CHAPTER 2
PALEOZOIC STRATIGRAPHY OF THE GRAND CANYON

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INTRODUCTION

The Paleozoic Era of the Phanerozoic Eon is defined as the time between 542 and 251 million years before the present (ICS 2010). The Paleozoic Era began with the evolution of most major animal phyla present today, sparked by the novel adaptation of skeletal hard parts. Organisms continued to diversify throughout the Paleozoic into increasingly adaptive and complex life forms, including the first vertebrates, terrestrial plants and animals, forests and seed plants, reptiles, and flying insects. Vast coal swamps covered much of mid- to low-latitude continental environments in the late Paleozoic as the supercontinent Pangaea began to amalgamate. The hardiest taxa survived the multiple global glaciations and mass extinctions that have come to define major time boundaries of this era. Paleozoic North America existed primarily at mid to low latitudes and experienced multiple major orogenies and continental collisions. For much of the Paleozoic, North America's southwestern margin ran through Nevada and Arizona – California did not yet exist (Appendix B). The flat-lying Paleozoic rocks of the Grand Canyon, though incomplete, form a record of a continental margin repeatedly inundated and vacated by shallow seas (Appendix A).

IMPORTANT STRATIGRAPHIC PRINCIPLES AND CONCEPTS

- ***Principle of Original Horizontality*** – In most cases, depositional processes produce flat-lying sedimentary layers. Notable exceptions include blanketing ash sheets, and cross-stratification developed on sloped surfaces.
- ***Principle of Superposition*** – In an undisturbed sequence, older strata lie below younger strata; a package of sedimentary layers youngs upward.
- ***Principle of Lateral Continuity*** – A layer of sediment extends laterally in all directions until it naturally pinches out or abuts the walls of its confining basin.
- ***Principle of Faunal Succession*** – The vertical ordering of fossils reflects the sequence of biotic evolution. Therefore, known taxa can provide age constraints on rock layers.
- ***Principle of Components*** – The particles that comprise a rock unit must be younger than the rock itself. For example, sand grains first erode from a parent material, then get transported and deposited before compacting and cementing into sandstone.
- ***Walther's Law*** – Vertical succession of facies (sediments and structures typical of a certain environment) in a sedimentary package reflect lateral migration of a depositional environment. This is especially important when considering the lithologic succession of marine transgressions and regressions.

STORY OF THE PALEOZOIC ERA IN NORTH AMERICA

Cambrian Period, 542-488 Ma

The Cambrian Period gave rise to the rapid evolution of most major animal phyla. The Cambrian Explosion refers to the unprecedented evolution and diversification event in early Cambrian seas. The Cambrian Explosion also marks the beginning of a significant global fossil record. The majority of the animals that evolved during the Late Precambrian were soft-bodied, but by the Cambrian Period, new fauna dominated that had evolved more preservable skeletal support systems: hard parts. Hard-bodied organisms in great variety persisted, and paleontologists speculate this novel adaption likely evolved to thwart increasingly adept predators, such as *Anomalocaris*, for whom soft-bodied specimens were easy prey. Trilobites dominated the interval, though they experienced extinction events in the late Cambrian, which also gave rise to the earliest vertebrate organisms (McKee & Resser 1945). Globally, sea level rose during the Cambrian, and Earth's continental cratons were clustered relatively closely, conditions favorable to develop abundant shallow seas (Appendix B, Stanley 2005).

The Tonto Group represents the oldest rocks of the Paleozoic Grand Canyon sequence. They were deposited during the Cambrian Period, a time during which a north-south trending shoreline was migrating slowly eastward across the North American craton (directions given in reference to modern continental configurations) (Appendix B). The sediments of the Tonto Group, progressing from sand to shale to limestone, suggest a sea level transgression associated with slow subsidence of the North American Cordillera (Middleton & Elliot 1990). The shoreline, as it progressed eastward with the transgression, was carved with embayments and buttressed with offshore islands, which affect the pattern of local shoreline sedimentation. The overall transgressive sequence is disrupted by a series of minor regressions and transgressions. Depositional environments of the Tonto Group include beach and intertidal flats with subtidal sand waves (Tapeats Ss); open shelf environments below wave base where the influence of storms produces normal grading of fine sands and muds (Bright Angel Shale); and subtidal carbonates (Muav limestone and undifferentiated dolomites) (Appendix C, McKee & Resser 1945, Middleton & Elliot 1990).

Ordovician and Silurian Periods, 488-416 Ma

Though not preserved in the Paleozoic sequence of the Grand Canyon, the Ordovician and Silurian Periods both recorded major events in Earth history. The Middle Ordovician gave rise to a vast increase in taxonomic diversity, known as the Ordovician Radiation, which persisted to the Late Ordovician and remains the greatest evolutionary expansion of all time, tripling the number of marine animal families. Specialized modes of life became more prominent in this time, such as deep burrowing. This was due in part to the likewise-expanding abundance and diversity of predatory animals, such as nautiloids. The end-Ordovician mass extinction marks the boundary between the Ordovician and Silurian Periods. It was likely related to the Late Ordovician glacial event, which also generated eustatic sea level regression (Stanley 2005).

The Silurian Period is best known as the period of the earliest fossil evidence for land plants, preserved as clusters of cells, spores, and stem fragments. By the Late Silurian, terrestrial plants, such as 1m-tall *Baragwanathia*, evolved vascular nutrient transport systems and lignin, a woody compound that allowed plants to grow rigid stems. These novel solutions to surviving in an unsupportive medium (air) were seminal – most modern plants still rely on lignin and vascular tissue to grow and survive in terrestrial settings. Sea level rose once more as the Late Ordovician glacial event ended and reef communities increased in size and ecological importance in shallow seas. The Late Silurian gave rise to the first jawed fishes, and the earliest fragmentary evidence of terrestrial animal life (Stanley 2005).

Devonian Period, 416-359 Ma

The Devonian Period marks an important milestone in Earth's evolutionary history because it gave rise to lobe-finned lungfishes, the precursor to all terrestrial vertebrates, including humans. The early Devonian also witnessed taxonomic radiation of vascular land plants, which diversified into

complex forms with more efficient vascular systems, roots for support and nutrient absorption, and leaves for photosynthesis. Seed plants evolved later in the Devonian Period and began to replace spore plants as the dominant plant group. Protective seeds freed these taxa from dependence on the moist conditions required for spore development and allowed them to colonize more diverse habitats. It was spore plants such as *Archaeopteris*, however, that formed Earth's first trees and forests in Late Devonian time. Later, not limited to marshy conditions as spores were, seed-bearing trees developed forests in more widespread, upland terrestrial habitats (Stanley 2005). Following the invasion of land by plants, evidence of significant terrestrial animal life dates to Early Devonian time, including millipedes, flightless insects, scorpions, centipedes, and spiders. The Latest Devonian preserves the first evidence of terrestrial vertebrate tetrapods (amphibians), as well as a few forms distinctly transitional between lobe finned fishes and amphibians, such as Greenland's *Ichthyostega* and *Acanthostega*. These very early forms likely maintained a semi-aquatic existence, venturing not far from water bodies. This period also experienced global cooling, widespread glaciation, and the resultant Late Devonian mass extinction. The early, widespread terrestrial forests and their associated soil weathering drew down atmospheric CO_2 in the Devonian Period. This greenhouse gas depletion generated global cooling and continental glaciation (Stanley 2005).

The Temple Butte Formation represents time from late Middle Devonian to Late Devonian and overlies the most significant time gap within the Paleozoic sequence in the Grand Canyon. The Temple Butte Formation is typically sandy dolomite with occasional limestone and sandstone beds. It crops out primarily in channel-fill lenses up to 400 ft wide in the eastern Grand Canyon and thin, but continuous beds that merge in places with the Redwall limestone in the western Grand Canyon (Appendix C, Beus 1990, "Temple Butte"). Conodonts and poorly preserved, indeterminate brachiopods, gastropods, corals, and fish plates comprise the sparse fossil assemblage of the Temple Butte Formation. Dolomitization and lack of interpretable fossils make the Temple Butte depositional environment difficult to construe. The regional setting was likely a very shallow, but open-circulation marine system, in which the Temple Butte was deposited in intertidal to shallow subtidal conditions (Appendix A, Beus 1990, "Temple Butte").

Mississippian Period, 359-318 Ma

The Mississippian Period dates just prior to the assembly of the supercontinent Pangaea Appendix B). This particular paleogeography, in conjunction with globally rising sea level, created abundant shallow marine shelf environments well suited to widespread limestone deposition. The Mg^{2+}/Ca^{2+} seawater ratio rose during the Mississippian, allowing aragonite to usurp calcite as the default inorganic carbonate species precipitated out of seawater. By extension, organisms that mineralize aragonitic skeletons flourished in the aragonite seas. Crinoid remains in particular are abundant in Mississippian limestones (Stanley 2005). Toward the end of the Mississippian Period, climatic cooling led to the expansion of glaciers at high latitudes across Gondwanaland, the southern continent that would later comprise half of Pangaea. Latitudinal gradients were steep during this time, such that warm conditions persisted as low latitudes, including in the shallow seas that covered much of western North America (Appendix B). The Late Paleozoic glaciation proved to be the biggest in all Paleozoic time. It lowered eustatic sea level, creating a global unconformity between Mississippian and Pennsylvanian strata. Around the time of the late Mississippian and early Pennsylvanian Periods, the southern continent Gondwanaland collided with northern Euramerica in what became known in North America as the Alleghenian Orogeny. The orogeny assembled the two major constituents of Pangaea, and raised the then-towering Appalachian Mountains to even greater heights (Stanley 2005).

Two formations represent the Mississippian Period in the Grand Canyon sequence: the Redwall Limestone and more recently described Surprise Canyon Formation. The four members of the Redwall Limestone record two sets of incursion and retreat of a shallow, epeiric sea that submerged the

continental shelf across the region (Appendix A). The Redwall Limestone occurs as a 500-800 ft cliff of grey limestone stained red by iron-bearing water seeping down from overlying units of the Supai Group. The time lost between the Temple Butte and Redwall Formations includes latest Devonian through earliest Mississippian time, and increases eastward due to the early Mississippian transgression in western North America (Beus 1990, "Redwall"). The Surprise Canyon Formation outcrops are remote and largely restricted to the western Grand Canyon, but provide excellently preserved estuarine deposits. Late Mississippian uplift exposed the upper section of the Redwall Limestone to fluvial erosion, which developed deep channels and karst features in the unit. Eventually, an invading shallow sea transformed the 150-200ft deep, ½ mile-wide channels into estuaries. Lithologies of the Surprise Canyon Formation include terrestrial conglomerate and sandstone, fossiliferous marine limestone, and marine siltstone with silty limestone (Appendix C, Beus 1990, "Redwall").

Pennsylvanian Period, 318-299 Ma
The Pennsylvanian Period, or Late Carboniferous, is noted for its vast coal deposits, the source of most coal mined all over the world. Lowland swamps covered sweeping tracts of land – far more than today. The wetlands accumulated plant biomass in huge quantities, and time and burial transformed it first to peat, then lignite, and finally bituminous, or in some pure cases anthracite, coal. The high-latitude glaciation that began in Mississippian time continued throughout the Pennsylvanian Period as organic carbon sequestration in coal swamps weakened atmospheric greenhouse gas warming (Stanley 2005). One major evolutionary advance in the Early Pennsylvanian was the appearance of reptiles. The distinct advantage for reptiles over amphibians was the amniotic egg, which holds all the requirements for a developing embryo in a self-contained protective shell. For the first time, this allowed terrestrial vertebrates to live and reproduce away from water bodies. The amniotic egg parallels the gradual replacement of spore plants by seed plants—these two adaptations exemplify the transition to more fully terrestrial modes of life in the Late Paleozoic. Foremost among seed plant groups were seed ferns and gymnosperms, including the now-extinct cordaites and living conifers. The Pennsylvanian Period is also known for the first appearances of winged insects. The first possessed fixed wings, such as dragonflies and mayflies, but were soon followed by insects with foldable wings. Furthermore, burial of huge amounts of organic carbon in the Pennsylvanian peat swamps inhibited bacterial decomposition. This decrease in respiration elevated atmospheric oxygen well beyond modern levels, a fact that allowed some Pennsylvanian insects to reach meter-scale proportions (Stanley 2005).

The lower three units of the Supai Group represent the Pennsylvanian Period in the Grand Canyon Paleozoic sequence. In ascending order, they are: the Watahomigi Formation, the Manakacha Formation, and the Wescogame Formation (Billingsley 1978, Blakey 1990). The Watahomigi Formation is dominantly red mudstone and siltstone, and gray limestone and dolomite. It can be divided into three general sections: the lower redbed slope, the middle carbonate cliff, and the upper redbed slope. The formation is also laterally variable and can be broadly divided into an eastern redbed facies and a western carbonate facies (Appendix C). The next-oldest Manakacha Formation represents the first occurrence of major sand facies since the Cambrian Tapeats Sandstone. It also thins westward, unlike most other Paleozoic units. The Manakacha Formation is largely fine to medium grained quartz sand cemented with calcite. It is bedded in a variety of thicknesses and geometries, and interbedded with limestone and red mudstone. The Wescogame Formation, of Late Pennsylvanian time, is similar in lithology to the underlying Manakacha Formation. It is sandstone-dominated, with increasing mudstone eastward and limestone westward (Blakey 1990). Though originally thought to be largely marine in origin, the cross-stratified sandstone units of the Manakacha and Wescogame Formations are primarily aeolian deposits with occasional shallow marine incursions, where siltstones and limestones interbed with sand (Appendix C). However, not all Supai limestone deposits are shallow marine; some are cross-stratified arenaceous limestones deposited by wind. The fine grained redbeds of the Supai Group are of

uncertain origin – their possible depositional environments range from fluvial floodplains, lakes, shoreline lagoons or mudflats, to nearshore, shallow marine settings (Billingsley 1978, Blakey 1990).

Permian Period, 299-251 Ma

By Permian time, Pangaea was fully assembled with the exception of southeast Asia (Appendix B). The conglomeration of the world continents constricted shallow marine shelf environments, uplifted major mountain belts, and limited transportation of moisture to the continental interior. Shrinking shallow seas produced vast evaporite deposits and gradual aridification dried out the coal swamps. Aridification decreased continental weathering rates and coal-swamp constriction allowed organic decomposition to increase at Earth's surface, both of which serve to increase atmospheric carbon dioxide (Stanley 2005). By the Middle Permian, elevated greenhouse gas levels helped warm the climate and bring an end to the Late Paleozoic ice age. Complex topography and steep latitudinal gradients spurred floral and faunal diversification. Gymnosperms, including conifers, though first appearing in the Pennsylvanian, came to dominate upland ecosystems in the Permian and expanded their dominance into the Mesozoic Era. Therapsids, mammal-like reptiles, emerged in the Late Permian. These precursors to mammals may have been endothermic (warm-blooded) and possibly even hairy (Stanley 2005). However, two major extinction events occurred during Permian time: one a few million years prior to end of the Permian, and the second, the largest and most devastating mass extinction on record, marks the Permian-Triassic boundary at 251Ma (ICS 2010). It devastated the diversity of nearly all marine taxa as well as most terrestrial forms, including therapsids. Significant groups that went extinct in the Late Permian include: trilobites, fusilinid foraminifera, and rugose and tabulate corals. While the direct causes of these two biotic crises are still debated, both coincide with well-documented periods of deep ocean anoxia. Low oxygen in the deep marine realm led to a stratified ocean with little circulation of oxygenated surface water. However, deep anoxia lasted for approximately 20 million years, and the lowest oxygen levels lasted about 10. So while marine anoxia certainly played a part in the late Permian extinctions, it was likely only one of several environmental extinction triggers, both in the marine and terrestrial biospheres (Stanley & Young 1994, Wignall 1996).

The upper five formations in the Grand Canyon Paleozoic strata date to the Permian Period: the Esplanade Sandstone, Hermit Shale, Coconino Sandstone, Toroweap Formation, and Kaibab Limestone. Similar to the other, underlying units of the Supai Group, the Esplanade Sandstone is generally an aeolian sandstone. It also contains evaporite deposits, particularly gypsum, interbedded with redbeds among aeolian sand. The evaporites could have formed in a coastal or sabkha (continental salt flat) environment. The overlying Hermit Formation is a steep, ledgy slope of alternating light red, silty sandstone with ripple laminations and deep red sandy mudstone. It was likely deposited in a low-energy, broad floodplain system (Appendix C, Billingsley 1978, Blakey 1990). Regionally, the Permian-Pennsylvanian Supai Group originated when northern Arizona flanked a shallow epicontinental sea to the west, and a coastal plain with aeolian dunes and wind-blown carbonate debris to the east (Appendices A and B). Repeated transgressive and regressive events created laterally and vertically transitioning aeolian and marine facies (Blakey 1990). The aeolian Coconino Sandstone unconformably overlies the Hermit Formation. The thick Coconino cliffs record an erg, or sand sea, environment with dunes sweeping north to south from Canada to Arizona. The timing of the Coconino Sandstone coincides with the Permian trend of global aridification. Large-scale dune features, wind ripple marks, and vertebrate and invertebrate tracks typify the Coconino Sandstone (Appendix C, Billingsley 1978, Middleton et al. 1990).

The three members of the Toroweap Formation (Seligman, Brady Canyon, and Woods Ranch) display significant lateral facies changes. Towards the west, the Toroweap is interbedded gypsum, sandstone, and limestone, but transitions eastward to cross-bedded sandstone similar to the Coconino Sandstone (Turner 1990). The development of evaporites and marine carbonate facies in the lower

Toroweap imply a sea level incursion following deposition of the Coconino Sandstone. Minor aeolian units within the member indicate brief regressive pulses. Location of the eastern cross-bedded aeolian sands indicates the lateral extent of the epicontinental sea. Cyclical deposits of evaporites, carbonates, and aeolian sands suggest repeated sea level fluctuations (Turner 1990, Appendix C). The Permian Kaibab Formation is the youngest unit of the Grand Canyon Paleozoic sequence, though it does not date to the Permian-Triassic boundary. Younger Paleozoic units overlying the Kaibab were likely lost to Mesozoic and Cenozoic erosion (Billingsley 1978). The two members of the Kaibab Formation, the Fossil Mountain and Harrisburg, record major lithofacies transitions associated with shifts from subtidal, shallow-marine environments to more open circulation marine settings and back (Hopkins 1990). The Fossil Mountain Member preserves an overall transgressive sequence punctuated by minor regressions. Beds of the thinner, younger Harrisburg Member reflect deposition in increasingly restricted marine settings during the gradual retreat of the Kaibab sea (Appendix C). The overall tectonic regime of North America during the Permian was fairly stable, suggesting that sea level flux was likely a result of glacial oscillations (Hopkins 1990).

MODERN MANAGEMENT CONSIDERATIONS

All of the Paleozoic lithologic units of the Grand Canyon are flat-lying (or nearly so) sedimentary layers. Depending on factors such as grain size, cementation between grains, mineral composition, etc. layers will be either generally resistant to erosion, or more susceptible to erosion. In the walls of the Grand Canyon, this variability creates the ubiquitous "stair stepped" pattern, where erodible layers (shale, siltstone) form slopes, and resistant layers (limestone, sandstone) form cliffs. At river level, this erodibility factor plays a major role in determining channel dimensions, flow hydrology, and sediment load (Kieffer 1990). Between Lees Ferry and Diamond Creek, the water surface loses 1780 ft in elevation, and where it passes into a new rock unit, the change in lithology can alter channel morphology. Where the Colorado River flows over more erodible units, such as the Bright Angel Shale, wider channels develop and meander more freely. Where it travels through resistant units, such as the Muav Limestone, the channel and canyon walls become narrower and steeper, and therefore flow velocity increases (Kieffer 1990). Distribution of rapids along the Colorado River is related to canyon width and river constriction by debris and large boulders discharged from tributary canyons. Paleozoic rock units source most of the debris flowing into the Colorado River from these side canyons. The erodible, slope-forming units are especially susceptible to debris flows and constitute a significant sediment source both in the tributary canyons and the trunk canyon. Since the construction of the Glen Canyon Dam, a lack of significant flood events coupled with constant, regulated discharge and decreased sediment loads has decreased the erosive power of the Colorado River below the dam, modifying and likely slowing the natural evolution of the canyon river system (Kieffer 1990).

REFERENCES CITED

Beus, S. S. (1990), Temple Butte Formation, in *Grand Canyon Geology*, edited by S. Beus and M. Morales, pp. 107-118, Oxford University Press/ Museum of Northern Arizona.

Beus, S. S. (1990), Redwall Limestone and Surprise Canyon Formation, in *Grand Canyon Geology*, edited by S. Beus and M. Morales, pp. 119-200, Oxford University Press/ Museum of Northern Arizona.

Billingsley, G. H. (1978), *A Synopsis of Stratigraphy in the Western Grand Canyon*, Museum of Northern Arizona Press, 27p.

Blakey, R. C. (1990), Supai Group and Hermit Formation, in *Grand Canyon Geology*, edited by S. Beus and M. Morales, pp. 147-201, Oxford University Press/ Museum of Northern Arizona.

Hopkins, R. L. (1990), Kaibab Formation, in *Grand Canyon Geology*, edited by S. Beus and M. Morales, pp. 225-245, Oxford University Press/ Museum of Northern Arizona.

International Commission on Stratigraphy (2010), International Stratigraphic Chart. Retrieved from <http://www.stratigraphy.org/column.php?id=Chart/Time%20Scale>.

Kieffer, S. W. (1990), Hydraulics and Geomorphology of the Colorado River in the Grand Canyon, in *Grand Canyon Geology*, edited by S. Beus and M. Morales, pp. 333-384, Oxford University Press/ Museum of Northern Arizona.

McKee, E.D., and Resser, C.E., 1945, Cambrian History of the Grand Canyon Region, Carnegie Institute Publication 563, 232 p.

Middleton L. T., and D. K. Eliott (1990), Tonto Group, in *Grand Canyon Geology*, edited by S. Beus and M. Morales, pp. 83-106, Oxford University Press/ Museum of Northern Arizona.

Middleton, L. T., D. K. Elliott, and M. Morales (1990), Coconino Sandstone, in *Grand Canyon Geology*, edited by S. Beus and M. Morales, pp. 183-202, Oxford University Press/ Museum of Northern Arizona.

Stanley, S. M., and X. Yang (1994), A double mass extinction at the end of the Paleozoic Era, *Science*, *266*, 1340-1344.

Stanley, S.M. (2005), *Earth System History*, 2nd ed, W.H. Freeman and Company.

Turner, C. E. (1990), Toroweap Formation, in *Grand Canyon Geology*, edited by S. Beus and M. Morales, pp. 203-223, Oxford University Press/ Museum of Northern Arizona.

Wignall, P. B., and R. J. Twitchett (1996), Oceanic anoxia and the end Permian mass extinction, *Science*, *272*, pp. 1155-1158.