Evidence for Deep Water Deposition of the Tapeats Sandstone, Grand Canyon, Arizona

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Abstract. The Tapeats Sandstone forms the basal Cambrian deposit of the Tonto Group and is generally interpreted as a shallow marine deposit. In the Grand Canyon, the sandstone was deposited on a low-relief pre-Cambrian surface broken by scattered remnant cliffs of Shinumo Quartzite and isolated granitic hills. Paleoslope measurements and sedimentological features were recorded at 63 sections from 21 localities in the Grand Canyon exhibiting significant pre-Cambrian topographic relief. At 24 of these sites, debris flows were apparently initiated by some catastrophic event that simultaneously broke and transported Shinumo clasts in a matrix of Tapeats Sandstone. These brecciated flows were deposited along the pre-Cambrian surface topography from the cliff-faces basinward. Widespread preservation of the breccias along topographic relief during the deposition of the entire thickness of Tapeats Sandstone and much of the overlying Bright Angel Shale indicates that deposition of even the shallowest material was below storm wave base. Thorium/uranium (Th/U) ratios from the breccia matrix in Ninety-one Mile Canyon indicate sediment deposition in a reducing environment. Such conditions are unlikely in a high-energy, nearshore facies. These submarine flows were deposited on a surface with over 140 m of vertical relief and would have required water depths in excess of 200 m below storm wave base. Sedimentary structures used to identify the Tapeats Sandstone as a shallow water marine facies need to be reevaluated. To explain the features documented in this research, we propose that the Tapeats Sandstone was deposited as a deep-water, submarine fan complex.

Key words: Breccia, Cambrian, deep water, monadnocks, Ninety-one Mile Canyon, Shinumo quartzite, trace elements.

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The Tapeats Sandstone crops out in the Grand Canyon and elsewhere in Central Arizona and forms the basal Cambrian deposit of the Tonto Group (Beus and Morales 1990). Various authors have postulated shallow marine as well as subaerial origins for the Tapeats Sandstone and other basal Cambrian deposits of the Western United States, based on detailed facies reconstructions (McKee and Resser 1945, Wanless 1973, Hereford 1977, Stewart and Suczek 1977, Middleton 1989, Middleton and Elliott 1990). Specifically, McKee, in the earliest definitive work describing the environment of deposition of the Tapeats Sandstone, interpreted the Tapeats Formation as representing deposition in a shallow (less than 20 m), subtidal to intertidal environment reflecting transgressive and regressive sequences (McKee and Resser 1945). This view was reinterpreted by Wanless (1973) who, on the basis of petrologic data from the overlying Muav Limestone, concluded that deposition of the Cambrian sediments occurred on a very shallow tidal to subaerial platform. Working in central Arizona, Hereford (1977) concluded the Tapeats was deposited as intertidal sand bars, beach, tidal flat and tidal channel sediments based on a variety of sedimentological features. Hereford's interpretation of the Tapeats Sandstone has been extended to the Tapeats sediments in the Grand Canyon area (Middleton 1989, Middleton and Elliott 1990).

Paleogeography of Cambrian and Pre-Cambrian Erosional Surface

At the onset of Paleozoic deposition, the pre-Cambrian paleogeographic surface exhibited low relief broken by a series of isolated monadnocks and by occasional granitic hills. These resistant cliffs of Shinumo Quartzite, some rising 250 m above the associated pre-Cambrian landscape, occur as a linear strike ridge trending to the northwest (Sharp 1940a).

Associated with the pre-Cambrian Shinumo Cliffs exposed in the Grand Canyon are Cambrian breccias or debris flows, first identified by Sharp (1940b) at Ninety-one Mile Canyon as a subaqueous "slide". The debris flow, containing large quartzite clasts from the Shinumo Cliffs, was deposited on the cliff-face and along the pre-Cambrian topographic relief, extending up to a kilometer or more from the monadnock.

The Shinumo Cliff and the associated breccias provide an opportunity to investigate the influence of the pre-Cambrian surface relief on Cambrian sedimentary processes and to re-examine the concept of an encroaching marine shoreline. Aspects of the breccias will be used to identify the conditions present during the deposition of the Tapeats Sandstone in the vicinity of the pre-Cambrian monadnocks.

Methods

Paleoslope measurements and sedimentological features were recorded from all outcrops in the Grand Canyon exhibiting significant pre-Cambrian topographic relief. These outcrops and the number of data collection localities include Red (4, collection localities), Mineral (1), Asbestos (4), Vishnu (4), unnamed canyon west of Vishnu [referred to in this paper as "Friday" Canyon] (2), Clear Creek (3), Zoroaster (3), Bright Angel (6), Phantom (3), Ninety-one Mile (6), Trinity (2), Dragon (2), Crystal (2), Shinumo (1), Galloway (2), Stone (1), and Tapeats Canyons (5), as well as the outcrop along the Kaibab Trail (1), the region above Phantom Ranch in the Tapeats Embayment (7), and Monadnock (3) and Hotauta (3) Amphitheaters (Fig. 1).

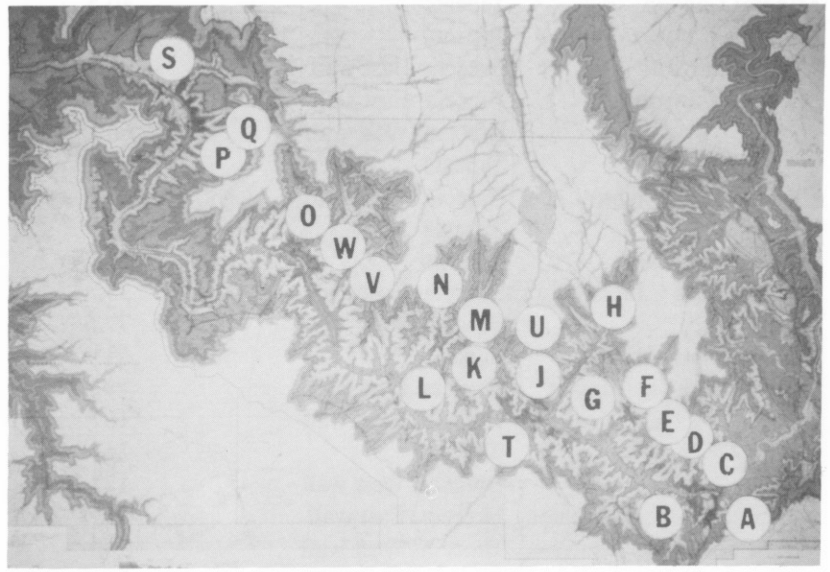

Fig. 1. Grand Canyon map: Outcrop and data collection localities: (A) Red Canyon, (B) Mineral Canyon, (C) Asbestos Canyon, (D) Vishnu Canyon, (E) "Friday" Canyon, (F) Clear Creek, (G) Zoroaster Canyon, (H) Bright Angel Canyon, (J) Phantom Creek, (K) Ninety-one Mile Canyon, (L) Trinity Creek, (M) Dragon Creek, (N) Crystal Canyon, (O) Shinumo Creek, (P) Galloway Canyon, (Q) Stone Canyon, (S) Tapeats Canyons, (T) Kaibab Trail, (U) Tapeats Embayment, (V) Monadnock Amphitheater, and (W) Hotauta Amphitheater (Huntoon et al. 1986).

Paleoslope measurements were generally made using a portable transit and rod, and occasionally using a Brunton compass when conditions prohibited use of the transit (Table 1). The paleotopographic detail required in a crucial region of Ninety-one Mile Canyon necessitated plane table mapping.

Table 1. Observable relief for Breccias and Tapeats Sandstone.

Location	Deposit	Relief (meters)
Red Canyon	Breccia: East wall	95 to >120
	Breccia: West wall	43
	Tapeats	20
Mineral Canyon	Tapeats	40.5
Asbestos Canyon	Tapeats	20
Vishnu Canyon	Breccia: East wall	91
"Friday" Canyon	Breccia: East wall	57
	Breccia: West wall	66
	Tapeats	71
Clear Creek Canyon	Breccia: West wall	>31
	Tapeats	57
Zoroaster Canyon	Tapeats	>16.4
Bright Angel Canyon	Breccia: East wall	33
	Breccia: West wall	77.6
Tapeats Embayment	Tapeats	61
Ninety-one Mile Canyon	Breccia: East wall	>92
	Breccia: West wall	167
	Tapeats	241
Crystal Canyon	Breccia: West wall	128.6
Monadnock Amphitheater	Breccia: East wall	113
East Fork	Breccia: West wall	160
West Fork	Breccia: East wall	87
	Breccia: West wall	73
Hotauta Amphitheater	Breccia: West wall	69
Shinumo Canyon	Breccia: East wall	>80
	Tapeats	>30
Galloway Canyon	Breccia: West wall	22
Stone Canyon	Breccia: West wall	30
Tapeats Canyon	Breccia	33

Seventy-four samples were collected from the Hakatai Shale, Vishnu Schist, Tapeats Sandstone and Bright Angel Shale along Ninety-one Mile Canyon (Fig. 2) for trace and major element analyses. X-ray diffraction data (summarized in Table 2) and X-ray fluorescence data (computed means and standard deviations summarized in Table 3) were compiled by a commercial testing laboratory.

Results

At 24 sites in Grand Canyon where Shinumo Quartzite paleocliffs are exposed, locally derived subaqueous debris flow breccias were identified. These sites range from Red Canyon at the eastern end of Grand Canyon to Tapeats Canyon in the west. Displaying complex sedimentological relationships with the overlying and underlying deposits, the breccias locally blanket pre-Cambrian topography including the cliff faces, as can be seen in localities where this relationship has not been destroyed by modern erosion. In those areas where the exhumed Shinumo Cliffs extend above the Tapeats and into the Bright Angel deposits, the breccias continuously underlie portions of both Tapeats Sandstone and Bright Angel Shale along the pre-Cambrian slope. For example, in Monadnock Amphitheater the original pre-Cambrian slope has been exhumed (Fig. 3). The breccia blankets this pre-Cambrian slope in unbroken continuity beneath both the Bright Angel Shale and Tapeats Sandstone over a vertical distance in excess of 150 m (Table 1). Similar relationships can be seen in outcrops at Red, "Friday", Clear Creek, Zoroaster, Bright Angel, Ninety-one Mile, Crystal, Shinumo, Hotauta, Galloway/Stone, and Tapeats Canyons. Breccias extend for vertical distances of up to 160 m and horizontally up to 2 km from the Shinumo outcrops. We walked these breccia outcrops in all possible localities and found a general absence of evidence for post-depositional erosion or reworking during the interval between deposition and final burial, as evidenced by the continuity of the breccia units and the absence of reworked breccia material in the immediately overlying Tapeats beds.

Clasts in the breccia flow range from pebble size to 10 m and larger. One large clast in Red Canyon contains a mine shaft driven by an ill-fated mining operation. Larger clasts 30 m or more in length were found occasionally in close proximity to the Shinumo Cliffs.

In many areas of the Canyon the basal Tapeats consist of alternating light and dark layers of well-sorted, medium to coarse grained, graded sandstone beds. The debris flows generally lie immediately above or within these lower Tapeats beds. Within the debris flows, the Tapeats sands form much of the matrix. In the west wall of Ninety-one Mile Canyon, portions of this basal Tapeats occur as rip-ups in the breccia (Fig. 4). In some areas near the cliffs, isolated Shinumo clasts are incorporated into the Tapeats Sandstone at various horizons (Fig. 5). In a number of localities paleoslope was determined

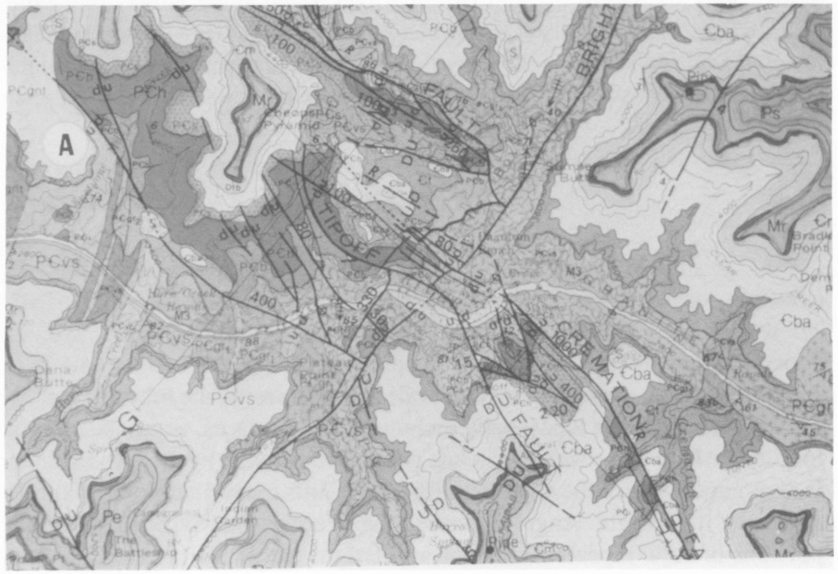

Fig. 2. Grand Canyon map showing the plateau (A) above canyon formed by Ninety-one Mile Creek to the right (Huntoon et al. 1986).

Table 2. XRD results.

Sample name	Major mineral	Minor minerals	Trace minerals
Tapeats Sandstone	quartz	mica, feldspar, hematite, kaolinite, calcite	
Hakatai Shale	quartz	feldspar, mica, hematite	kaolinite
Bright Angel Shale	quartz	feldspar, mica, kaolinite	calcite

Table 3. XRF results.

Formation	Number of samples	Mean Th/U ratio	Standard deviation
Tapeats Sandstone	47	2.6	0.17
Bright Angel Shale	5	2.6	0.06
Hakatai Shale	3	2.2	0.07

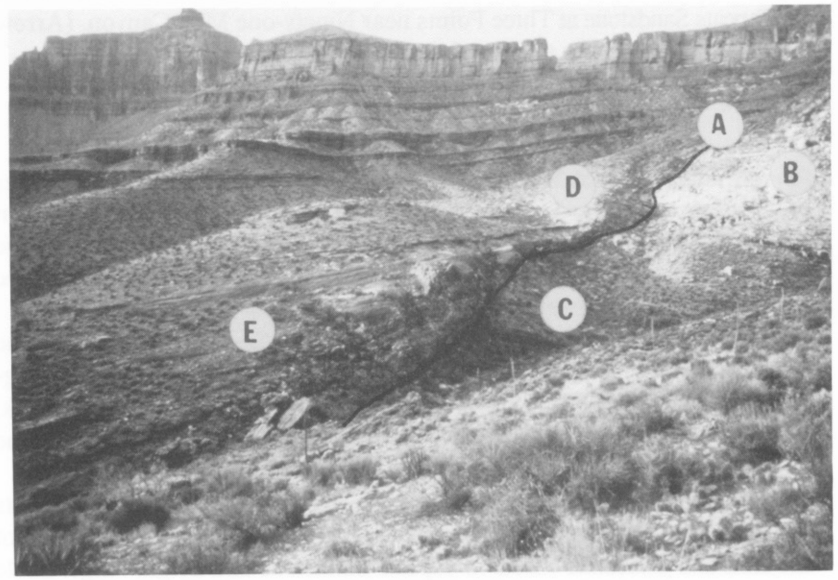

Fig. 3. Breccia (A) blanketing pre-Cambrian Shinumo Quartzite (B) and Hakatai Shale (C) and underlying Cambrian Bright Angel Shale (D) and Tapeats Sandstone (E) at Monadnock Amphitheater. (Breccia overlying Shinumo Cliff is <1 m thick.)

Fig. 4. Rip-up of Tapeats Sandstone (A) within the breccia near the base of the Tapeats Sandstone at Three Points near Ninety-one Mile Canyon. (Arrow indicates man pointing to base of rip-up for scale.)

for individual beds of Tapeats Sandstone (Table 1). The vertical relief over which single beds were deposited exceeded 50 m. In Ninety-one Mile Canyon where the highest Shinumo Cliff is preserved, infillings of Tapeats Sandstone were found in relict drainages atop the cliff, 250 m higher than the base of the Tapeats deposits adjacent to the cliff.

Sedimentary features observed in the Tapeats Sandstones located in the Tapeats Embayment include festoon cross-stratification and isolated herring-bone cross-stratification occurring only in association with the monadnock, graded beds, planar cross-beds, and isolated Shinumo clasts within the sandstone.

XRD analyses revealed similar mineralogy for the Hakatai Shale, Tapeats Sandstone, and Bright Angel Shale (Table 2) with quartz dominating all of the units and glauconite visible in Tapeats Sandstone and Bright Angel Shale hand samples. Trace to minor presence of hematite, indicative of diagenetic alteration of the deposits, had little impact on the Th/U ratios. Mean Th/U ratios for the samples from Ninety-one Mile Canyon are 2.6 (Table 3). Based on a comparison of the means, these ratios for the Tapeats Sandstone and Hakatai Shale occurring in the breccia as matrix and the Bright Angel Shale do not differ appreciably.

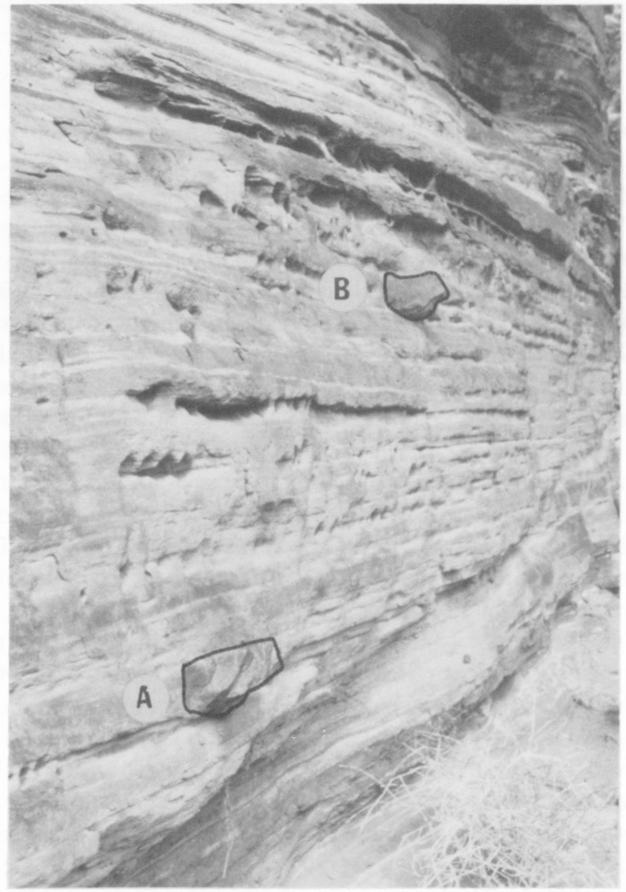

Fig. 5. Clasts outlined at (A) and (B) within bedded Tapeats Sandstone along the south Kaibab Trail. (Clasts are approximately 22 cm across.)

Discussion

Brecciated debris flows containing large clasts require high energy, fluidized depositional processes (Cook et al. 1972). Large clast sizes, synchronous deposition and ubiquitous occurrence of the breccias associated with the Shinumo Quartzite cliffs require a high energy source during Lower Cambrian deposition. The inclusion of large, matrix-supported clasts in the

Tapeats Sandstone suggests that this formation also was deposited under high energy conditions (Fig. 5). It seems likely that deposition of all of these units took place within a high energy marine system associated with the Shinumo Cliffs.

The alternating layers of light and dark sandstone commonly seen in the basal portion of the Tapeats Sandstone were documented previously by Sharp (1940a) and McKee and Resser (1945). Subsequently these beds, consisting of well-sorted, normal graded sands were identified as turbidites (Burgert 1972). This interpretation is consistent with a high energy, marine environment but inconsistent with deposition in a tidal marine environment.

Beds of Tapeats Sandstone blanketing the Shinumo paleocliffs typically show original dip parallel with the pre-Cambrian highs (McKee and Resser 1945). Similar relationships between sandstones and relict cliffs in the Ozarks were noted by Dake and Bridge (1932). In addition, the complex sedimentary structures in the Tapeats Sandstone against the Shinumo paleocliffs at the Tapeats Embayment suggests upslope flow of the sands during deposition. Muck and Underwood (1990) have documented such upslope flow in turbidity currents and have reproduced this effect in laboratory experiments.

In the 24 localities where debris flows, associated with the cliff face and occasionally in direct contact with the face, can be traced laterally into the basin, vertical distances exceed depths typically attributed to nearshore marine environments. Numerous beds of Tapeats Sandstone in the Grand Canyon display vertical relief of 50 m or more (Table 1). At Monadnock Amphitheater and other localities where exhumation of the Shinumo Cliff is occurring and the relationship between the breccia and the original cliff face is preserved, the lack of post-depositional erosion or reworking of the breccia precludes a Cambrian shore line in this region. In most of these localities, portions of the breccia were unprotected during the entire deposition of Tapeats Sandstone and during deposition of a significant part of the overlying Bright Angel Shale. The breccia was not covered entirely until Bright Angel Shale buried the associated Shinumo Cliff. The unreworked and widespread preservation of the breccia would require that it not only be covered by water, but that the unit exist below storm wave base. For this to be true, water depths in excess of 200 m would be required during the deposition of the Lower and Middle Cambrian sediments associated with the breccias and monadnocks in the Grand Canyon region.

In "Friday," Vishnu, Stone, Gallaway and Shinumo Canyons, and other localities where the relationship can be seen, Tapeats Sandstone is deposited directly against the Shinumo Cliff face with little evidence of erosion along the face that would be expected if the cliffs were subaerially exposed or formed part of a shore facies for extended periods of time (Fig. 6). This reinforces the previous conclusion that the cliffs were covered with water while the Tapeats sand accumulated, and thus, were protected from shoreline erosion. Again, water depths in excess of 200 m would be required.

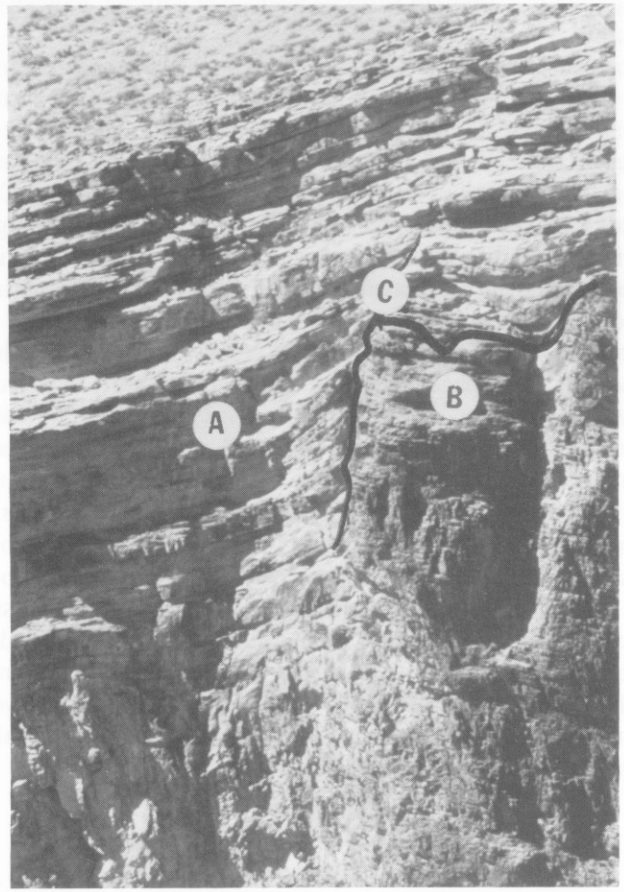

Fig. 6. Near the head of the west arm of Vishnu Temple, Tapeats Sandstone (A) abuts Shinumo Quartzite Cliff (B) with contact marked by line (C). (Tapeats beds are <1 m thick.)

Thorium/uranium ratios have been used to differentiate between oxidizing and reducing environments (Bhatia and Taylor 1981). Oxidation of uranium produces ratios in excess of 5.0 with reducing/low oxygen environments having Th/U ratio values less than 5.0. Samples from the breccia matrix in this research have a mean Th/U ratio of 2.6 (SD = 0.2) indicating a reducing environment consistent with deep water and low oxygen conditions (Table 3). Bhatia and Taylor (1981) also noted that reworking of the sediments would tend to increase the Th/U ratios to values greater than

5.0. This provides additional support for the interpretation that the breccias blanketing the pre-Cambrian surfaces associated with the monadnocks are undisturbed.

The presence of Tapeats Sandstone in relict drainages in the top of the Shinumo Cliff at Ninety-one Mile Canyon, 250 m above the surrounding Tapeats depositional surface, along with paleocurrent trends in the Tapeats Sandstones from northeast to southwest across the pre-Cambrian highs, requires water depths in excess of 250 m above the surrounding pre-Cambrian floor. In this research the presence of herringbone and festoon/trough cross-bedding in association with the upper reaches of the monadnocks indicates complex current activity concentrated near the tops of the pre-Cambrian cliffs. The lack of these features lower in the Tapeats Sandstone sections adjacent to the Shinumo paleocliffs suggests that such activity may be due to the effects of storm wave base near the apex of the monadnocks. If true, this would place the surrounding planar pre-Cambrian surface at depths greater than 250 m plus storm wave base. The primary objection that could be raised to this interpretation is based on the sedimentary structures and facies relationships attributed in the literature to shallow, nearshore marine environments (McKee and Resser 1945, Wanless 1973, Hereford 1977, Middleton and Elliott 1990). Caution is warranted in this application of paleoenvironmental interpretations due to the paucity of information available in regard to sedimentary structures and facies relationships in modern deep water environments. A wide variety of large scale features have been described (Sharp 1940b, McKee and Resser 1945, Middleton and Elliott 1990) in the Grand Canyon; however, the application of sedimentary structures to shallow water models may also apply to the as yet poorly understood deep water settings.

Conclusions

During deposition of the Tapeats Sandstone in the Grand Canyon, water depths exceeded 200 m plus the depth to storm wave base. This conclusion is suggested by the following data: (1) submarine breccia flows blanket the pre-Cambrian surface with over 150 m of vertical relief; (2) flows appear undisturbed by any event subsequent to subaqueous emplacement; (3) apparent absence of Cambrian erosion of the pre-Cambrian cliff faces precludes extended exposure as a shallow, high energy system; (4) Th/U ratios are characteristic of unreworked, deep-water deposits; and (5) the occurrence of Tapeats Sandstone atop the highest Shinumo Cliffs requires water depths over a vertical relief in excess of 200 m for the surrounding pre-Cambrian surface. Based on the data in this study, the authors are reluctant to discount the deep-water model solely on facies relationships easily found in modern shallow water settings but difficult to document in deep water deposits.

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