GEOLOGIC MAP OF GRAND CANYON'S MIDDLE GRANITE GORGE

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This map and cross section were prepared as part of Jason Boryszewski's UNM MS thesis (2025), with Karl Karlstrom as thesis advisor. New field mapping on several 2023–2025 UNM research river trips was combined with legacy basement mapping from Ilg and Karlstrom (in Hamboo et al., 1996, Ilg et al., 1996), Karlstrom et al. (2003), and numerous research trips in the past two decades. Unkar Group, Paleozoic strata, and Phanerozoic faults were modified from Noble (1914), Hamboo et al. (1996), and Billingsley et al., (2000) using mapping and Google Earth mosaic satellite imagery, GCMRC 2014 orthomosaic imagery, and Maxar Vivid standard 1.2-0.6 m aerial imagery. The Surprise Valley Landslide Complex was mapped by Jesse Robertston and Karl Karlstrom (Robertson et al., 2021). Updated geochronology is from numerous published papers as summarized in Karlstrom et al. (2021).

Author roles were as follows: Jason Boryszewski: map compilation in GIS, creation of GDMs database, structural analysis using stereonets and microstructures, field mapping, mapping based on remotely sensed datasets (e.g., satellite imagery and aerial photography), writing. Karl Karlstrom: conceptualization, field mapping, map compilation, structural interpretation, down-plunge projection, writing, editing, and thesis supervision. Map layout by Allyson Mathis.

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DESCRIPTION OF MAP UNITS

QUATERNARY SURFICIAL DEPOSITS

- **Qaf** — **Alluvium and colluvium deposits (Holocene to Pleistocene)**: clay, silt, fine- to coarse-grained sand, and gravel deposited by alluvial processes in the Colorado River corridor and subterranean tributaries.
- **Qc** — **Colluvium and talus (Holocene to Pleistocene)**: abundant small to large angular blocks of local country rock mixed with silt, sand, and gravel distributed on hillslopes due to rock fall and down-slope gravity-driven creep of bedrock.
- **Qtr** — **Travertine deposits (Holocene to Pleistocene)**: freshwater limestone associated with active and nonactive springs, formed by CO_2 degassing and chemical precipitation of calcium carbonate. Elves Chasm cliffs have travertine up to 10s-thick draped on bedrock and the contorted Colorado River gravels up to 1–2 million years old (Crow et al., 2014).
- **Qtg** — **Older terrace gravels of Colorado River (early to middle Pleistocene)**: ancestral Colorado River gravels preserved as terrace remnants above modern river level, correlate fan-travertine clasts (e.g., quartzite and chert) and Kaibab Limestone clasts. Gravels are inset into Surprise Valley Fm. and Qls1 and are capped by 189 m.a. above the river and range in age from 677 ka (1,877 a.a.l.) (Crow et al., 2014). In Surprise Valley area, gravels that underlie landslides constrain timing of formation of landslide elements; those that overlie landslides indicate timing of overstepping of landslide deposits (Robertson et al., 2021).
- **Qls** — **Landslide deposits undivided (Holocene to Pleistocene)**: mass movement deposits consisting of unconsolidated to partially consolidated angular rock debris resulting from discrete mass failures of various types ranging from rock topples to slides.
- **Qsl, Qsl1** — **Paleolake facies in the Surprise Valley Landslide Complex (Pleistocene)**: sediments deposited in a lacustral, swamp, or bog environments in a headwater basin.

Surprise Valley Landslide Complex Paleozoic strata: Torova blocks of identifiable, displaced Paleozoic strata.

- **Qsl/Pc** — Qtp/Pc: Wescogame, Manakacha, and Watahomigi members of the Supai Group undifferentiated
- **Qsl/Ph** — Qsl/Ph: Redwall Limestone
- **Qsl/Pe** — Qsl/Pe: Temple Butte Formation
- **Qsl/Pr** — Qtr/Pr: Muav Formation.
- **Qsl/Cc** — Qtr/Cc: Rampart Cave and Sanup Plateau members of the Muav Formation.
- **Qsl/Ct** — Qtr/Ct: Tapeats Sandstone.

- **Qs/Xb** — **Backeddy landslide (~0.17 Ma)**: was a subsequent slide from SV4 and SV7 that filled the Colorado River paleochannel and pushed the river farther to the south.
- **Qs/Xf** — **Fishtail landslide (~0.48 Ma)**: was a subsequent slide from SV4 that re-routed Deer Creek #2 (DC2) to its present position (Deer Creek #1, DC1) to form Deer Creek Falls and the narrows. The landslide is visible as "the Patio" above Deer Creek Falls.
- **Qs/Xs** — **153-Mile landslide (~0.61–0.71 Ma)**: was a subsequent slide caused by a landslide lake formed from SV3 and/or SV4 that undermined southside bedrock and slid on the Bass Formation ash.
- **Qs/Xt** — **Tapeats landslide (~0.53 Ma)**: involved slide of Rampart Cave dolostone that slid down into Tapeats Creek.
- **Qs/Xw** — **Powhow landslide (~0.63 Ma)**: slabs of Rampart Cave dolostone and Redwall Limestone detached from above the Patio landslide on the north side and were thrust up the south side of the river.
- **Qs/Xp** — **Piano landslide (~0.674 Ma)**: can be seen on "Piano" hike at RM 133.6ft. Qtg gravels beneath the landslide are capped by a 674 ± 0.022 Ma basalt flow (Crow et al., 2014). Basalt clasts in landslide stratified from this gravel given an age of 674 ± 0.022 Ma yielding an incision rate of ~138 m/Ma.
- **Qs/Xf2** — **Cogswell West landslide (~0.82–0.9a Ma)**: was a secondary slide from SV1 that pushed initial Deer Creek location (Deer Creek #1, DC1, near River Mile (RM) 136.3) to near RM 137.1 (DC2).
- **Qs/Xs** — **Surprise Valley initial landslide (~2.09 Ma)**: Torova blocks filled an ancestral path of the Colorado River through Surprise Valley ~2.09 Ma based on 209-m-height of the base of this landslide above the modern bedrock strath and applying an inferred steady incision rate of 138 m/My derived from SV1. This same method is applied to estimate age of the rest of the landslides (Robertson et al., 2021).

PALEOZOIC SEDIMENTARY STRATA

average thicknesses from Beus and Billingsley (1989) for ~RM 140; ages from Karlstrom and Crossey (2019) and Karlstrom et al. (2021)

- **Ka** — **Kaibab Formation (Lower Permian, ~267–272 Ma)**: 163-m thick, forms the cliffs at the rim of the Grand Canyon. Limestone and siltstone deposited in shallow sea.
- **Ks** — **Toroweap Formation (Lower Permian, ~272–278 Ma)**: 227-m thick, slope-forming gypsiferous siltstone, sandstone, and thin-bedded limestone; deposited in evaporative mudflats of Kaibab seaway.
- **Kcs** — **Coconino Sandstone (Lower Permian, ~280 Ma)**: 46-m thick, white, fine-grained, well-sorted, cross-bedded quartz sandstone with large-scale cross-bedding and fossil reptile tracks, cliff former; deposited in transitional sand sheet adjacent to Kaibab seaway.
- **Kh** — **Hermit Formation (Lower Permian, ~290–284 Ma)**: 177-m thick, red, slope-forming, fine-grained, thin-bedded siltstone and sandstone; deposited in mudflats.
- **Kp** — **Esplanade Sandstone (Lower Permian, ~294–290 Ma)**: 107-m thick; light-red and pinkish-gray, cliff-forming, fine- to medium-grained, well-sorted, calcareous sandstone, mostly of eolian origin; Esplanade platform in map area.
- **Pwp** — **Wescogame and Manakacha Formations (Pennsylvanian, ~299–317 Ma)**: 101-m thick; sandstone, calcareous sandstone, dark-red siltstone, and gray limestone.
- **Pwc** — **Watahomigi Formation (Pennsylvanian, ~318–323 Ma)**: 61-m thick, gray and purplish-red, slope-forming limestone, siltstone, mudstone, and conglomeratic sandstone.
- **Mm** — **Surprise Canyon Formation (Mississippian, ~324–326 Ma)**: 0–18-m thick, siltstone, sandstone, limestone, and pebble to cobble chert conglomerate; present in paleovalleys and karst caves eroded into top of Redwall Limestone (Mr).
- **Mr** — **Redwall Limestone (Mississippian, ~333–348 Ma)**: 183-m thick, cliff-forming gray fossiliferous limestone, stained red by iron oxide coating from overlying Supai Group; deposited in a regional seaway; karsted at top.
- **Dtb** — **Temple Butte Formation (Devonian, ~375–385 Ma)**: 61-m thick, dark-gray fine-grained dolostone unconformably bounded from underlying Cambrian carbonates by thick basal dark-gray chert layer.
- **Unconformity**: ~110–160 million years "missing" (not recorded) due to erosion of uppermost Cambrian, Ordovician, Silician, and Early Devonian strata.

- **Cbm** — **Frenchman Mountain Formation (Cambrian, ~497–501 Ma)**: 81-m thick, several-m-scale layering of gray dolostone and tan sandstone; appearance in carbonate cliffs often continuous with units above and below.
- **Cmc** — **Muav Limestone (Cambrian, ~501–502 Ma)**: 142-m thick, thin-bedded mottled, fossiliferous, silty limestone and dolostone with several slope-forming shales.
- **Cbs** — **Bright Angel Formation (Cambrian, ~502–505 Ma)**: 113-m thick, slope-forming green and purple-red mudstone shale. Red lines are rarely brown dolostone tongues of Bright Angel Fm formation that correlate with Rampart Cave and Sanup Plateau Members of Muav Formation to the west.
- **Ctp/Cc** — **Tapeats Sandstone (Cambrian, ~505–506.4 Ma)**: 46-m-thick, brown cliff-forming sandstone and conglomerate with upper slope-forming transition beds.

Sub-Tonto Group Great Angular Unconformity: contact where ~0.5 Ma Tonto Group was deposited across 1,840–1,375 Ma basement plus tilted 0.250–750 Ma tilted Cardenas Supergroup with variable time missing (not recorded) due to erosion of underlying units.

UNKAR GROUP OF GRAND CANYON SUPERGROUP

Bisikiwnon from Noble (1922)

- **Xd** — **Diabase sills and dikes (Mesoproterozoic, 1,098 Ma)**: black, medium- to coarse-grained intrusive Proboc geomorphic segregation yields (1.09-dun of 1,098.2 ± 0.6 Ma (Mohr et al., 2024). Unit has distinctive diabase texture with interlocking, lath-shaped plagioclase feldspar crystals within anhedral olivine and pyroxene crystals. Sills are up to 200-m thick near Bass Rapids, intrusive contacts caused contact metamorphism (hornfels) of Unkar Group sedimentary rocks.
- **Xv** — **Dox Formation (Mesoproterozoic, 1,100–1,130 Ma)**: up to 700-m thick in map area, top not exposed. Rusty red-brown fine- to medium-grained sandstone and interbedded slope-forming shale and mudstone; interpreted to have formed in fluvial and deltaic environments (Timmons et al., 2012). Contact with the underlying Shinumo Sandstone is gradational and located at lowest shaley slope of Dox Formation.
- **Xcz** — **Nankoweap Formation (Mesoproterozoic, 1,140–1,170 Ma)**: 477-m thick, white to purple cliff-forming silica-cemented sandstone; cliff bands shown with gray overlay. Interpreted to have formed in a high-energy shallow-marine environment (Timmons et al., 2012) with tide-modulated sediment from Texas Grenville thrust sheets (Mulder et al., 2017).
- **Xbt** — **Bass Limestone (Mesoproterozoic, 1,230–1,250 Ma)**: 177-m thick, purple and red mud-cracked and ripple-marked limestone, sandstone, and minor conglomerate. Middle slope unit is dominated by mudstone and sandstone; lower contact gradational with Vb. Interpreted to have been deposited in a marginal marine-tidal flat environment (Timmons et al., 2012).
- **Xbm** — **Bass Formation (Mesoproterozoic, 1,250–1,255 Ma)**: 100-m thick, purple ledge-forming dolostone, silty mudstone, and conglomerate. White dolostone with ash beds shown by white line. Hematite Conglomerate Member (Xbmc) is a 0–30-m-thick, cliff-forming, clast-supported, pebble to cobble conglomerate rounded to subangular clasts of granite, quartzite, and schist derived from underlying Early Proterozoic igneous and metamorphic rocks. Ash bed in eastern Grand Canyon yielded a U-Pb age of 1,255 Ma (Karlstrom et al., 2001).

Sub-Bass Great Nonconformity: contact recording the erosion of the Vishnu Mountains from ~1,660 to 1,250 Ma and exhumation of middle crustal basement rocks from 20-km depths, with ~600 Ma of time "missing" (not recorded).

VISHNU BASEMENT ROCKS

- **Xgp** — **Granite, granitic pegmatite, and aplite (Paleoproterozoic, 1,625–1,697 Ma)**: network of tabular granitic dikes emplaced along S1 and cross-cutting S1; variably deformed by D2 folds indicating syn-D2 emplacement. Gamet dike swarm: 1,695 ± 3 Ma at RM 111.8 (Hawkins et al., 1996) and 1,678 ± 27 Ma at RM 114.9. Specter Dike swarm: 1,625 ± 8 Ma at RM 131. Deer Creek granite: 1,646 ± 17 (Boryszewski et al., 2026).
- **Xgr** — **Ruby granodiorite (Paleoproterozoic, 1,716 Ma)**: gabbro-diorite-granodiorite pluton exposed from RM 109.2 to RM 110.5 (Ilg et al., 1996; Hawkins et al., 1996). Ruby pluton has sharp, discordant contacts and mixing relationships between co-magmatic mafic to intermediate melts and local primary shoot-like cumulate layering; interpreted to have formed in magmatic arc batholith, variably deformed by D2.
- **Xgn** — **Ultramafic rocks (Paleoproterozoic)**: variably serpentinized peridotite (ultramafic) bodies preserved as boudinaged tectonic slivers within Vishnu Schist near mouth of Wildhorse Canyon; interpreted to be magmatic arc cumulates (Sumner et al., 2021).
- **Xv** — **Vishnu Schist (Paleoproterozoic, ~1,740 Ma)**: massive, fine-grained, quartzofeldspathic schist and gneiss with S1 foliation; dikes to intermediate-textural-intrusive origin, dated in eastern Grand Canyon as 1,741 ± 1 Ma (Hawkins et al., 1996) and in western Grand Canyon as 1,735.5 Ma ± 0.85 Ma (Bailey et al., 2024), interbedded with Brahma and Vishnu schists.
- **Xb** — **Brahma Schist (Paleoproterozoic, ~1,750 Ma)**: amphibolite, hornblende-biotite-plagioclase schist, biotite-plagioclase schist, schist, and gneiss interpreted to be metabasalt of submarine origin based on primary volcanic features (Xbqtb) such as relic pillow structures, hyaloclastic breccia, amygdules, and interbedded chert (RM 120.2B). Less foliated and coarser-grained amphibolites may have been mafic dikes. Unit yielded a U-Pb zircon date of 1,750 ± 2 Ma in eastern Grand Canyon (Hawkins et al., 1996).
- **Xv** — **Vishnu Schist (Paleoproterozoic, ~1,750 Ma)**: quartz-mica and pelitic schist interpreted as metamorphosed felsic-arenites (meta-greywackes); contains calc-silicate lenses and shows common evidence for graded bedding interpreted to be Bouma sequences from submarine turbidity flows. Depositional age: ~1,750 Ma based on youngest detrital zircon dates and interlayering with Brahma and Zoroaster Plutonic Suite rocks. Unit shows a bimodal detrital zircon age distribution with major modes at ~2,400 and ~1,800 Ma (Doe&Holt et al., 2010; Holland et al., 2016).
- **Xzpg** — **Elves chasm zone (Paleoproterozoic)**: ~100-m-wide contact zone of the Elves Chasm Gneiss with tectonic stripping top of Granite Gorge Metamorphic Suite orthoamphibolite-bearing gneiss, siliimanite-kyanite gneiss, and felsic gneiss with garnet ± felsic leucosome textures reflecting biotite dehydration melting. Kinematic indicators show dextral-normal, top-to-south movement, interpreted as D1 shear zone that has been folded by a regional F2 fold.
- **Xzpf** — **Elves Chasm Gneiss (Paleoproterozoic, 1,840 Ma)**: orthogneiss of granodiorite to tonalite composition dated as 1,840 ± 3 Ma (Hawkins et al., 1996); includes tabular amphibolite bodies (Xzgb) that may be ortho-amphibolite dikes and/or tectonic slivers of Brahma Schist. The margins of the pluton are the D1 Xenz; interior is variably deformed and includes L-tectonites, L/S tectonites, and weakly deformed plutonic rock.

EXPLANATION OF MAP SYMBOLS

- Contacts: dashed where approximate; dotted where inferred beneath younger deposits
- Dip and strike of bedding
- Dip and strike of overturned bedding
- Younging direction from graded bedding
- Dip and strike of S1 foliation and L1 stretching lineation (dominant foliation)
- Dip and strike of S2 foliation and L2 stretching lineation; mark foliation in D2 shear zones
- Dip and strike of S3 foliation and L3 stretching; mark kinks and crenulations that fold S2
- Bearing and plunge of minor fold axis showing symmetrical (M-shaped) profile view
- Bearing and plunge of minor fold axis showing clockwise (Z-shaped) asymmetrical profile view
- Bearing and plunge of minor fold axis showing counterclockwise (S-shaped) asymmetrical profile
- Normal fault, showing dip (if measured); U: on upthrown block; D on downthrown block
- Reverse fault, teeth on upthrown block
- Anticline; arrows show dip direction of limbs
- Overturned (inclined) anticline; arrows show dip direction of limbs
- Syncline; arrows show dip direction of limbs.
- Overturned (inclined) syncline, arrows show dip direction of limbs
- Monocline; arrow shows dip direction of steep limb
- Shear zone
- Form line showing dominant foliation
- Inferred pathway of ancestral Colorado River beneath Surprise Valley landslides
- Landslide detachment

CORRELATION OF MAP UNITS AND GEOLOGIC HISTORY

5 Ma to present: Carving of Grand Canyon by the Colorado River and deposition of Quaternary surficial deposits.

90 Ma to present: Uplift of the Colorado Plateau from approximately sea level and erosion of ~2 km of Mesozoic strata that were once present in the region.

307–270 Ma: Deposition of ~1 km of Paleozoic strata; region remained near sea level as strata accumulated and depressed continent.

1,000–500 Ma: Formation of Great Angular Unconformity: Precambrian units eroded to near sea level except for a Cambrian Shinumo archipelago formed by the resistant Shinumo Sandstone.

~1,100 Ma: Tilting of Grand Canyon Supergroup due to NE–SW extension on NW-striking domino-style normal faults during the greater Grenville orogeny and assembly of the supercontinent of Rodinia across collisional mountain belt forming in Texas.

1,098 Ma: Intrusion of diabase sills due to movement of North America over a mantle plume to form the NW USA large igneous province.

1,250–1,100 Ma: Deposition of Unkar Group in foreland of Grenville orogenic belt (located in Texas). Wheeler monocline forms from NW–SE compression.

1,680–1,250 Ma: Great Nonconformity formed from erosion of ~ 20 km of crust from Vishnu Mountains to expose middle crustal levels.

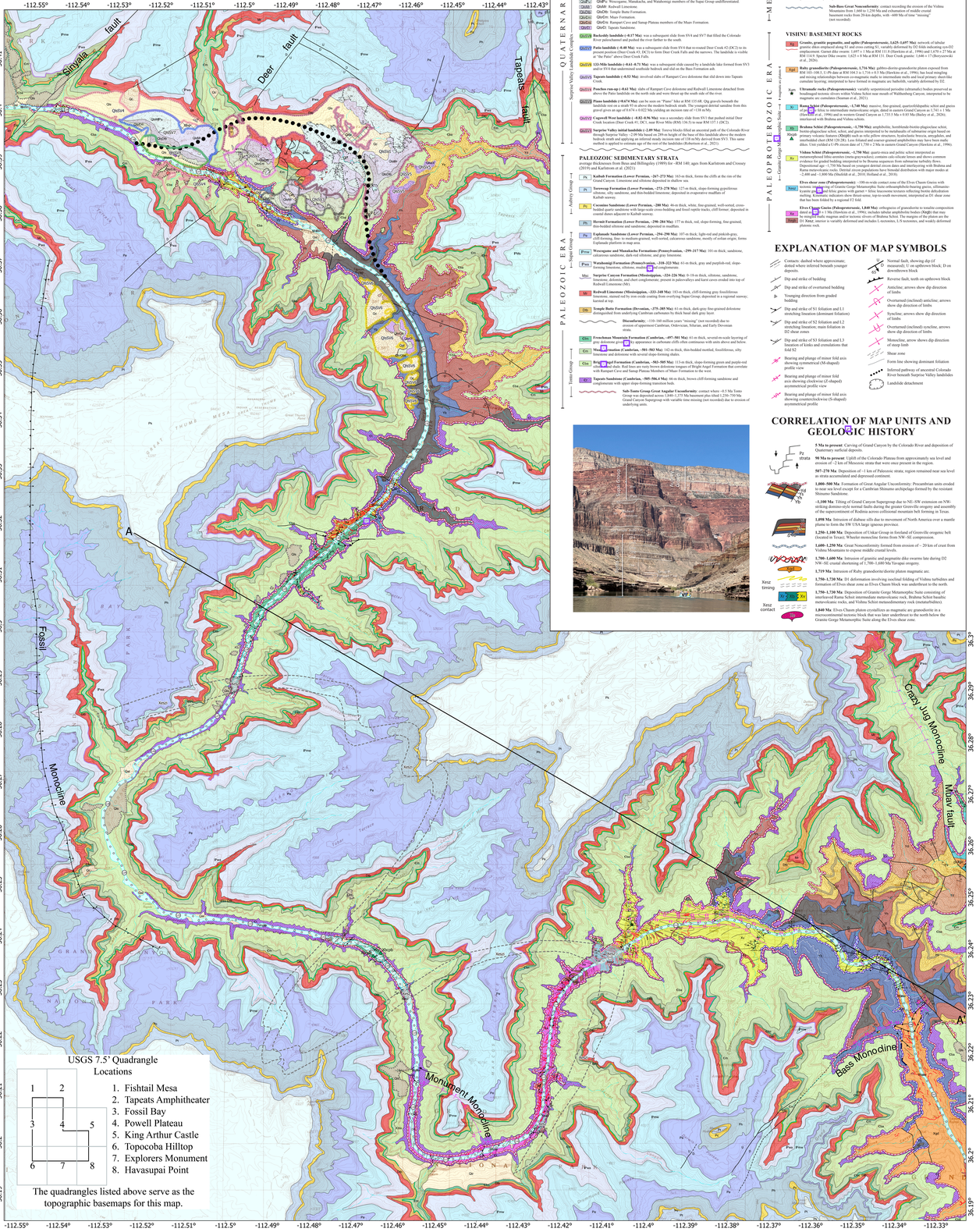
1,700–1,680 Ma: Intrusion of granitic and pegmatitic dike swarms late during D2 NW–SE crustal shortening of 1,700–1,680 Ma Yavapai orogeny.

1,719 Ma: Intrusion of Ruby granodioritic/diorite pluton magmatic arc.

1,750–1,730 Ma: D1 deformation involving isoclinal folding of Vishnu turbidites and formation of Elves shear zone as Elves Chasm block was underthrust to the north.

1,750–1,730 Ma: Deposition of Granite Gorge Metamorphic Suite consisting of interlayered Rama Schist intermediate metavolcanic rock, Brahma Schist basaltic metavolcanic rocks, and Vishnu Schist metasedimentary rock (metaturbidite).

1,840 Ma: Elves Chasm pluton crystallizes as magmatic arc granodiorite in a microcontinental tectonic block that was later underthrust to the north below the Granite Gorge Metamorphic Suite along the Elves shear zone.



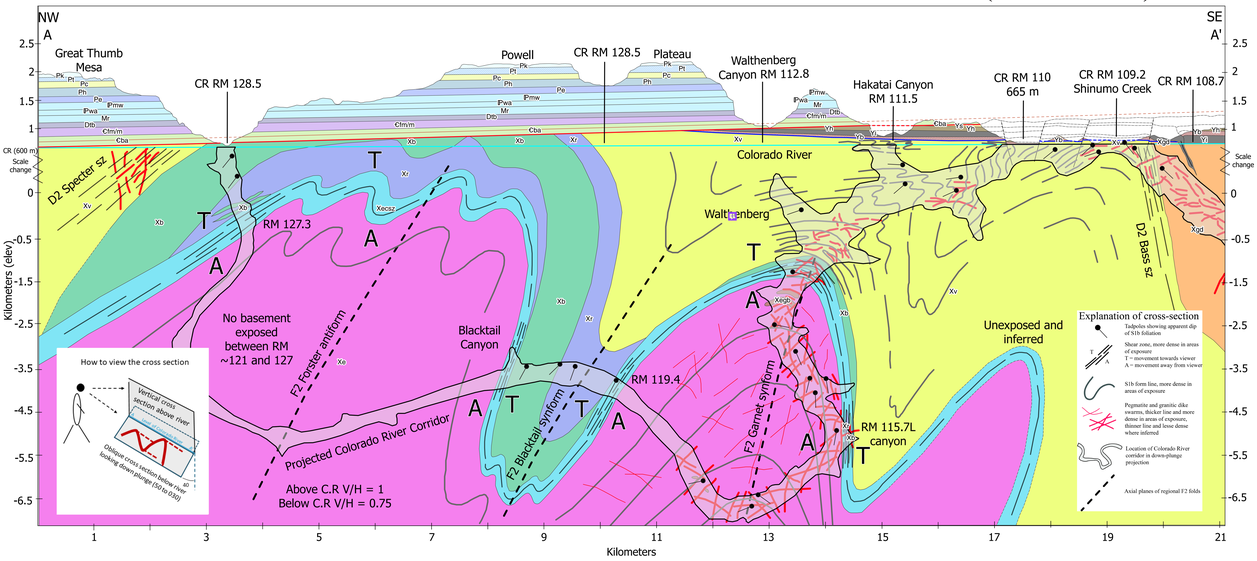
USGS 7.5' Quadrangle Locations

1. Fishtail Mesa
2. Tapeats Amphitheater
3. Fossil Bay
4. Powell Plateau
5. King Arthur Castle
6. Topocoba Hilltop
7. Explorers Monument
8. Havasupai Point

The quadrangles listed above serve as the topographic basemaps for this map.

0 1.5 3 4.5 6 Kilometers
0 1 2 3 Miles

10°E
True North
Magnetic North

1:24,000
Coordinate system: NAD83 UTM Zone 12N
Projection: Transverse Mercator

MIDDLE GRANITE GORGE CROSS SECTION AND DOWN-PLUNGE PROJECTION (50° toward 030°)