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Redefining the Tonto Group of Grand Canyon and recalibrating the Cambrian time scale

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ABSTRACT

We applied tandem U-Pb dating of detrital zircon (DZ) to redefine the Tonto Group in the Grand Canyon region (Arizona, USA) and to modify the Cambrian time scale. Maximum depositional ages (MDAs) based upon youngest isotope-dilution DZ ages for the Tapeats Sandstone are ≤508.19 ± 0.39 Ma in eastern Grand Canyon, ≤507.68 ± 0.36 Ma in Nevada, and ≤506.64 ± 0.32 Ma in central Arizona. The Sixtymile Formation, locally conformable below the Tapeats Sandstone, has a similar MDA (≤508.6 ± 0.8 Ma) and is here added to the Tonto Group. We combined these precise MDAs with biostratigraphy of trilobite biozones in the Tonto Group. The Tapeats Sandstone is ca. 508–507 Ma; the Bright Angel Formation contains *Olenellus*, *Glossopleura*, and *Ehmaniella* biozones and is ca. 507–502 Ma; and the Muav Formation contains *Bolaspidella* and *Cedaria* biozones and is ca. 502–499 Ma. The Frenchman Mountain Dolostone is conformable above the Muav Formation and part of the same transgression; it replaces McKee's Undifferentiated Dolomite as part of the Tonto Group; it contains the *Crepicephalus* Biozone and is 498–497 Ma. The Tonto Group thickens east to west, from 250 m to 830 m, due to ~300 m of westward thickening of carbonates plus ~300 m of eastward beveling beneath the sub-Devonian disconformity. The trilobite genus *Olenellus* occurs in western but not eastern Grand Canyon; it has its last appearance datum (LAD) in the Bright Angel Formation ~45 m above the ≤507.68 Ma horizon. This extinction event is estimated to be ca. 506.5 Ma and is two biozones below the Series 2–Miaolingian Epoch boundary, which we estimate to be ca. 506 Ma. Continued tandem dating of detrital grains in stratigraphic context, combined with trilobite biostratigraphy, offers rich potential to recalibrate the tempo and dynamics of Cambrian Earth systems.

INTRODUCTION

The Tonto Group of Grand Canyon (Arizona, United States) was defined by G.K. Gilbert (1875, his figure 82) and John Wesley Powell (1876, p. 60) and recognized to be Cambrian by Charles Walcott (1895, p. 317). It is now a textbook example of a marine transgressive sequence. Sloss (1963) applied the term "Sauk sequence" in mid-Laurentia where this transgressive sequence overlies the basement unconformity, and he challenged geologists to correlate successions from the plate margins to the interior in order to understand driving mechanisms. Six decades later, the timing, duration, and mechanisms for the Sauk transgression(s) and much of the Cambrian time scale remain incompletely understood, in part because of limited precise dating (Landing et al., 2015). This study builds on the research of Karlstrom et al. (2018) by dating detrital zircon (DZ) from above the Great Unconformity in Grand Canyon. The Sixtymile Formation, beneath the Great Unconformity and previously considered Precambrian, contains youngest Cambrian zircon populations that provide maximum depositional ages (MDAs) from ≤527.4 ± 0.7 Ma to ≤508.6 ± 0.8 Ma. These ages suggest that the protracted Neoproterozoic to Cambrian rifting history of western Laurentia is recorded by earlier Sauk I fault-bounded rift basins, followed by Sauk II successions that record rapid flooding of the continent at 510–500 Ma (Karlstrom et al., 2018).

Figure 1 shows the extent of the Tonto Group and equivalent strata. Marine inundation took place across a generally low-relief erosion surface that had local, up to 200-m-high, rock ridges and knobs that formed islands (monadnocks) in the advancing seaway (Rose, 2003, 2006). Here, we contribute new ages for DZs from the Tapeats Sandstone over a wide region of the eastern Grand Canyon, Nevada, and central Arizona, from the craton to the rift hinge line. We also combine our precise U-Pb MDAs with globally calibrated ages of trilobite biozones (Sundberg et al., 2020). More than 120 years since it was defined, and 70 years after the last extensive trilobite collections of McKee and Resser (1945), we propose a new stratigraphic nomenclature for the Tonto Group, recalibrate the Laurentian Series 2–Miaolingian Epoch boundary of the Cambrian time scale to ca. 506 Ma, and better date the Sauk II transgression in western Laurentia.

METHODS

Tandem U-Pb DZ dating merges two techniques to produce highly accurate and precise U-Pb zircon dates: laser-ablation–inductively coupled plasma–mass spectrometry (LA-ICP-MS), followed by chemical abrasion–isotope dilution–thermal ionization mass spectrometry

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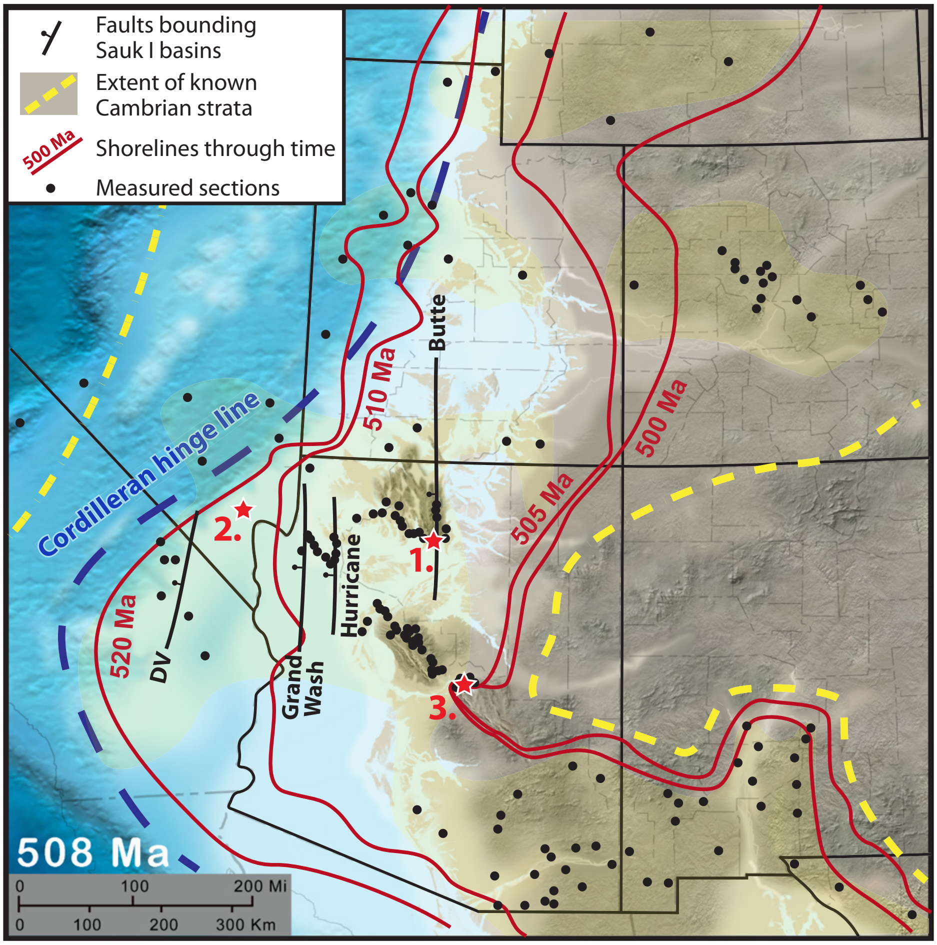


Figure 1. Paleogeographic map of the Sauk II transgression in the southwestern United States shows the progression of 510–500 Ma shorelines (red) as shallow seas inundated a very low-relief continent, leaving ~100-m-thick sheet sandstones (yellow) of the Tapeats Sandstone and correlatives, followed by mudstones and carbonates of the rest of the Tonto Group. Stars and numbers show locations of newly dated samples discussed in the text. Prior Sauk I basins (Karlstrom et al., 2018) may have developed near faults like the Butte fault. Tapeats deposition in the eastern Grand Canyon was strongly influenced by northwest-trending fault-blocks that formed monadnocks. See Figures DR1A–DR1D (see footnote 1) for more detailed time-slice maps. DV—Death Valley region. Red stars with numbers 1, 2, and 3 are locations of dated Tapeats Sandstone samples discussed in text.

(CA-ID-TIMS). LA-ICP-MS dating was applied to 100–300 grains per sandstone sample to identify provenance signatures and the youngest grain populations (Matthews et al., 2017; Karlstrom et al., 2018). Most grains in regional Cambrian successions have ca. 1.7 Ga, 1.4 Ga, and locally 1.1 Ga ages that document unroofing of basement and Mesoproterozoic and Neoproterozoic basin successions (Dehler et al., 2017; Mulder et al., 2017; Matthews et al., 2017). The youngest grains from these sandstones were plucked from the LA-ICP-MS epoxy grain mounts and analyzed with higher accuracy and precision via CA-ID-TIMS. Some grains were broken into multiple fragments, and each fragment was analyzed separately to affirm reproducibility of the U-Pb measurements for single zircon grains. Further details of the CA-ID-TIMS method applied to these samples were described by Macdonald et al. (2018). Our analyses utilized the EARTHTIME ET535 isotope-dilution tracers (Condon et al., 2015; McLean et al., 2015), the decay constants of Jaffey et al. (1971), and the data reduction algorithms of Schmitz and Schoene (2007). We report our interpreted MDAs for sandstones as the mean and 95% confidence interval of the youngest peak in the probability density plot of CA-ID-TIMS $^{206}Pb/^{238}U$ zircon dates.

U-Pb GEOCHRONOLOGIC RESULTS

Figure 2, and Table DR1 in the GSA Data Repository[1], show new CA-ID-TIMS results from three key Tapeats samples from the region:

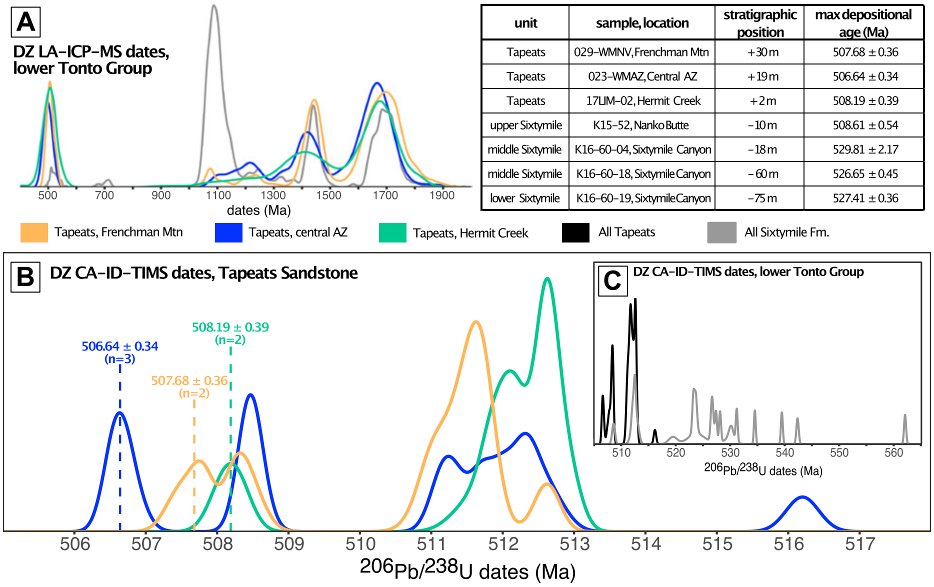
(1) Sample 1 (17LIM-02; sample F of Karlstrom et al. [2018]) is from 2 m above the base of the Tapeats Sandstone in Hermit Creek and ~25 km southwest of the ages previously reported from Sixtymile Formation outcrops. Its weighted mean LA-ICP-MS maximum depositional age of 505 ± 8 Ma (*n* = 12) is superseded by CA-ID-TIMS dates on 14 grains that resolve distinct age populations of ca. 512.7, 512.0, and 508.2 Ma, and a refined MDA of ≤508.19 ± 0.39 Ma (Fig. 2A).

(2) Sample 2 (029-WMNV; sample G of Karlstrom et al. [2018]) is from a coarse-grained, cross-bedded sandstone ~30 m above the base of the Tapeats Sandstone of Frenchman Mountain, Nevada, 18 m below its contact with the overlying Bright Angel Formation (Matthews et al., 2017). Its youngest detrital zircon LA-ICP-MS weighted mean age was 505 ± 2 Ma (*n* = 28); this is superseded by CA-ID-TIMS age populations at ca. 512.6, 511.5, 508.4, and 507.7 Ma, and a new MDA of ≤507.68 ± 0.36 Ma.

(3) Sample 3 (023-WMAZ; sample H of Karlstrom et al. [2018]) is from near the southeastern limit of Tapeats exposures in central Arizona, where Matthews et al. (2017) sampled a coarse-grained, pebbly, cross-bedded sandstone ~19 m above the unconformity with granitic basement. The youngest LA-ICP-MS dates yielded a weighted mean MDA of 501 ± 4 Ma (*n* = 19) that is now superseded by CA-ID-TIMS age populations of ca. 516.2, 512.2, 511.2, 508.5, and 506.6 Ma, and a new MDA of ≤506.64 ± 0.32 Ma.

Figure 2 and Table DR1 show statistically defined, discrete age populations of Cambrian zircons detected thus far in the lower Tonto Group. Older detrital populations in the lower Sixtymile Formation span much of the early Cambrian and constrain its MDA to ≤526.65 ± 0.45 Ma (Fig. 2C). All three Tapeats localities, plus the uppermost Sixtymile Formation, contain clusters of DZ ages in two ranges from 508.5 to 506.5 Ma and 512.9 to 511.0 Ma (Fig. 2B). Based on our present data set of 42 precisely dated Cambrian grains from the Tapeats Sandstone and 24 from the Sixtymile Formation, youngest grains generally get younger up section, and older populations progressively disappear up section (Fig. 2C; Table DR1), raising the question of what is known about near-contemporaneous distant volcanism. Candidates for the source of the zircons include the 510 ± 5 Ma Florida Mountains granite in New Mexico (Amato and Mack, 2012), 535–511 Ma alkaline magmatism in the Wet Mountains of Colorado (Armbrustmacher, 1988), the 535–525 Ma Wichita igneous province in southern Oklahoma (Hanson et al., 2014), Cambrian magmatism in Sonora, Mexico (Barrón-Díaz et al., 2018), or in Idaho (Link et al., 2017).

[1]GSA Data Repository item 2020116, Table DR1 (U-Pb CA-ID-TIMS data showing populations), Figure DR1 (paleogeographic time-slice reconstructions for the Tonto Group transgression), Figure DR2 (age calibration of Laurentian trilobite zones and description of Tonto Group taxa), and an extended caption and additional references for Figure 4, is available online at http://www.geosociety.org/datarepository/2020/, or on request from editing@geosociety.org.



unit	sample, location	stratigraphic position	max depositional age (Ma)
Tapeats	029-WMNV, Frenchman Mtn	+30 m	507.68 ± 0.36
Tapeats	023-WMAZ, Central AZ	+19 m	506.64 ± 0.34
Tapeats	17LIM-02, Hermit Creek	+2 m	508.19 ± 0.39
upper Sixtymile	K15-52, Nanko Butte	−10 m	508.61 ± 0.54
middle Sixtymile	K16-60-04, Sixtymile Canyon	−18 m	529.81 ± 2.17
middle Sixtymile	K16-60-18, Sixtymile Canyon	−60 m	526.65 ± 0.45
lower Sixtymile	K16-60-19, Sixtymile Canyon	−75 m	527.41 ± 0.36

Figure 2. Probability density plots and summary table of detrital zircon (DZ) U-Pb tandem dating results from Cambrian rocks of the Tonto Group (Grand Canyon, Arizona, USA). (A) Laser-ablation–inductively coupled plasma–mass spectrometry (LA-ICP-MS) dates for ~3000 grains from the Lower Tonto Group show peaks at 1.7, 1.4, and 1.1 Ga that reflect unroofing of older Precambrian basement and the Grand Canyon Supergroup, and a strong Cambrian peak. (B) Chemical abrasion–isotope dilution–thermal ionization mass spectrometry (CA-ID-TIMS) analyses resolve the Cambrian peak into precise maximum depositional ages for different Tapeats Sandstone samples. (C) Aggregate of 66 CA-ID-TIMS grains from the Cambrian Tonto Group resolve into ~12 statistically distinct zircon age populations in the pre-Tapeats Cambrian depositional system. Note how grains older than 518 Ma are common in the Sixtymile Formation but absent in all three Tapeats samples. Stratigraphic position column in the table represents elevation above (+) or below (–) basal Tapeats contact. AZ—Arizona.

STRATIGRAPHIC RESULTS

Figure 3 is a synthesis of the Tonto Group results using more than 60 measured sections (McKee and Resser, 1945; Rose, 2006) and a specific type section for the Tonto Group at Blacktail Canyon proposed by Rose (2011). McKee and Resser (1945) summarized how formal stratigraphic nomenclature evolved, and Figure 3 shows our suggested revisions with correlated measured sections and names for units and marker beds. Our proposed stratigraphic changes are as follows:

(1) The Sixtymile Formation is added to the Tonto Group, based on its similar MDA and locally gradational relationship with the Tapeats Sandstone. Its known locations are restricted to the eastern Grand Canyon, and its type section, in Sixtymile Canyon, is described by Elston (1979).

(2) The Tapeats Sandstone includes both the massive cliff-forming sequence and the "transition beds" of intercalated sandstone, siltstone, and shale (McKee and Resser, 1945).

(3) The Bright Angel "Formation" (Wheeler and Kerr, 1936) is preferred to "shale" (Noble, 1922) or "Shale" (Middleton and Elliott, 2003) because it contains interbedded shale (mudstone), siltstone, sandstone, and dolostone. Rusty-brown dolostone tongues in the western Grand Canyon (McKee and Resser, 1945) are considered approximately correlative to maroon arkosic sandstones in the east (Rose, 2006).

(4) The Muav "Formation" (Wheeler and Kerr, 1936) is preferred to Muav "limestone" (Noble, 1922), or "Limestone" (Middleton and Elliott, 2003) because it also contains interbedded limestone, dolostone, sandstone, siltstone, and shale. Its gradational base with the Bright Angel Formation is placed at the base of the lowest massive mottled limestone above the highest maroon sandstone and brown dolostone of the Bright Angel Formation (McKee and Resser, 1945).

(5) The Frenchman Mountain Dolostone (after Rowland and Korolev, 2011) is added to the Tonto Group to replace McKee and Resser's (1945) Undifferentiated Dolomite and Brathovde's (1986) "Grand Wash Dolomite." Its base is a package of thick-bedded dolostone that overlies the highest cliff-forming limestone beds of the Havasu Member of the Muav Formation; its top is marked by the overlying Dunderberg Shale Member of the Nopah Formation at Frenchman Mountain or the sub-Devonian disconformity farther east. Both the Frenchman Mountain and Muav Formations thicken considerably to the west (Fig. 3), whereas thickening is modest in the Tapeats and Bright Angel Formations.

Our new biostratigraphic working hypothesis (Fig. 3; Fig. DR2) summarizes and calibrates Tonto Group trilobite biozones based on available precisely dated regional and global sections (Schmitz, 2012; Sundberg et al., 2016, 2020). The Tapeats Sandstone has abundant trace fossils such as *Arenicolites*, *Cruziana* and *Skolithos*, but relatively few body fossils. Trilobites from the lower Bright Angel Formation represent the *Nephrolenellus multinodus* to *Mexicella mexicana* trilobite biozones low in western Grand Canyon sections (ca. 506–505 Ma; McKee and Resser, 1945; Sundberg, 2011). As noted by McKee and Resser (1945), and confirmed by our work, trilobites of the *Glossopleura walcotti* Biozone (ca. 505 Ma; Sundberg, 2018) occur high in the Bright Angel Formation to the west and lower in the east (Fig. 3). The upper Bright Angel Formation has *Ehmaniella* Biozone (ca. 504 Ma) trilobites. The upper Muav Formation contains the genus *Spencella* (McKee and Resser's [1945] *Solenopleurella* horizon) and is assigned to uppermost *Ehmaniella* and *Bolaspidella* biozones, ca. 504–501 Ma (Fig. DR2). The Frenchman Mountain Dolostone may correlate in part to the *Crepicephalus* Biozone, based on its stratigraphic position below the Nopah Formation, whereas lowermost strata in the Las Vegas area contain *Aphelaspis* to *Elvinia* biozones (Palmer, 1965; Miller et al., 1981).

REGIONAL AND GLOBAL IMPLICATIONS

Figure 4 shows our suggested regional correlations for the Tonto Group, our suggested modifications of the Cambrian time scale (Cohen et al., 2013), and a working hypothesis for revised timing of Laurentian trilobite biozones, $\delta^{13}C$ excursions, and $^{87}Sr/^{86}Sr$ variation for the global Cambrian system. In addition to abrupt biologic changes, many stage boundaries are hypothesized to be synchronous with sharp changes in the physical-chemical conditions of the global ocean as recorded by $\delta^{13}C$ excursions (Montañez et al., 2000).

The most unexpected and consequential result of our integrated DZ and biostratigraphic analysis is that the extinction of *Olenellus* and closely related taxa in Laurentia took place well after (45 m above) the ≤507.7 ± 0.4 Ma MDA (Sundberg et al., 2020). Hence, the last appearance datum (LAD) of *Olenellus* in southwest Laurentia can be estimated to have been ca. 506.5 Ma, based on applying depositional rates of 50 m/Ma, compatible with 200 m of deposition of the Tapeats + Bright Angel Formations in ~4 Ma, as required by the combined MDAs, biozone, and stratigraphic data. This estimate is also compatible with the ≤506.64 ± 0.32 Ma age from the Tapeats Sandstone of central Arizona. In Nevada (Sundberg, 2018), the LAD of *Olenellus* is two biozones and tens of meters below the first appearance datum (FAD) of *Oryctocephalus indicus*, which marks the Series 2–Miaolingian Epoch boundary (Fig. DR2), so we suggest an age of ca. 506 Ma for this epoch boundary.

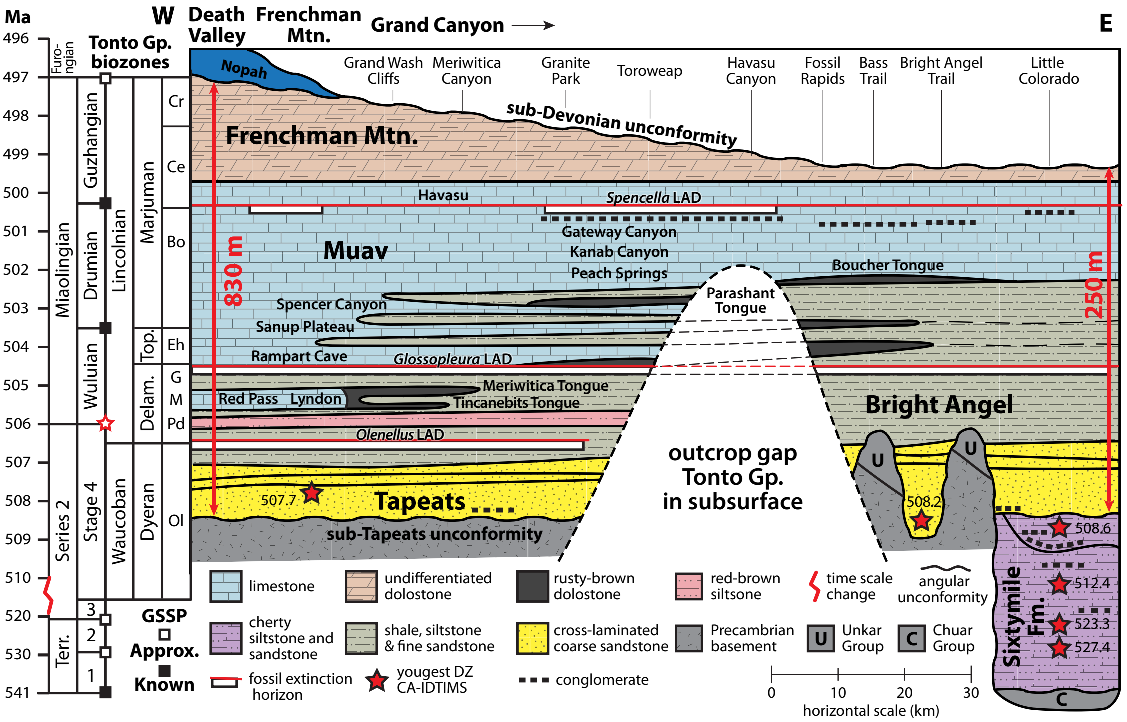


Figure 3. Diagrammatic cross section of the Tonto Group (Grand Canyon, Arizona, USA), modified from McKee and Resser (1945) and Rose (2006). Vertical scale is time; red scale bars show approximate thicknesses at each margin of the cross section. Biochronology shown is our working hypothesis, that can be refined with additional precise U-Pb detrital zircon (DZ) bracketing dates. The Lower Tonto Group is in the subsurface in the central part of the transect, making correlations tentative. The Sub–Tonto Group angular unconformity has a variety of different-age Precambrian rocks beneath it, and hence a variable hiatus. Above the unconformity in the eastern part of the transect, islands (monadnocks) of tilted Unkar Group strata (resistant Shinumo Sandstone) created up to 200 m of relief and were not covered until Bright Angel time. Tonto Group biozones mentioned in text are: OL—*Olenellus*; Pd—*Poliela denticulata*; M—*Mexicella mexicana*; G—*Glossopleura walcotti*; Eh—*Ehmaniella*; Bo—*Bolaspidella*; Ce—*Cedaria*; Cr—*Crepicephalus* (see Fig. DR2 [see footnote 1]). GSSP—global stratotype section and point; CA-ID-TIMS—chemical abrasion–isotope dilution–thermal ionization mass spectrometry; LAD—last appearance datum; Terr.—Terreneuvian; Delam.—Delamaran Top.—Topazan.

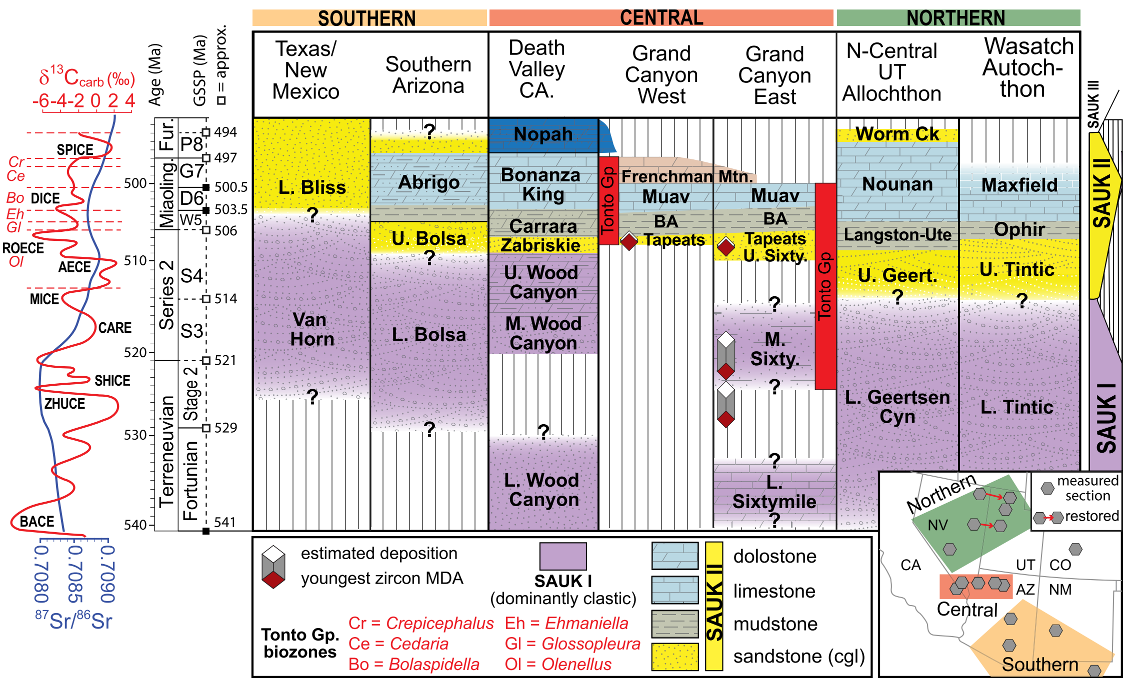


Figure 4. Working hypothesis for correlation of the Tonto Group strata in western Laurentia with other regional formation names; predicted biochronology and chemostratigraphy (red curves were modified from Babcock et al. [2017] and He et al. [2019]). Detrital zircon data are shown with a lower (red) diamond for maximum depositional age based on detrital zircon population (errors less than the size of the symbol) and an upper (white) diamond for our best estimate of depositional age based on globally calibrated biozones (Fig. DR2 [see footnote 1]). Red bars indicate Tonto Group biozones and their suggested approximate time boundaries. See the Data Repository (see footnote 1) for an extended caption and additional references used to construct this figure. GSSP—global stratotype section and point; U—upper; L—lower; BA—Bright Angel; Ck—creek; Cyn—canyon; cgl—conglomerate; MDA—maximum depositional age; Gp.—Group; Miaoling.—Miaolingian; S3,S4—Stages 3 and 4; W5—Wuliuan; D6—Drumian; G7—Guzhangian; P8—Paibian; Sixty. —Sixtymile; Geert—Geertsen Canyon; CA—California; CO—Colorado; NM—New Mexico; UT—Utah.

This revision of ~3 Ma younger than previous chemostratigraphic and chronostratigraphic compilations (Taylor et al., 2012; Peng et al., 2012; Zhao et al., 2019) must now reverberate through proposed correlations between trilobite biostratigraphy and global seawater $\delta^{13}C$ and Sr isotope curves (Fig. 4; Palmer, 1998; Montañez et al., 2000).

CONCLUSIONS

The long-proposed time-transgressive nature of the Tonto Group is supported because *Olenellus* is found in western, but not eastern, Grand Canyon. However, the time frame for the deposition of the initial sheet sands and muds of the Tapeats Sandstone and Bright Angel Formation transgression likely took place in less than ~4 Ma (ca. 508–504 Ma) rather than 40–60 Ma (McKee and Resser, 1945). The Sixtymile Formation has MDAs of ≤527 to ≤508 Ma. A ≤507.7 Ma MDA for the Tapeats Sandstone below the last appearance datum for *Olenellus* in southwest Laurentia falsifies the previous ca. 509 Ma estimate for this global extinction and requires a revised numerical calibration of the Series 2–Miaolingian Epoch boundary to ca. 506 Ma (see also Sundberg et al., 2020). Based on these new data, our testable working hypothesis for the ages of the Tonto Group units is: Tapeats Sandstone (508–507 Ma); Bright Angel Formation (507–502 Ma); Muav Formation (502–499 Ma); and Frenchman Mountain Dolostone (498–497 Ma). Additional tandem dating of DZs in stratigraphic context has the potential to refine correlations of Cambrian sections, discriminate different styles of rifting and deposition during Sauk I and Sauk II transgressive pulses, and calibrate Laurentian trilobite zones, $\delta^{13}C$ excursions, and proposed extinctions, and thereby improve our understanding of the Cambrian System.

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