metamorphic, and sedimentary rocks comprise the Proterozoic section below the Great Unconformity in the Grand Canyon. These rocks record a history of volcanism, continental collision, supercontinent formation, continental rifting and passive margin formation. Several angular unconformities throughout the stratigraphy of the Unkar and Chuar Groups represent sedimentation synchronous with these tectonic processes. A depositional hiatus at the end of the Proterozoic time was disrupted by renewed sedimentation in the Cambrian. Deposition of Phanerozoic strata above the Great Unconformity progressively buried the Proterozoic geology until incision of the modern Grand Canyon exposed this complex and enigmatic story.

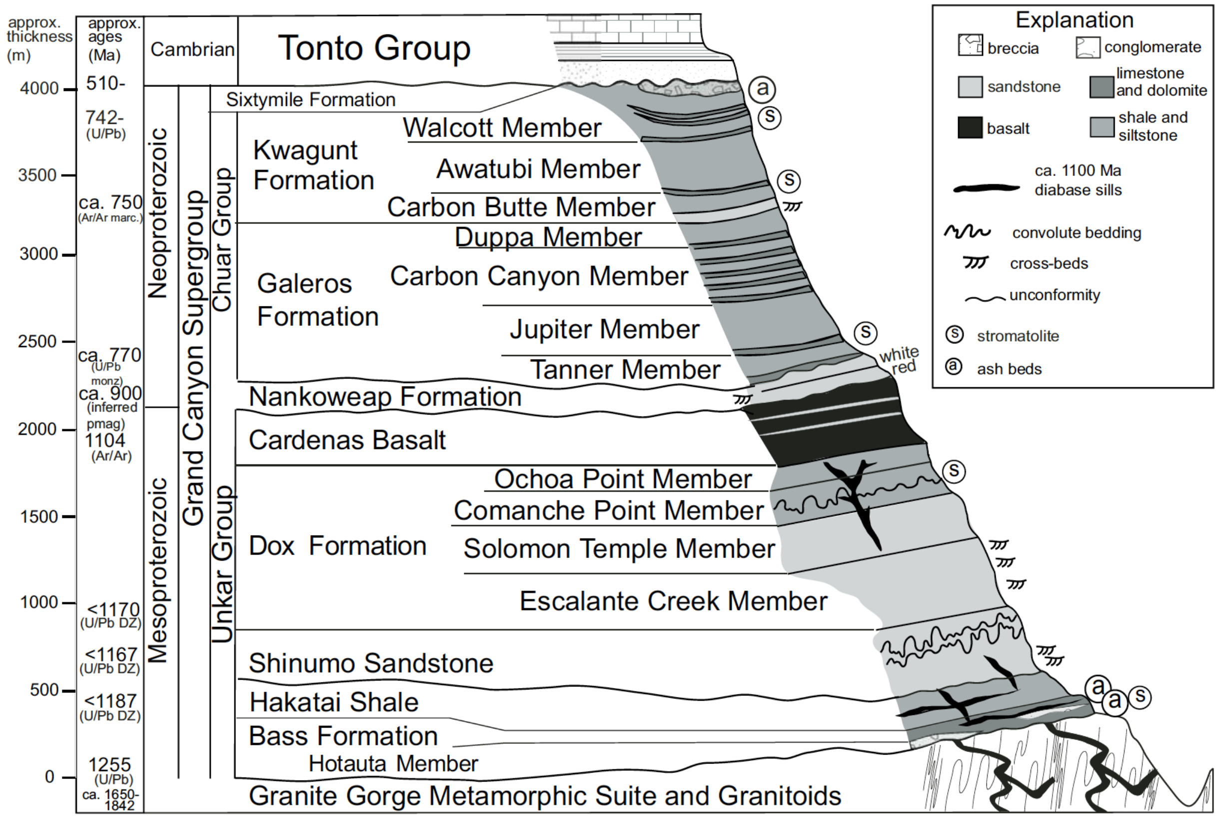

Figure 1*:* Stratigraphic section through the Grand Canyon Supergroup. From Timmons et al., (2005).

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