Chapter 3. Stratigraphy of Grand Canyon National Park

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Introduction

The story that Grand Canyon tells is a spectacle of approximately two billion years of earth history (approximately one-half of the age of the earth) in its rock record, with an equally extensive paleontological component. There is no other place on Earth where the pages of Earth's story can be read so easily by the observer to reveal such a long, rich, geologic history of events that are recorded in the layers. Dr. John Strong Newberry said it best in the mid-19th century: "the most splendid exposure of stratified rocks that there is in the world" (Beus 2003).

Grand Canyon rocks can be simplified into three main packages: Vishnu Basement rocks, Grand Canyon Supergroup rocks, and layered Paleozoic rocks. These are each separated by major unconformities and indicate formation under differing geologic conditions and during different time intervals (Mathis 2006). Colorado Plateau uplift and recent downcutting in the canyon and volcanic activity are also responsible for younger geologic materials as well.

Grand Canyon National Park (GRCA) hosts extensive exposures of many Precambrian and Phanerozoic units ranging in age from Proterozoic to Triassic (Figure 3-1, Table 3-1 and 3-2). These units consist of igneous and metamorphic rocks and numerous sedimentary lithologies (siltstones, sandstones, conglomerates, limestones, and dolostones), many of which are extremely fossiliferous. Paleozoic sedimentary rocks are responsible for approximately 900 m (3,000 ft) of the stairstep topography and viewshed in the Grand Canyon. Mesozoic sedimentary rocks likely once covered the Paleozoic section, but these rocks are now only seen in rare isolated outcrops in GRCA (Billingsley et al. 2019).

This summary presents a focused overview of the stratigraphy of GRCA and does not delve into the broader and complex geologic topics and themes associated with the origin and geologic history of the Grand Canyon itself. It is a brief overview focused on the stratigraphic framework for Grand

Canyon to provide a context for the rich and diverse paleontological resources presented in this report and establishes consistency for the other chapters.

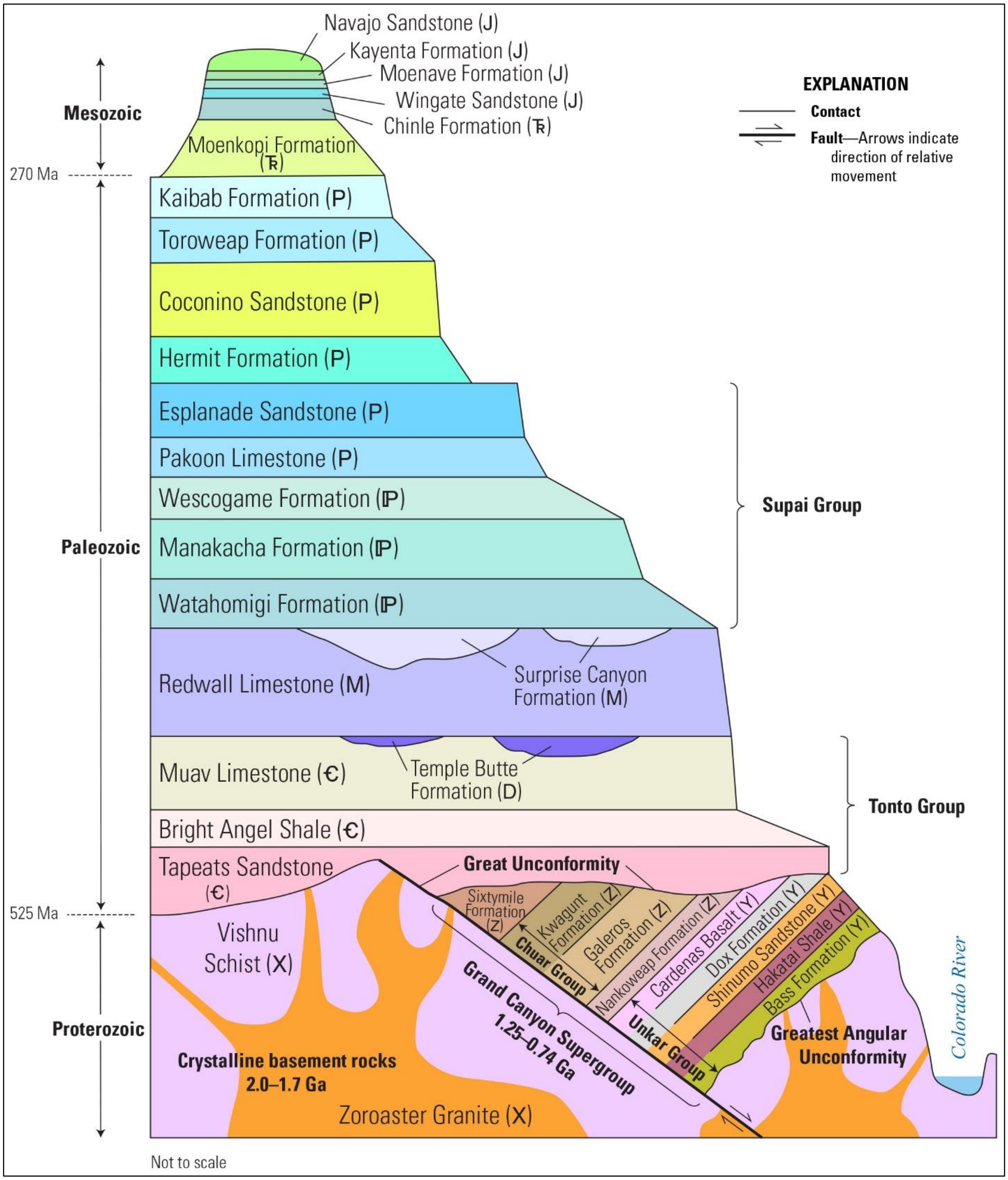

Figure 3-1. Grand Canyon stratigraphy and structural relations (Billingsley et al. 2019: Figure 2). Recently, the Sixtymile Formation was proposed to be Cambrian (not Proterozoic) (Karlstrom et al. 2018, 2020) and the Nankoweap was moved into the Chuar Group (Dehler et al. 2017). Mesozoic rocks younger than the Chinle Formation are not found within the boundaries of GRCA, but are present in the immediate vicinity.

Table 3-1. Grand Canyon area stratigraphy (after Billingsley et al. 2019: Table 2, with updates). Lower case denotes informal names. Mesozoic rocks younger than the Chinle Formation are not found within the boundaries of GRCA, so are omitted, but are present in the immediate vicinity.

Era	Period/Subperiod	Formation	Member
Mesozoic (Mz)	Triassic (Tr)	Chinle Formation	Shinarump Member
	Triassic (Tr)	Moenkopi Formation	Holbrook Member
	Triassic (Tr)	Moenkopi Formation	Moqui Member
	Triassic (Tr)	Moenkopi Formation	Wupatki Member
Paleozoic (Pz)	Permian (P)	Kaibab Formation	Harrisburg Member
	Permian (P)	Kaibab Formation	Fossil Mountain Member
	Permian (P)	Toroweap Formation	Woods Ranch Member
	Permian (P)	Toroweap Formation	Brady Canyon Member
	Permian (P)	Toroweap Formation	Seligman Member
	Permian (P)	Coconino Sandstone	–
	Permian (P)	Hermit Formation	–
	Permian (P)	Esplanade Sandstone	–
	Permian (P)	Pakoon Limestone	–
	Pennsylvanian (IP)	Wescogame Formation	–
	Pennsylvanian (IP)	Manakacha Formation	–
	Pennsylvanian (IP)	Watahomigi Formation	–
	Mississippian (M)	Surprise Canyon Formation	–
	Mississippian (M)	Redwall Limestone	Horseshoe Mesa Member
	Mississippian (M)	Redwall Limestone	Mooney Falls Member
	Mississippian (M)	Redwall Limestone	Thunder Springs Member
	Mississippian (M)	Redwall Limestone	Whitmore Wash Member
	Devonian (D)	Temple Butte Formation	–
	Cambrian (Ꞓ)	Frenchman Mountain Dolostone	–
	Cambrian (Ꞓ)	Muav Limestone	Havasu Member
	Cambrian (Ꞓ)	Muav Limestone	Gateway Canyon Member
	Cambrian (Ꞓ)	Muav Limestone	Kanab Canyon Member
	Cambrian (Ꞓ)	Muav Limestone	Peach Springs Canyon Member
	Cambrian (Ꞓ)	Muav Limestone	Rampart Cave Member
	Cambrian (Ꞓ)	Bright Angel Shale	Flour Sack Member
	Cambrian (Ꞓ)	Bright Angel Shale	red-brown member
	Cambrian (Ꞓ)	Tapeats Sandstone	–
	Cambrian (Ꞓ)	Sixtymile Formation	–
Neoproterozoic (Z)	–	Kwagunt Formation	Walcott Member
	–	Kwagunt Formation	Awatubi Member
	–	Kwagunt Formation	Carbon Butte Member
	–	Galeros Formation	Carbon Canyon Member
	–	Galeros Formation	Jupiter Member
	–	Galeros Formation	Tanner Member
	–	Nankoweap Formation	–
	–	Cardenas Basalt	–

Table 3-1 (continued). Grand Canyon area stratigraphy (after Billingsley et al. 2019: Table 2, with updates). Lower case denotes informal names. Mesozoic rocks younger than the Chinle Formation are not found within the boundaries of GRCA, so are omitted, but are present in the immediate vicinity.

Era	Period/Subperiod	Formation	Member
Mesoproterozoic (Y)	–	Dox Formation	Ochoa Point Member
	–	Dox Formation	Comanche Point Member
	–	Dox Formation	Solomon Temple Member
	–	Dox Formation	Escalante Creek Member
	–	Shinumo Sandstone	–
	–	Hakatai Shale	–
	–	Bass Formation	Hotauta Conglomerate Member
Paleoproterozoic (X)	–	Zoroaster Granite	–
	–	Vishnu Schist	–

Table 3-2. Overview of GRCA stratigraphy and paleontology. See the various chapters for more paleontological information.

Formation	Age	Paleontological Resources
Upper Cenozoic sediments	Pleistocene–Holocene	Almost entirely late Pleistocene–Holocene fossils, predominantly from dry cave and crevice deposits; horsetails, ferns, gnetales, conifers, and angiosperms (macrobotanical), driftwood, pollen, nematodes and their eggs (in dung), bivalves, aquatic and terrestrial gastropods, ostracodes, arthropods (ticks, scorpions, millipedes, beetles, flies, hemipterans, cicadas, hymenopterans, lepidopterans, antlions, grasshoppers), osteichthyans, frogs, salamanders, turtles, lizards, snakes, birds (accipitriforms, anseriforms, apodiforms, cathartiforms, charadriiforms, columbiforms, falconiforms, galliforms, gruiforms, passeriforms, pelecaniforms, piciforms, podocipediforms, strigiforms), mammals (sloths, shrews, rodents, rabbits, bats, carnivorans, proboscidean, horses, artiodactyls), dung (lizard, mammal), bird regurgitation pellets, packrat middens, ringtail middens, and bird eggshell and nests
Chinle Formation	Late Triassic	Petrified wood
Moenkopi Formation	Early–?Middle Triassic	Invertebrate trace fossils and vertebrate tracks (*Rotodactylus*)
Kaibab Formation	early Permian	Dasycladacean algae, sponges, rugose corals, conulariids, bryozoans, brachiopods, bivalves, nautiloids, gastropods, scaphopods, trilobites, crinoids, echinoids, chondrichthyans (ctenacanthiforms, hybodontiforms, euselachians, petalodontiforms, and holocephalans), platysomid actinopterygians, indeterminate actinopterygian teeth and scales, and invertebrate burrows and trails
Toroweap Formation	early Permian	Bryozoans, brachiopods, bivalves, nautiloids, gastropods, scaphopods, ostracodes, crinoids, echinoids, and stromatolites
Coconino Sandstone	early Permian	Invertebrate burrows, trails, and tracks, anamniote tracks (cf. *Amphisauropus* and *Ichniotherium*), reptile tracks (cf. *Dromopus*, *Erpetopus*, and *Varanopus*), synapsid tracks (cf. *Tambachichnium*), and undetermined tetrapod tracks

Table 3-2 (continued). Overview of GRCA stratigraphy and paleontology. See the various chapters for more paleontological information.

Formation	Age	Paleontological Resources
Hermit Formation	early Permian	Horsetails, “seed ferns”, ginkgoes, conifers, undetermined plants, eurypterids, insects, invertebrate burrows, trails, and tracks, anamniote tracks (*Amphisauropus*, *Batrachichnus*, and *Ichniotherium*), reptile tracks (*Dromopus*, *Erpetopus*, and *Hyloidichnus*), synapsid tracks (*Dimetropus*), undetermined tetrapod tracks, and possible microbial features
Esplanade Sandstone (in west transitions to Pakoon Limestone)	early Permian	Conifers (*Walchia*), undetermined plants, bioclasts of marine invertebrates (corals, bryozoans, pelmatozoans, and brachiopods or bivalves), invertebrate burrows and trails, and foraminifers
Wescogame Formation	Late Pennsylvanian	Undetermined plants, bioclasts of invertebrate fossils (bryozoans, pelmatozoans, and brachiopods or bivalves), holocephalan chondrichthyans, invertebrate burrows, trails, and tracks, anamniote tracks (cf. *Amphisauropus*, *Batrachichnus*, and cf. *Limnopus*), of reptiles (*Varanopus*), undetermined tetrapod tracks, foraminifers, and microbial features
Manakacha Formation	Middle Pennsylvanian	Undetermined ferns and other plants, bioclasts of invertebrate fossils (bryozoans, ostracodes, pelmatozoans, and brachiopods or bivalves), microbial trace fossils (stromatolites), invertebrate burrows, trails, and tracks, undetermined tetrapod tracks, foraminifers, and “algal” bioclasts (calcispheres and *Girvanella*)
Watahomigi Formation	Early–Middle Pennsylvanian	Equisetopsids (*Calamites*), “seed ferns” (*Neuropteris*), conifers (*Cordaites* and *Walchia*), *Taeniopteris*, undetermined plants, corals including tabulates, conulariids, bryozoans, brachiopods, bivalves, gastropods, trilobites, crinoids, echinoids, conodonts, chondrichthyans (holocephalan and indeterminate dermal denticles), undetermined fish teeth, microbial trace fossils (stromatolites), invertebrate burrows and trails, foraminifers, and “algae”
Surprise Canyon Formation	Late Mississippian	*Calamites*, *Lepidodendron*, *Lepidostrobophyllum*, undetermined wood and other plant fossils, rugose and tabulate corals, bryozoans, brachiopods, bivalves, gastropods, trilobites, ostracodes, asteroids, blastoids, crinoids, echinoids, conodonts, chondrichthyans (thrinacodontids, xenacanthiforms, symmoridforms, ctenacanthiforms, hybodontiforms, euselachians, indeterminate elasmobranchs, paraselachians, orodontiforms, eugenodontiforms, petalodontiforms, and holocephalans), indeterminate actinopterygians, indeterminate tetrapods, microbial trace fossils (“algal” laminations, oncolites, stromatolites), invertebrate burrows and trails, foraminifers, and “algae”
Redwall Limestone	Early–Middle Mississippian	Rugose and tabulate corals, bryozoans, brachiopods, nautiloids, gastropods, trilobites, blastoids, crinoids, holocephalan chondrichthyans, undetermined fish teeth, invertebrate burrows and trails, foraminifers, “algae”, and calcispheres
Temple Butte Formation	Middle–Late Devonian	Rugose corals, brachiopods, gastropods, conodonts, placoderms, sarcopterygians, indeterminate fish, invertebrate burrows and trails, and trace fossils or stromatoporoid sponges
Frenchman Mountain Dolostone	middle–late Cambrian	Invertebrate burrows and trails

Table 3-2 (continued). Overview of GRCA stratigraphy and paleontology. See the various chapters for more paleontological information.

Formation	Age	Paleontological Resources
Muav Limestone	middle Cambrian	Sponges, brachiopods, hyoliths, helcionelloids, trilobites, eocrinoids, enigmatic invertebrates (*Chancelloria*, *Scenella*), invertebrate burrows and trails, and *Girvanella*-like structures (oncolites)
Bright Angel Shale	middle Cambrian	Cryptogam spores, brachiopods, hyoliths, trilobites, bradoriids, eocrinoids, enigmatic invertebrates (*Chancelloria*, *Tontoia*), microbial wrinkle structures, invertebrate burrows and trails, leiospheres, filament mats resembling *Nematothallus*, non-marine cryptospores, terrestrial algal cell clusters, enigmatic fossils (*Margaretia*), and possibly sponges
Tapeats Sandstone	early–middle Cambrian	Brachiopods, trilobites, and invertebrate burrows and trails
Sixtymile Formation	early Cambrian	Potential undetermined fragment
Kwagunt Formation	middle Neoproterozoic (late Tonian)	Stromatolites and other microbial features, acritarchs and colonial organic-walled microfossils, microbial filaments, vase-shaped microfossils, various unspecified microfossils, "vampire traces" on microfossils, chemical evidence for possible sponges, and possible meiofaunal traces
Galeros Formation	middle Neoproterozoic (late Tonian)	Stromatolites and other microbial features, acritarchs and colonial organic-walled microfossils, microbial filaments, various unspecified microfossils, and "vampire traces"
Nankoweap Formation	middle Neoproterozoic (late Tonian)	None to date, unless *Brooksella canyonensis* is organic
Cardenas Basalt	late Mesoproterozoic	None to date; fossils are unlikely but not impossible
Dox Formation	late Mesoproterozoic	Stromatolites; also dubiofossils
Shinumo Quartzite	late Mesoproterozoic	None confirmed; also dubiofossils
Hakatai Shale	late Mesoproterozoic	Stromatolites and other microbial features in the Bass–Hakatai transition zone; also dubiofossils
Bass Formation	middle–late Mesoproterozoic	Stromatolites and other microbial structures, possible microfossils, and possible microbial filaments; also dubiofossils
Paleoproterozoic–Mesoproterozoic basement	late Paleoproterozoic–early Mesoproterozoic	Unfossiliferous igneous and high-grade metamorphic rocks

Precambrian Stratigraphy of Grand Canyon

The Precambrian rocks of GRCA consist of igneous, metamorphic, and sedimentary rocks. Precambrian sedimentary and igneous rocks are generally only exposed in the eastern and central Grand Canyon regions along the canyon depths, while Proterozoic crystalline rocks are only exposed along the Colorado River and tributaries in eastern and western Grand Canyon (Billingsley et al. 2019).

The base of the Precambrian section is composed of various igneous and metamorphic bodies of Paleoproterozoic age, overlaid by a series of primarily sedimentary units. The "Vishnu Basement rocks" (consisting of generically the Elves Chasm Gneiss, and granites and schists) will not be treated here as they do not contain paleontological resources. The “Grand Canyon Supergroup rocks” are divided into the Mesoproterozoic Unkar Group (consisting of the Bass Formation, Hakatai Shale, Shinumo Sandstone, Dox Formation, and Cardenas Basalt), and the Neoproterozoic Chuar Group (Nankoweap Formation, Galeros Formation, and Kwagunt Formation). These sedimentary rocks are discussed in further detail in the Precambrian paleontology chapter; capsule descriptions are included here.

Grand Canyon Supergroup: Unkar Group

The Unkar Group consists of the Mesoproterozoic Bass Formation, Hakatai Shale, Shinumo Sandstone, Dox Formation, and Cardenas Basalt (Figures 3-2 and 3-3).

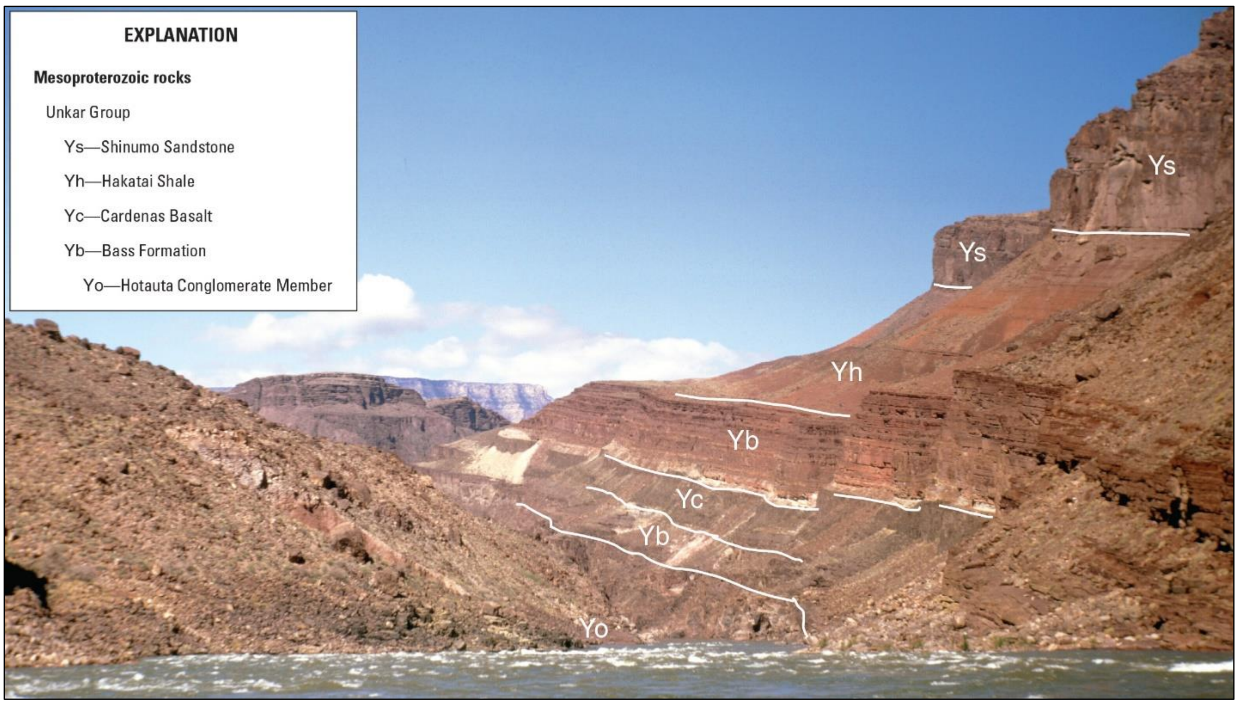

Figure 3-2. Mesoproterozoic rocks of the Unkar Group (Grand Canyon Supergroup) in eastern Grand Canyon. Yo=Hotauta Conglomerate Member; Yb=Bass Formation; Yc=Cardenas Basalt; Yh=Hakatai Shale; Ys=Shinumo Sandstone (Billingsley et al. 2019: Figure 3).

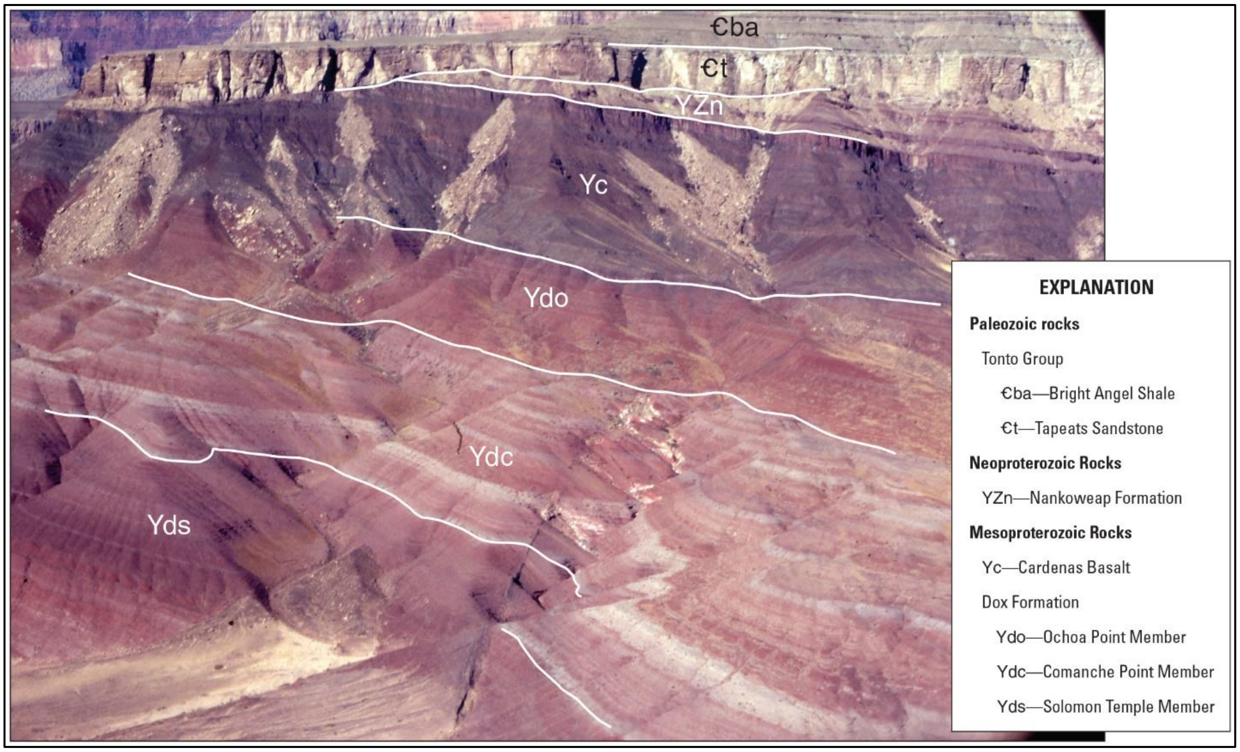

Figure 3-3. Mesoproterozoic rocks in contact with lower Tonto Group (Tapeats Sandstone and Bright Angel Shale) in eastern Grand Canyon (Billingsley et al. 2019: Figure 4).

Unkar Group: Bass Formation (Mesoproterozoic)

The Bass Formation is primarily composed of dolomite, with some interbedded sandstone, mudstone, and pebble conglomerate, about 60 to 100 m (200 to 330 ft) thick. The basal part of the formation is a cobble conglomerate known as the Hotauta Member. The Bass Formation is interpreted as mostly shallow to restricted marine, with increasing clastic input over time. It grades into the overlying Hakatai Shale. The base of the formation dates to approximately 1254 Ma (million years ago) (Timmons et al. 2005, 2012). This formation is significant for preserving the oldest evidence of life in GRCA.

Unkar Group: Hakatai Shale (Mesoproterozoic)

The Hakatai Shale is a clastic unit consisting of primarily siltstone and fine-grained sandstone, with lithologies ranging from mudstone to conglomerate, varying from 137 to 300 m (450 to 980 ft) thick. The upper contact with the Shinumo Sandstone is unconformable. It is interpreted as a shallow water unit from marginal marine, tidal flat and deltaic settings, deposited at least in part after 1187 Ma (Timmons et al. 2005, 2012).

Unkar Group: Shinumo Sandstone (Mesoproterozoic)

The Shinumo Sandstone is a mostly quartzitic sandstone interpreted as a high-energy shoreface unit. It is approximately 355 to 410 m (1,160 to 1,350 ft) thick and has a gradational contact with the overlying Dox Formation (Timmons et al. 2005, 2012). It may be as old as ca. 1170 Ma (Timmons et al. 2012) or as young as 1140 Ma (Mulder et al. 2017).

Unkar Group: Dox Formation (Mesoproterozoic)

The Dox Formation is predominantly composed of red sandstone. It is interpreted as initially a fluvial to deltaic unit, becoming more marine over time (Timmons et al. 2012; Mulder et al. 2017). It has been divided into four members, in ascending order: the Escalante Creek, Solomon Temple, Comanche Point, and Ochoa Point Members, with a combined thickness of approximately 920 m (3,020 ft) (Elston 1989a). Deposition occurred between approximately 1140 and 1104 Ma (Timmons et al. 2012; Mulder et al. 2017).

Unkar Group: Cardenas Basalt (Mesoproterozoic)

The Cardenas Basalt is an unfossiliferous basalt unit formed by eruptions that began near the end of Dox Formation deposition, as shown by interfingering Dox beds and Cardenas lava flows. It is about 300 m (980 ft) thick and dates to approximately 1104 Ma. Its upper contact with the Nankoweap Formation is unconformable (Timmons et al. 2005, 2012).

Grand Canyon Supergroup: Chuar Group

The Chuar Group consists of the Neoproterozoic Nankoweap, Galeros and Kwagunt Formations, each with their own members.

Chuar Group: Nankoweap Formation (Neoproterozoic)

The Nankoweap Formation can be divided into a lower red unit of hematite-cemented sandstone and mudstone, and an upper white unit of siltstone and sandstone (Timmons et al. 2012). These two informal members have an unconformable contact, and the overall thickness of the formation varies greatly from 113 to more than 250 m (370 to more than 820 ft) (Elston 1989a). This unit was recently found to be much younger than previously inferred by dating detrital zircons, at less than approximately 782 Ma, and has been added to the Chuar Group (Dehler et al. 2017).

Chuar Group: Galeros Formation (Neoproterozoic)

The Galeros Formation is a dominantly clastic unit, mostly mudstones with some sandstone and dolomite beds. It is divided into four members, in ascending order the Tanner, Jupiter, Carbon Canyon, and Duppa Members. Like the similar overlying Kwagunt Formation, it is interpreted as representing primarily wave- and tidal-influenced marine deposition and supratidal. The upper contact with the Kwagunt Formation is gradational, and the two together are about 1,600 m (5,250 ft) thick (Dehler et al. 2001, 2012). It dates from after 782 Ma to approximately 751 ± 7.6 Ma (Rooney et al. 2018).

Chuar Group: Kwagunt Formation (Neoproterozoic)

The Kwagunt Formation is lithologically similar to the Galeros Formation and is also divided into several members (in ascending order the Carbon Butte, Awatubi, and Walcott Members). It was also primarily deposited in shallow subtidal to intertidal settings, with more frequent episodes of subaerial exposure than the Galeros Formation (Dehler et al. 2001, 2012). Deposition occurred after approximately 751 Ma to about 729 ± 0.9 Ma (Rooney et al. 2018).

Paleozoic Stratigraphy of Grand Canyon

Outcrops of 17 distinct Paleozoic formations have been reported in GRCA, ranging in age from the Cambrian to the Triassic. These rocks vary greatly in depositional environments ranging from open marine to eolian terrestrial. As discussed in following chapters, they also preserve a broad array of fossils, from Cambrian invertebrate burrows and trails, to Devonian fish, to Mississippian crinoids, to Pennsylvanian vertebrate tracks, to Permian plants and insects. GRCA boasts one of the most complete Paleozoic records in the National Park System, particularly from the Late Devonian through the end of the Permian.

Tonto Group (lower–middle Cambrian)

The Tonto Group (Figures 3-3 and 3-4) consists of the Sixtymile Formation, Tapeats Sandstone, Bright Angel Shale (or Formation), Muav Limestone (or Formation), and Frenchman Mountain Dolostone (Karlstrom et al. 2020). Historically it included only the Tapeats, Bright Angel, and Muav Formations. It is misleading to consider these three units as simple "layer cake" beds. The formations are defined by lithology and because deposition occurred over many small-scale marine regressions and transgressions during the overall marine transgression, the lithologies intertongue extensively, making mapping complicated (Beus and Billingsley 1989; Huntoon 1989).

Tonto Group: Sixtymile Formation (lower Cambrian)

The Sixtymile Formation was thought to be Precambrian in age until recently, when dating of detrital zircons established it as Cambrian in age (Karlstrom et al. 2018). It is only found in a few areas of eastern GRCA and is composed of red- to white sandstone and siltstone with chert and interformational breccia (Elston 1979). What had previously been described as the lowest part of the formation has been transferred to the upper Kwagunt Formation (Timmons et al. 2001). The Sixtymile Formation was deposited in lacustrine, fluvial, and shallow marine settings in fault-controlled basins. Detrital zircons indicate it was deposited between 520 and 509 Ma, making it contemporaneous in part with rocks of the lower Tonto Group in the western Grand Canyon and Lake Mead regions (Karlstrom et al. 2018). There is an angular unconformity between the Sixtymile Formation and the overlying Tapeats (Tonto Group) (A. Mathis, pers. comm., December 2019).

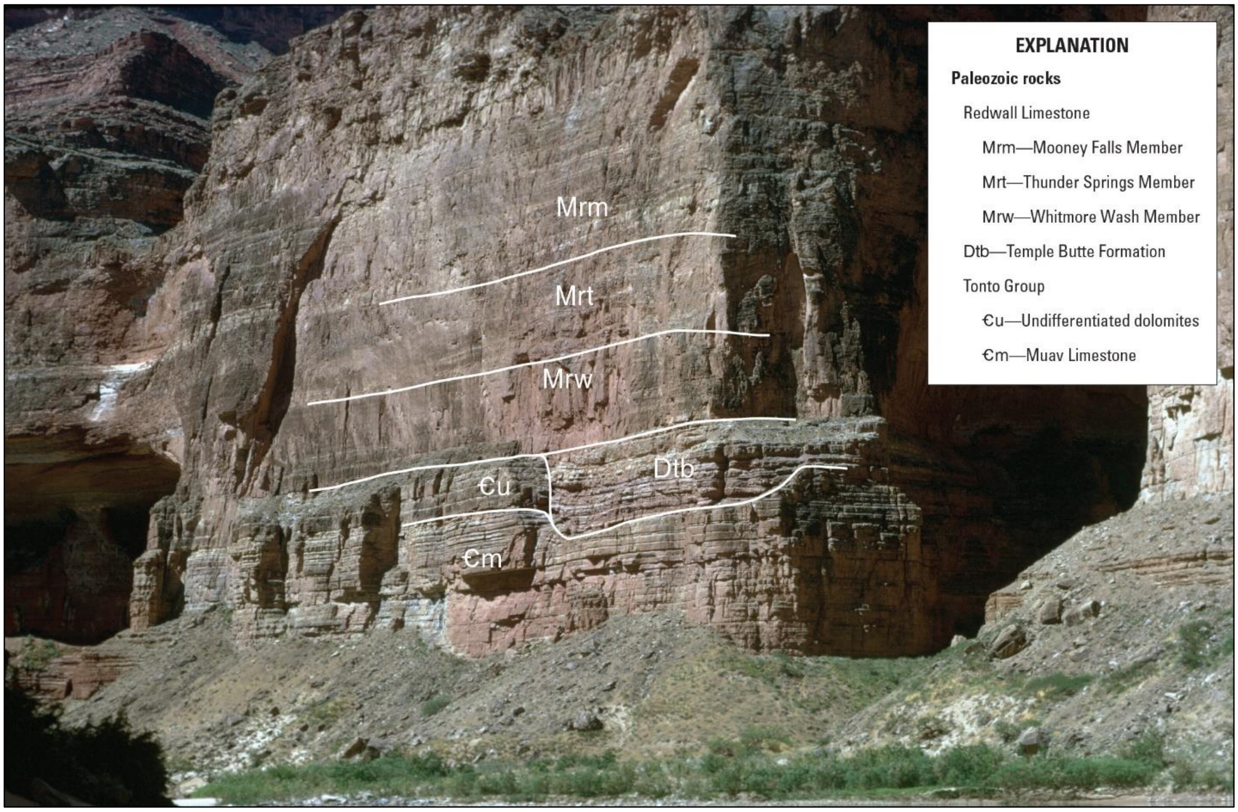

Figure 3-4. Upper Tonto Group (Cm=Muav Limestone; Cu="undifferentiated dolomites", now the Frenchman Mountain Dolostone), Temple Butte Formation (Dtb), and Redwall Limestone (Mrw=Whitmore Wash Member; Mrt=Thunder Springs Member; Mrm=Mooney Falls Member) in eastern Grand Canyon (Billingsley et al. 2019: Figure 5).

Tonto Group: Tapeats Sandstone (lower–middle Cambrian)

The Tapeats Sandstone is a medium- to coarse-grained, cliff-forming conglomeratic sandstone (Beus and Billingsley 1989). At GRCA, this unit is deposited on what had been the hilly terrain of weathered Precambrian rocks (the Grand Canyon Supergroup in eastern GRCA, the older Vishnu Basement in western GRCA) (Middleton and Elliott 2003). The unconformity with all underlying Precambrian rocks is known as the Great Unconformity. The base of the Tapeats Sandstone is locally conglomeratic, with mudstone and fine sandstone becoming common toward the top, where the Tapeats Sandstone forms a transition zone with the overlying Bright Angel Shale (Middleton and Elliott 2003). Three members may be apparent in the western part of the canyon, with a shale (mudstone)-rich member sandwiched between sandstone members (Elston 1989d).

Historically, the Tapeats Sandstone and the rest of the Tonto Group were considered to span much of the Cambrian and were interpreted as a classic example of a gradual marine transgression in which the nearshore sands of the Tapeats Sandstone were replaced by successively deeper marine deposits of the Bright Angel Shale and Muav Limestone (McKee and Resser 1945). More recent study indicates that the marine transgression responsible for the Tonto Group took place over a much shorter time frame (Karlstrom et al. 2018). West of GRCA, the upper Tapeats Sandstone includes rocks deposited approximately 508 to 504 Ma, while in eastern GRCA, the Tapeats Sandstone has a maximum depositional age of 505.4 ± 8.0 Ma (Karlstrom et al. 2018).

The Tapeats Sandstone is typically interpreted as representing shallow marine sand deposition under significant tidal influence, with more terrestrial environments toward the base (Hereford 1977; Middleton 1989; Middleton and Elliott 2003). However, the formation may have been more continental overall, perhaps a fluvial braidplain (Baldwin et al. 2004). The thickness of the formation varies from very thin or absent where deposited over prominent paleotopographic highs, to 90 m (300 ft), 12 to 15 m (40 to 50 ft) of which are part of a transition zone (Beus and Billingsley 1989).

Tonto Group: Bright Angel Shale (Middle Cambrian)

The Bright Angel Shale is a mixed formation mostly composed of shale (mudstone) to fine-grained sandstone (Middleton and Elliott 2003). The rocks are sometimes divided into numerous members (McKee 1945; Spamer 1984; Beus and Billingsley 1989). It appears to have been deposited between approximately 505 to 501 Ma in Grand Canyon (Karlstrom et al. 2018). It has a complex gradational and intertonguing relationship with the overlying Muav Limestone (Middleton 1989). To simplify matters, Elston (1989d) has suggested transferring the lower portion of the Muav Limestone to the Bright Angel Shale. The Bright Angel Shale is about 107 to 150 m (350 to 500 ft) thick (Billingsley 2000).

The Bright Angel Shale is generally interpreted as a shallow marine shelf unit (Middleton and Elliott 2003). The various members correspond to minor transgressions and regressions (Elston 1989d; Beus and Billingsley 1989). When interpreted as more continental, the rocks are instead seen as representing estuary and tidal flat settings (Baldwin et al. 2004) influenced by storm events (Elliott and Martin 1987). The lack of acritarchs in the mudstones, the dominant lithology of the formation, may be evidence for minimal marine influence in those rocks (Baldwin et al. 2004).

Tonto Group: Muav Limestone (middle Cambrian)

The Muav Limestone is composed of limestone, dolomite, thin shale (mudstone) and siltstone, and conglomerate (Spamer 1984; Middleton and Elliott 2003), and forms cliffs at GRCA (Middleton and Elliott 2003). Like the Bright Angel Shale, it can be divided into multiple members (Spamer 1984; Middleton 1989; Middleton and Elliott 2003). Trilobites of the Muav Limestone can be attributed to the same part of the Cambrian as the Bright Angel Shale of eastern GRCA (Karlstrom et al. 2018), so it is likely not substantially younger. It is between 45 and 245 m (150 and 800 ft) thick (Spamer 1984). Its upper contact is an unconformity with the unnamed dolomite unit (Beus and Billingsley 1989).

The Muav Limestone is interpreted as representing subtidal to supratidal offshore deposits (Middleton and Elliott 2003). The various members correspond to minor transgressions and regressions (Elston 1989d; Beus and Billingsley 1989). There are also some tidal flat deposits, particularly in the western part of GRCA (Wanless 1973; Baldwin et al. 2004).

Tonto Group: Frenchman Mountain Dolostone (middle–?upper Cambrian)

Above the Muav Limestone at GRCA is a unit historically known as the "undifferentiated dolomites", now assigned to the Frenchman Mountain Dolostone by Karlstrom et al. (2020). It consists of white to gray dolomite unit with thin layers of shale (mudstone) between beds, especially in the lower part of the unit. Its exact age is uncertain, due to the paucity of fossils. The thickness varies from 60 to 140 m (200 to 450 ft) (Beus and Billingsley 1989). This unit is found in western GRCA (Middleton 1989). It is also sometimes called the "Supra-Muav" or "Grand Wash Dolomite" in the literature (Middleton 1989), although the latter name is precluded from formal usage because "Grand Wash" is already in use for a different unit in the area (Elston 1989d). This unit is interpreted as shallow subtidal to possibly intertidal in depositional setting (Middleton and Elliott 2003), deposited in a regressing sea (Spamer 1984).

Temple Butte Formation (Middle–Upper Devonian)

The Temple Butte Formation (Figure 3-4) is a dolomite (dolostone) and sandstone unit, becoming mostly dolomitic in western GRCA (Beus 1989). In eastern GRCA, it is discontinuous, filling channels cut into the underlying Cambrian rocks. It becomes a thicker and continuous layer in the western part of the park, with dolomite over the channel fill (Spamer 1984). Some descriptions have combined part of the unnamed Cambrian dolomite with the formation (Beus 2003a). Conodont fossils have been used to date the Temple Butte Formation to the late Middle and early Late Devonian (Beus 1980). Where present, it is up to 135 m (450 ft) thick in western GRCA (Beus and Billingsley 1989). Both the lower contact with Cambrian rocks and the upper contact with the Redwall Limestone are unconformities (Spamer 1984).

Most of the Temple Butte Formation is interpreted as representing shallow, subtidal, open marine settings in western Grand Canyon, although some of the dolomite may be supratidal and the channel fill could correspond to tidal channels in eastern Grand Canyon (Beus 2003a). A transgression occurred during the deposition of this unit, moving west to east (Beus 1989).

Redwall Limestone (Lower–Middle Mississippian)

The Redwall Limestone (Figures 3-4 and 3-5) is made up mostly of limestone, with some dolomite, chert, and mudstone (Beus et al. 1989). The most detailed description of the unit is McKee and Gutschick (1969a), which includes data from a number of GRCA localities. This cliff-forming unit is actually gray, but in the canyon it has been stained red on the surface by iron oxides washed from the overlying Supai Group (McKee and Gutschick 1969b). There are four members, all present at GRCA; from oldest to youngest, they are the Whitmore Wash, Thunder Springs, Mooney Falls, and Horseshoe Mesa Members (McKee 1963). The Whitmore Wash Member is mostly limestone and dolomite, thickening from 15 m (50 ft) in eastern GRCA to 36 m (120 ft) in western GRCA, which dates to the Early Mississippian. The Thunder Springs Member is a distinctively banded unit, due to alternating carbonate and chert beds. It is 30 m (100 ft) thick in eastern GRCA, increasing to 43 m (140 ft) in western GRCA. It is slightly younger than the Whitmore Wash Member. The Mooney Falls Member is a massive cliff-forming limestone, and spans from 76 m (250 ft) thick in eastern GRCA to 104 m (340 ft) thick in western GRCA. It dates to the early Middle Mississippian. Finally, the Horseshoe Mesa Member, composed of limestone ledges, is thinnest, ranging from 0 to 30 m (0 to 100 ft) thick. It is absent where the overlying channel-filling Surprise Canyon Formation is present. It is slightly younger than the Mooney Falls Member (Beus and Billingsley 1989). Within the formation, there is a depositional hiatus between the Thunder Springs and Mooney Falls Members that becomes progressively greater from west to east (Beus 1989). Shortly after its deposition, the upper part of the Redwall Limestone eroded to form a karst terrain (McKee and Gutschick 1969d) and erodes into overhangs and caves today (McKee and Gutschick 1969b).

Figure 3-5. Redwall Limestone (Mr), Surprise Canyon Formation (Ms), and overlying Supai Group (Pwa=Watahomigi Formation; Pm=Manakacha Formation; Pwe=Wescogame Formation; Pe=Esplanade Sandstone) (Billingsley et al. 2019: Figure 6).

The Redwall Limestone records two marine transgression-regression cycles. The older and larger cycle is represented by the transgressional Whitmore Wash Member and the regressional Thunder Springs Member, and the second cycle is represented by the transgressional Mooney Falls Member and the regressional Horseshoe Mesa Member (Beus 1989). The marine body transgressed from west to east, forming a shallow sea (Beus 2003b). Several types of limestone and other rocks are found throughout the members and correspond to different environments on the shelf (McKee and Gutschick 1969c). Distinct fossil assemblages are found from these different settings. For example, featureless limestone appears to represent lime mud deposits that were not conducive to life, with the only numerous fossils being massive colonial corals. Oolitic limestone (limestone composed of small spherical particles) is probably from warm shallow water with moderate energy, and has a faunal assemblage of foraminifera, corals, ostracodes, and sea cucumbers, with algal structures (McKee and Gutschick 1969d).

Fossil preservation in the Redwall Limestone is quite variable, depending on the matrix, organisms, and environment. Fossils found in chert are often the best, though usually preserved as molds (McKee and Gutschick 1969d). Fossils in GRCA's Whitmore Wash Member were often destroyed when limestone was altered to dolomite (Beus 2003b), a common phenomenon in southeastern GRCA (McKee and Gutschick 1969e). Fossils are common in the Thunder Springs and Mooney Falls members (Beus and Billingsley 1989). The limestone beds of the Thunder Springs Member are crinoid-rich, while the chert beds are formed by silicified bryozoan limestones and mudstones (Beus and Billingsley 1989). The best fossils are found in the chert beds (Beus 2003b). Bryozoans dominate the Thunder Springs Member fossil assemblages in eastern GRCA, while crinoids dominate central GRCA, and a mixed bryozoan-brachiopod-gastropod-crinoid fauna is present in western GRCA. Fossils of the Mooney Falls Member are only well-preserved in a few scattered zones. Otherwise, specimens are fragmentary (McKee and Gutschick 1969e). Fossils are rare again in the Horseshoe Mesa Member (Beus and Billingsley 1989); however, when present, Horseshoe Mesa Member fossils are well-preserved (Beus 2003b).

Surprise Canyon Formation (Upper Mississippian)

The Surprise Canyon Formation (Figure 3-5) is a discontinuous unit found filling paleo-valleys and other karst features eroded in the upper Redwall Limestone. The Surprise Canyon Formation also occurs in caves in the Redwall Limestone's Mooney Falls and Horseshoe Mesa Members (Billingsley and Beus 1985). It is found only in the Grand Canyon region. Formally named in 1985, its outcrops were first thought to be part of the Redwall Limestone or the Watahomigi Formation (Billingsley and Beus 1985). After it was recognized as a distinct unit, but before it was formally described, it was known as the pre-Supai buried valleys or canyons (Billingsley and McKee 1982; Spamer 1984). The lower portion is composed of fluvial conglomerate and sandstone with some mudstone and siltstone (Beus 2003b). The coarsest material is found near the base, grading up into sandstone (Beus and Billingsley 1989). The middle portion is a cliff-forming marine limestone. Finally, the upper part includes marine slope-forming siltstone, sandstone, and silty to sandy limestone (Beus 2003b). Most of the limestone of the upper unit is at the top, so there is a siltstone-sandstone slope above the middle unit's cliff leading to a cliff higher in the upper unit (Billingsley and McKee 1982). The valleys filled by the Surprise Canyon Formation are as much as 120 m (400 ft) deep. It was deposited a few million years after the Redwall Limestone, and dates to the end of the Mississippian (Beus 2003b). The upper contact is an unconformity with the Watahomigi Formation (Beus 1989).

The Surprise Canyon Formation forms a dendritic drainage system that can be traced through GRCA (Billingsley and Beus 1999). Flow moved from east to west (Beus 2003b). The three parts of the formation formed under different conditions. In general, the lower sandstone/conglomerate portion is interpreted as fluvial, the middle limestone portion is interpreted as marine, and the upper silty portion is interpreted as estuary. The eastern depositional area may have been fluvial during its entire deposition (Beus 2003b). An alternate paleoenvironmental interpretation for the entire formation is as a more widespread shallow sea. This interpretation would be more consistent with the distribution of some of the marine fossils, but is not favored (Beus 2003b).

Supai Group

The Supai Group (Figure 3-5) was recognized for many years as the Supai Formation in the Grand Canyon. It was designated as a group and was divided into four formations in 1975. In ascending order, these are the Watahomigi Formation, Manakacha Formation, Wescogame Formation, and Esplanade Sandstone (McKee 1975). The coeval Pakoon Limestone intertongues with the Esplanade Sandstone in western GRCA (Blakey and Knepp 1989). The Supai Group as a whole is thought of as a broad coastal plain, over which the sea advanced from the west and retreated several times. The four formations represent different stages of several transgressive-regressive cycles, with the depositional setting oscillating between continental (particularly eolian) and shallow marine environments (Blakey 2003).

Supai Group: Watahomigi Formation (Lower–Middle Pennsylvanian)

The Watahomigi Formation (Figure 3-5) is composed of mudstone, siltstone, limestone, and dolostone. The lower and upper portions are slope-forming red beds, and the middle is a ledge-forming carbonate (Blakey 2003). These parts can be recognized throughout the Grand Canyon (Beus and Billingsley 1989). Carbonates dominate western GRCA and mudstone dominates the eastern outcrops in the park, with very little of the middle unit present (McKee 1982b). It is 24 to 91 m (80 to 300 ft) thick at GRCA, becoming thicker from east to west (Beus and Billingsley 1989). The formation mostly dates to the Early Pennsylvanian. An erosional horizon represented by a conglomerate marks both the base of the upper section and the Early–Middle Pennsylvanian boundary (McKee 1982b). It was deposited after a short hiatus following the deposition of the Surprise Canyon Formation (Beus 1989). The upper contact with the Manakacha Formation may be another unconformity (Blakey and Knepp 1989), or conformable (Blakey 2003).

The Watahomigi Formation is interpreted as a shoreline unit, deposited in shallow marine to coastal plain settings (Blakey and Knepp 1989). It is part of a marine transgression (McKee 1982c). The upper portion had more marine influence than the lower portion (Blakey 2003). During the Early Pennsylvanian, a sea was present west of the modern Little Colorado River, which expanded to the east during the early middle Pennsylvanian (McKee 1982a). Fossils in the Watahomigi Formation suggest low energy conditions (McKee 1982d), but possibly too energetic or with too much sand and silt for extensive coral growth (Gordon 1982).

Supai Group: Manakacha Formation (Middle Pennsylvanian)

The Manakacha Formation (Figure 3-5) is primarily a mix of sandstone and limestone, with some mudstone, conglomerate, and dolostone (Blakey and Knepp 1989). It is usually exposed as a lower cliff and upper slope, with a conglomeratic zone between the two. Unlike other Supai Group formations, there is not a basal conglomerate (Beus and Billingsley 1989). Carbonates are prominent in western GRCA, grading to sandstone and mudstone in central GRCA, and then mudstone and sandstone in eastern GRCA. The top of the unit is a widely recognized channeled surface that marks an unconformity (McKee 1982b). Its thickness is relatively consistent throughout the park, ranging from 61 to 84 m (200 to 275 ft) thick (Beus and Billingsley 1989). The Manakacha Formation dates to the early Middle Pennsylvanian.

The Manakacha Formation was initially interpreted as a dominantly marine formation (McKee 1982c), representing marine shelf to open marine environments, with mudstone limited to restricted marine environments and the dominant sandstone and limestone deposited under high energy (Blakey and Knepp 1989). More recently, it has been interpreted as dominantly eolian. Eolian deposition began encroaching from the north into the area that had been submerged by the marine transgression of the Watahomigi Formation (Blakey 2003).

Supai Group: Wescogame Formation (Upper Pennsylvanian)

The Wescogame Formation (Figure 3-5) is a mixed unit, with limestones prominent in extreme western GRCA, sandstones dominant in central GRCA, and mudstones increasing in prominence in eastern GRCA. It is exposed as a lower cliff and upper slope (Blakey 2003). It is the most complex of the Supai Group formations, with rapidly shifting rock types (Blakey and Knepp 1989). The thickness is between 30 and 69 m (100 and 225 ft) at GRCA (Beus and Billingsley 1989). Both the upper and lower contact are unconformities (Blakey 2003). The Wescogame Formation dates to the end of the Late Pennsylvanian.

The Wescogame Formation is interpreted as predominately eolian, representing one or more large dune fields (Blakey 2003). Fluvial, coastal plain, shoreline, shelf, and open marine settings are also likely represented in its various rock types (Blakey and Knepp 1989).

Supai Group: Esplanade Sandstone (lower Permian)

The Esplanade Sandstone (Figures 3-5 and 3-6) is a quartz-rich sandstone, with basal and upper slope-forming beds of finer sediments (McKee 1982c). It was deposited during the early Permian (McKee 1982d). The lower portion of the Esplanade Sandstone intertongues with the Pakoon Limestone in western GRCA (Blakey and Knepp 1989). The combined Esplanade Sandstone–Pakoon Limestone thickens from east to west, going from 91 m (300 ft) thick in eastern GRCA to more than 137 m (450 ft) in the western part of the park (Billingsley 1997). The lower contact with the Wescogame Formation and the upper contact with the Hermit Formation are unconformable. The base of the unit in eastern and central GRCA is a conglomerate that fills paleochannels in the Wescogame Formation (Beus and Billingsley 1989).

The depositional environment of this formation has been interpreted in multiple ways. The marine interpretation sees the Esplanade Sandstone as mostly high-energy marine sandstone with more terrestrial beds at the top and bottom (McKee 1982c; Blakey and Knepp 1989). The more current interpretation is that it is an eolian unit (Beus and Billingsley 1989; Blakey 2003), or part of a large coastal plain (Blakey 2003). The base was probably less eolian than the rest of the unit (Blakey 2003). Marine influence increased to the west, as evidenced by the change into the Pakoon Limestone (McKee 1982c). Some gypsum is also present (Blakey 2003).

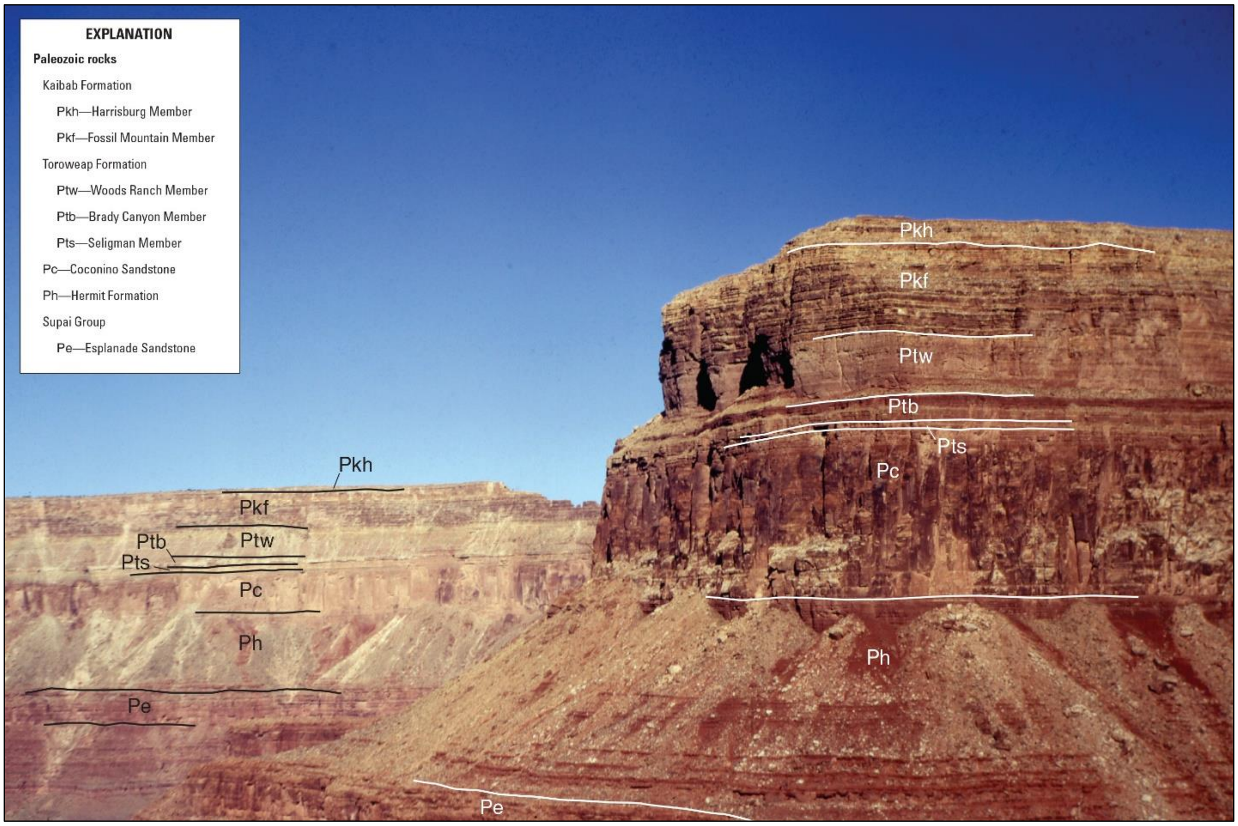

Figure 3-6. Uppermost Supai Group (Pe=Esplanade Sandstone), Hermit Formation (Ph), Coconino Sandstone (Pc), Toroweap Formation (Seligman Member=Pts; Brady Canyon Member=Ptb; Woods Ranch Member=Ptw), and Kaibab Formation (Fossil Mountain Member=Pkf; Harrisburg Member=Pkh) (Billingsley et al. 2019: Figure 7).

Pakoon Limestone (lower Permian)

The Pakoon Limestone is a heterogeneous unit including dolomite, limestone, sandstone, mudstone, and gypsum (Blakey and Knepp 1989). It is mostly dolomite and limestone in the Grand Canyon region (Blakey 2003). It intertongues with the lower Esplanade Sandstone in western GRCA (Blakey and Knepp 1989), and dates to the earliest Permian (Blakey 2003). The Pakoon Limestone is interpreted as a clear water, shallow marine unit (Blakey 2003). It is not mapped separately from the Esplanade Sandstone within GRCA (Billingsley and Wellmeyer 2004; Billingsley et al. 2006a).

Hermit Formation (lower Permian)

The Hermit Formation (Figure 3-6; formerly known as Hermit Shale) is a mixed red bed unit composed of very fine grained sandstone, siltstone, and minor mudstone. At GRCA, it is known as a reddish-brown, slope-forming unit (Blakey 2003). Its common alternate name is a misnomer, as it includes very little true shale. The thickness varies greatly from 49 m (160 ft) in eastern GRCA to 244 m (800 ft) in western GRCA (Beus and Billingsley 1989). It dates to the late early Permian (Blakey 2003). Although there is an unconformity between the Hermit Formation and the underlying Esplanade Sandstone with deep channel cuts, there was probably little time between the two (White 1927). The upper contact, with the Coconino Sandstone, is also disconformable, but is sharp (Beus and Billingsley 1989). The Hermit Formation is interpreted as a broad coastal plain and fluvial, but was also deposited as loess and scattered eolian dunes (Blakey and Middleton 2012). The climate was probably semi-arid, with long hot, dry seasons (White 1929).

Coconino Sandstone (lower Permian)

The Coconino Sandstone (Figure 3-6) is a fine-grained eolian sandstone, changing from white and tan, to brown or red in western GRCA (Beus and Billingsley 1989). This unit is bracketed by other units dated to the late early Permian (Blakey and Knepp 1989). From east to west, the unit thickens rapidly in eastern GRCA to 210 m (700 ft) and then thins to practically nothing in western GRCA. Its base forms a sharp unconformity with the Hermit Formation (Beus and Billingsley 1989). The upper contact with the Toroweap Formation intertongues (Blakey and Knepp 1989). The Coconino Sandstone is interpreted as an eolian unit formed as an erg (Hunt et al. 2005). Sand was deposited by wind action (Blakey and Knepp 1989).

Toroweap Formation (lower Permian)

The Toroweap Formation (Figure 3-6) has been studied extensively and offers striking lateral and vertical changes in lithofacies over a relatively small area. Members with carbonate and evaporite lithologies are more easily discerned in western outcrops and these distinctions become absent in the eastern phase that is mostly cross-bedded sandstone (Turner 2003).

In the west it can be divided into three members in the GRCA area; in ascending order these are the Seligman, Brady Canyon, and Woods Ranch Members The relatively thin Seligman Member appears to intertongue and be conformable with the underlying Coconino Sandstone and is no thicker than 15 m (45 ft) at GRCA (Turner 2003). Above the Seligman Member is the overlying Brady Canyon Member, a cliff-forming carbonate unit composed of limestone and mixed dolostone in western GRCA. The Brady Canyon Member is thickest in western GRCA, up to 93 m (280 ft) thick. The Brady Canyon Member thins uniformly to the east to its depositional edge near Marble Canyon and grades into the overlying Woods Ranch Member, mostly made of repetitive evaporites, limestone, and sandstone. The Woods Ranch Member forms distinctive slopes and attains a maximum thickness of about 60 m (180 ft) (Turner 2003). The Woods Ranch Member is interpreted as a shallow evaporitic marine shelf. The climate during deposition of the Toroweap Formation is thought to have been semi-arid to arid (Turner 2003). At GRCA, gypsum and/or contorted sandstones of the Woods Ranch Member always underlie the Kaibab Formation. (Hopkins and Thompson 2003).

Most fossils in the Toroweap Formation are from the Brady Canyon Member, with fossils in the Woods Ranch Member limited to an unusual *Schizodus* bed near the top of the member (McKee 1938; Rawson and Turner 1974).

Kaibab Formation (lower–middle Permian)

The Kaibab Formation (Figure 3-6) is a complex sedimentary package of numerous lithologies. At GRCA, it forms the canyon rim and is 90 to 120 m (300 to 400 ft) thick (Hopkins and Thompson 2003). Early workers divided the Kaibab Formation into the Gamma, Beta, and Alpha Members (McKee 1938), which have since been subsumed into the Fossil Mountain and overlying Harrisburg members. The Fossil Mountain Member is the equivalent of the Gamma and Beta Members, and the

Harrisburg Member is the equivalent of the Alpha Member (Blakey and Knepp 1989). Chert is a major feature of the Fossil Mountain Member at GRCA, and it is quite voluminous and varied in character and weathers to form distinct recesses along cliff faces. It is mostly attributed to the original distribution and abundance of siliceous sponges and spicules. In the west, the Fossil Mountain Member is more carbonate-rich (fossiliferous limestone) but becomes more siliciclastic eastward (sandstone, sandy carbonate, and dolomite) (Hopkins and Thompson 2003). It thickens westward and ranges from 75 to 205 m (250 to 300 ft) thick, to approximately 60 m (200 ft) at the type section at Fossil Mountain along the south rim. The Harrisburg Member constitutes the uppermost cliffs and ledges at GRCA and is a mixed unit including gypsum, dolostones, sandstone, redbeds, chert, and minor limestone. Thicknesses range from 25 to 90 m (80 to 300 ft) at GRCA, and numerous subunits are discernable in its overall extent (Hopkins and Thompson 2003).

The Kaibab Formation is evidence of an ancient seaway covering the GRCA area in the Permian. A complex depositional history is evidenced by the mixing of carbonates and siliciclastics with numerous variations of subtidal to shallow-marine settings. The Fossil Mountain Member documents a west to east shift of fossiliferous open-marine limestones to restricted-marine sandy dolostones and the Harrisburg records retreat of the Kaibab Sea (Hopkins and Thompson 2003).

Mesozoic Stratigraphy of Grand Canyon

Limited exposures of Mesozoic formations are found at Cedar Mountain near Desert View in GRCA, including the Lower–Middle Triassic Moenkopi Formation and the Upper Triassic Chinle Formation. These units were evaluated for paleontological resources during the 2019 GRCA PaleoBlitz and are discussed in Chapter 10 of this volume. Additionally, the Lower Jurassic Wingate Sandstone, Moenave Formation, Kayenta Formation (and Springdale Sandstone Member), and Navajo Sandstone are known in the surrounding Grand Canyon region (Billingsley et al. 2019) but not within GRCA.

Moenkopi Formation (Lower–Middle Triassic)

The Moenkopi Formation (Figure 3-7) is a continental red-bed unit found across the American Southwest (McKee 1954; Stewart et al. 1972a) that includes marginal marine depositional facies in its western exposures (Nevada and Utah) and regressive freshwater fluvial and lacustrine facies in its eastern exposures (Arizona and New Mexico). The only complete section of Moenkopi Formation exposed within GRCA occurs at Cedar Mountain, adjacent to the far eastern boundary near Desert View. This 2 km (1.2 mi) wide feature is largely covered by loose talus and juniper trees, but includes the Wupatki, Moqui, and Holbrook Members, all of which are also exposed along the nearby Little Colorado River Valley from Cameron to Holbrook, Arizona. Noble (1922) determined that the Moenkopi Formation at Cedar Mountain is nearly 150 m (490 ft) thick. The Wupatki Member at Cedar Mountain is characterized by low mounds of ripple-laminated sandstone, the Moqui Member is a slope-former with interbedded evaporite/channel complexes, and the Holbrook Member includes the cliff-forming “upper massive sandstone”. Fossils have been reported from the Moenkopi Formation at GRCA (Marsh et al. this report), and similar sections nearby are known for producing actinopterygian fish, mastodonsauroid, trematosaurian, and brachyopid temnospondyl amphibians, tanystropheid reptiles, and pseudosuchian archosaurs (Welles 1947, 1969; Nesbitt 2000, 2005a, 2005b). Terrestrial vertebrate (Lucas 2010; Martz and Parker 2017), ichnological biochronology (McKee 1954; Klein and Lucas 2010; Henderek et al. 2017), and U-Pb detrital zircon geochronology (Dickinson and Gehrels 2009) suggest that at least the uppermost part of the Moenkopi Formation is Middle Triassic in age.

Figure 3-7. Mesozoic rocks in eastern GRCA at Cedar Mountain (NPS/DIANA BOUDREAU).

Chinle Formation (Upper Triassic)

The only exposure of the Chinle Formation (Figure 3-7) within eastern GRCA caps the Moenkopi Formation section at Cedar Mountain and is represented by the Shinarump Member (formerly the "Shinarump Conglomerate"; Noble 1922; Repenning et al. 1969; Stewart et al. 1972b). It is approximately 8 m (26 ft) thick here and is characterized by well-cemented channel conglomerates with mud rip-up clasts and pieces of (or entire) petrified conifer trees. No vertebrate fossils are known from the Chinle Formation (Shinarump Member) at GRCA, but terrestrial vertebrate biochronology and U-Pb detrital zircon geochronology of overlying and/or equivalent units constrain the entire Chinle Formation to the Late Triassic (Lucas 2010; Atchley et al. 2013; Riggs et al. 2016; Martz and Parker 2017; Kent et al. 2019).

Conclusions

The Grand Canyon serves as a geologic and paleontologic window into the past. The park contains colorful, awe-inspiring rocks and traces of life that showcase spectacular stratigraphy and tell a vast story of almost two billion years of earth history and organism evolution, making it one of the geologic wonders on Earth. The Vishnu Basement rocks, Grand Canyon Supergroup rocks, and Layered Paleozoic rocks combine to present a story like no place on Earth. These old rocks contrast nicely with the geologically "young" age of the canyon. Magmatism, volcanism, metamorphism, deposition, and erosion are all visible on a grand scale at Grand Canyon, leaving their evidence for the viewer to decipher this planet's rich geologic history and record of organism evolution over the eons.

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