Origin and Significance of Sand-Filled Cracks and Other Features near the Base of the Coconino Sandstone, Grand Canyon, Arizona, USA

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Abstract

Conventional geology proposes that the Coconino Sandstone formed when wind-blown desert sand migrated over the mud-cracked floodplains of the Hermit Formation. The contact between these two Permian formations was studied along ten trails in the Grand Canyon. Special attention was given to sand-filled cracks that occur at the base of the Coconino penetrating the Hermit, features usually interpreted as mud cracks. The most notable cracks are widest (up to 25 cm) and deepest (up to 10 m) along the Bright Angel Fault on the South Rim. Cracks are always present near major faults, but become narrower, shallower and are sometimes absent altogether as horizontal distance from faults increases and vertical displacement along faults decreases. Vertical laminations within the cracks, U-shaped cracks, cracks that dissipate upwards, slickensides not caused by faulting and other features make the mud crack theory suspect. They might be better explained as clastic dikes (or sand intrusions) which originated by injection during tectonic activity *after* the deposition of the Coconino Sandstone. Evidence near the base of the Coconino such as load casts, burrows and vertebrate trackways, suggests the Coconino was rapidly deposited in an aqueous environment. Cross-cutting relationships indicate the Bright Angel Fault was active during the Precambrian, then quiescent until the Cenozoic (Miocene to Pliocene). If the clastic dikes were caused by tectonic activity, either the Coconino was unlithified or only partially lithified in excess of 200 million years (unlikely, in a conventional scenario) or that only a short amount of time passed between deposition and faulting, greatly reducing the supposed duration of geologic time.

Introduction

The boundary between the Permian Coconino Sandstone and the underlying Hermit Formation is one of the most distinct contacts observable around the rim of the Grand Canyon in Arizona. Most works that discuss these formations mention the sand-filled cracks that occur at the base of the tan, cross-bedded Coconino Sandstone and penetrate the brick-red Hermit Formation. White (1929) and McKee (1934) were the first to describe these features in detail. No one has since questioned their interpretation that these features were giant desiccation mud cracks that were filled by Coconino desert sand blown across the flood plains of the Hermit. Since McKee, the cracks have been little studied. The most notable cracks are up to 25 cm wide and up to

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10 m deep along the Bright Angel Fault on the South Rim. A reconnaissance study was made by Whitmore and Peters (1999) of the Coconino/Hermit contact. They found that crack length varies from location to location, cracks are absent at some locations, load casts and burrows occur at some locations near the base of the Coconino, and that the contact is transitional in the eastern end of the Grand Canyon. Sipes and Peters (2000) came to the conclusion the cracks were true mud cracks, primarily because of their polygonal nature. They compared the cracks to large desiccation polygons that can sometimes form in playa lake beds (Fife, 1977; Goetz, 1980; Lang, 1943).

The dominant view of the Coconino is that its large cross beds are remnants of ancient desert sand dunes because of their similarity to modern desert dunes (McKee, 1979). From a creationist perspective, very little work has been done on the Coconino and Hermit, and both formations need to be thoroughly reexamined before we can definitively determine how they might have been deposited during the Flood. To this end, Austin (1994) challenged the desert sand dune interpretation for the Coconino, suggesting the cross bedded deposits are the result of large submarine sand waves. Brand (1979) and Brand and Tang (1991), found that vertebrate trackways, most common in the lower part of the Coconino, might be best explained as being formed in an underwater environment, not in an exposed, dry environment.

This work will help creationists further understand how the Coconino and Hermit may have formed during the Flood, within short biblical time constraints. I will argue that the sand-filled cracks could not have formed as a result of desiccation, but are likely sand intrusions or clastic dikes that can form only when sand becomes fluidized. I will also show how a clastic dike interpretation questions the validity of the passage of more than 200 million years in the Grand Canyon.

Methods

The Coconino/Hermit contact was studied along seven trails on the South Rim and three trails on the North Rim of the Grand Canyon (Figure 1). South Rim locations included (from east to west) Tanner, Hance, South Kaibab, Bright Angel, Waldron, Dripping Springs, and South Bass

Figure 1. Trail locations and northeast trending faults, pertinent to this study. Sand-filled crack lengths are indicated by ovals and vertical fault displacements are indicated by rectangles. Fault locations are approximate.

Table I

Diagnostic Criteria for Mud Cracks	Refs	Comparison with Sand-Filled Cracks at Grand Canyon
V or U cross section; can have parallel sides	1,2	Present
Infilled from above	1,3	Yes
Fill shows internal stratification and great range of fill and texture	2,4	No, homogeneous texture
Multiple generations (orders) of cracking	1,5	Possibly present
Associated with surficial features (e.g., tracks, rain impressions, etc.)	1	Not present
Usually small, but can be very large	6,7,8,9	All sizes present, but most are large
Commonly, though not always, form complete (connected) polygonal patterns	2,5,10	Incomplete polygons?
Usually straight; sometimes curved	3,5	Most straight
Cracks of same generation have similar depths	11	Depths vary
Can branch and change width	3	Present
Horizontal cracks develop at depth; depth is ~1/3 polygon size	12	Not present
Associated with "mud curls"	9,13	Not present
Correlate to high clay percentage in sediments	14	Hermit is clay rich
Can have radial pattern	2	Unknown

1. Pummer and Gostin (1981); 2. Shrock (1948); 3. Smoot (1981); 4. Diller (1889); 5. Reineck and Singh (1980); 6. Fife (1977); 7. Goetz (1980); 8. Lang (1943); 9. Longwell (1928); 10. Kidder (1990); 11. Sipes and Peters (1990); 12. Konrad and Ayad (1997); 13. Allen (1986);14. Olsen and Haugen (1998)

Trails. The Hermit Trail was also investigated, but the contact was poorly exposed. North Rim locations included (from east to west) North Kaibab, North Bass and Thunder River Trails. The Bill Hall Trail was investigated, but the contact was covered (although it can be seen a few hundred meters from the trail). The Nankoweap trail was not hiked since Abbott and Cook (2004) described the contact as poorly exposed. Along the eastern North Rim, the contact is present between Point Imperial and Cape Royal, but there is no trail access. Cracks were seen with a small telescope at some locations there, but could not be observed in detail. Data are not available for the remote western Grand Canyon where there are few roads and trails. Field work was done in 1997, 1999, and 2004. Field notes, photographs, and measurements were made at most locations.

The literature was examined to develop criteria for mud cracks, syneresis cracks, diastasis cracks, and clastic dikes (or sand intrusions) so the Grand Canyon cracks could be properly identified (Tables I–IV). The literature was also examined for background information on the respective formations and processes. Large playa mud cracks were examined at Lake Lucerne, near Lucerne Valley, California for comparison.

Results

The Hermit Formation

Blakey and Knepp (1989, p. 334) described the Hermit formation as being comprised of "red mudstone, siltstone, flat-bedded, ripple-laminated, and cross-stratified sandstone, aphanitic limestone and sedimentary-pebble conglomerate." Blakey (1990a) described the Hermit as fine-grained, consisting of brownish red siltstones, mudstones, and fine-grained sandstones. It forms a slope, just below the resistant, cliff-forming Coconino Sandstone. The Hermit varies in thickness from about 30 m in the eastern part of the Grand Canyon to about 270 m in the western part of the Grand

Table II

Diagnostic Criteria for Syneresis Cracks	Refs	Comparison with Sand-Filled Cracks at Grand Canyon
V or U cross sectional shape	1,2,3	Present
Infilled from above or below	3	Present from above
Generally only one generation of cracks	3	Many sizes of cracks
From salinity change, loading, or shrinkage of mineral lattices	1,2,3,4,5	Hance Trail cracks possibly from loading
Slight bend or branching at base of crack common	2	Present
Can form polygonal shapes; commonly less regular than mud cracks and often incomplete	2,4,6,7	Hints of incomplete polygons
Compaction often results in oblique orientation of cracks to bedding planes	4	Present at Hance Trail
Can form from tectonic disturbance	8,9	Link to Bright Angel Fault?
Can have preferred orientation	4	Possible
Display bulbous elements when formed by compaction	4	A few are present
Curling of polygons can occur	1	Not present
High sinuosity	3,7	Not present
Muddy fill	7	Not present
Can form radiating (star-like) patterns	10	Unknown

1. Burst (1965); 2. Kidder (1990); 3. Pummer and Gostin (1981); 4. Donovan and Foster (1972); 5. White (1961); 6. Moore (1914); 7. Smoot (1983); 8. Flower and Ives (1946); 9. Pratt (1998a;b); 10. Snyman (1950)

Table III

Diagnostic Criteria for Diastatis Cracks	Refs	Comparison with Sand-Filled Cracks at Grand Canyon
When viewed on bedding planes, they can show orthogonal intersections	1	Present
Vary from complete to incomplete polygons	1	Possible
Most cracks jagged and irregular	1	Present
Many bifurcate downward, and have multiple branches both upward and downward	1	Present
Cracks can be uniformly open, tapered (up or down), or dilated along verticals	1	All present
Cracks can pinch, bulge, or swell	1,2	Present
Cracks are often of varying lengths and not always vertical. Compaction can distort both length and orientation	1	Present
Experiementally reproduced in layers of hardening plaster and sand subjected to shearing	3	Link to Bright Angel Fault?

1. Cowan and James (1992); 2. Kriz and Stepanek (1979); 3. Cowan et al. (2001)

Table IV

Diagnostic Criteria for Clastic Dikes	Refs	Comparison with Sand-Filled Cracks at Grand Canyon
Caused by tectonism, sudden loading, sudden failure, or high fluid pressure	1,2,3,4,5,6,7	Caused by Bright Angel Fault?
Generally massive; but can show flow structures and oriented and deformed mica grains	1,2,8,9,10,11, 12,13,14	Most are massive; some have flow structures; some have aligned grains
Dike walls can show flute and groove marks	13	Not observed
Grading of sedimentary grains may occur parallel to crack walls	13	Unknown; no thin section study
Most consist of coarse silt to fg-mg sand. Well sorted, spherical, fg sand is most susceptible to intrusion	1,2,4,9,15,16	Coconino is well sorted, rounded sand
Dikes vary greatly in thickness and spacing	9,16,17	Present
Dikes can branch and branches can then coalesce	2,7,9,14,16,18,19	Present
Dikes can intersect other dikes	16	Present
Megapolygons can develop in subsurface	20,21	Possibly present
Incomplete and complete polygonal patterns exist	21,22,23	A few are present
Dikes can have preferred orientation based on tectonic factors	1,4,9,17,18, 21,24	Not present
Slickensides or evidence of shearing can occur on sides of dikes; intrusions are associated with faulting and can occur along fault planes	4,9,14	Present at Bright Angel and North Kaibab trails
Dikes can be injected downwards	5,21	Dikes injected from Coconino to Hermit
Dike formation requires: (1) pressure gradient between fluid in intrusion and fluid in fracturing rock, (2) trigger mechanism, (3) tensile strength in fracturing rock	4	Relatively lower permeability in Hermit may have caused pressure differential; Hermit appears to have some tensile strength

1. Diller (1889); 2. Dott (1966); 3. Flower and Ives (1946); 4. Jolly and Lonergan (2002); 5. Pogue (1998); 6. Reimintz and Marshall (1965); 7. Shoulders and Cartwright (2004); 8. Haff (1944); 9. Harms (1965); 10. Hiscott (1979); 11. Jenkins (1925); 12. Laird (1970); 13. Peterson (1968); 14. Waterston (1950); 15. Lowe (1975; 1976); 16. Newsom (1903); 17. Jolly et al. (1998); 18. Boehm and Moore (2002); 19. Truswell (1972); 20. Bellamy (1977); 21. Silver and Pogue (2002); 22. Froede (1998); 23. Raza et al. (1981); 24. Anderson (1951)

Canyon (McNair, 1951). White (1929), performed a comprehensive study of the Hermit, but he focused primarily on plant fossils and a few animal tracks within the unit. He noted that the formation varies from shale to conglomerate, but consists mostly of intensely rippled sandy shales and silts, with angular to subangular sand grains. He claimed that "stream ripples are omnipresent throughout the formation" (p. 17). This could not be confirmed and I saw few sedimentary structures near the top of the Hermit.

The lower contact of the Hermit is with the Esplanade Sandstone, and is clearly unconformable in some places, but not in all. Noble (1922) and White (1929) described huge "hollows" cut into the Esplanade by the Hermit. The largest of these were 21 m deep, 0.8 km wide, and filled with shale (see White, 1929, p. 13, plates B and C). He commented that the Esplanade must not have been well lithified when the Hermit was deposited because the hollows appear to have been easily cut into the sandstones and there are no lithified pieces of Esplanade within the Hermit. Blakey (1990a) agreed with White's (1929) original conclusion that the Hermit was deposited on broad flat floodplains.

The Coconino Sandstone

The most outstanding sedimentary features of the Coconino Sandstone are its giant cross beds. Middleton et al. (1990) reported that the sand advanced to the south, based on cross bed orientations. The Coconino is thickest south of the Grand Canyon where it reaches a maximum of 300 m, near Pine, Arizona (McKee, 1934). It thins and disappears at the Arizona/Utah border, just north of the Grand Canyon and to the east in Monument Valley. It is about 180 m thick in the central Grand Canyon region (Middleton et al., 1990). The formation is nearly all rounded to subangular, fine grained, pure quartz (88–95%) sandstone. Accessory minerals include carbonates, feldspar, and heavy minerals (McKee, 1934). McKee (1934) also noted frosting and pitting of the grains, and that the Coconino contained noticeably finer sand in its upper part compared to the lower.

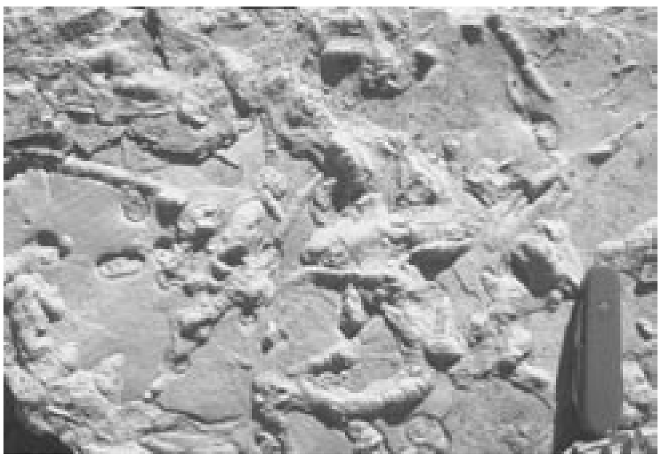

Figure 2. Burrows in the Coconino Sandstone on inclined cross bedded surfaces along the Tanner Trail. The pocket knife insignia is about 1 cm high.

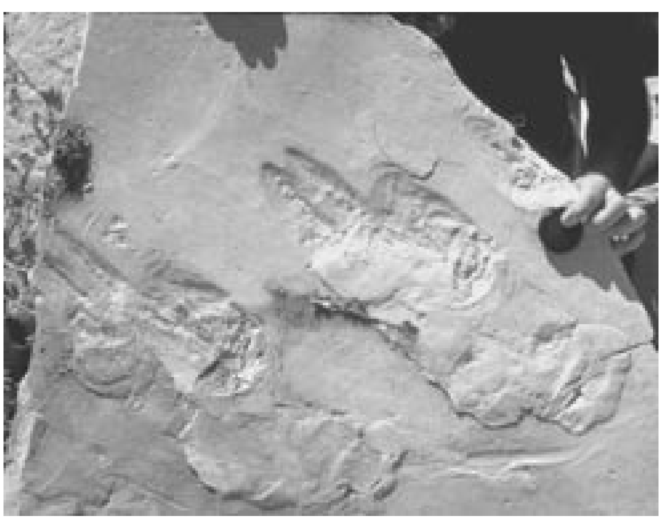

Figure 3. Three sets of large tracks from an unknown track maker near the base of the Coconino Sandstone, Tanner Trail. The lens cap is approximately 6 cm in diameter. The slab was found in float.

He correctly concluded that the pitting and frosting of the Coconino grains are evidence of wind transportation. But he also noted it did not automatically indicate the Coconino was formed in a desert. Bedding planes (laminations) within the Coconino are very clear at all locations, as well as just above the contact with the Hermit. At most locations, the Coconino sands are horizontal at the Hermit contact, but occasionally cross bedding occurs immediately above the contact.

The Coconino is well known for its burrows and trackways (Brady, 1947; Gilmore, 1925; 1926; McKee, 1934), but body fossils have yet to be found. During this research, extensive burrows were found near the base of the Coconino only along the Tanner and Bright Angel trails (Figure 2). Brady (1947) reported additional burrows in the Little Colorado River Canyon, near Seligman, and near Ash Fork,

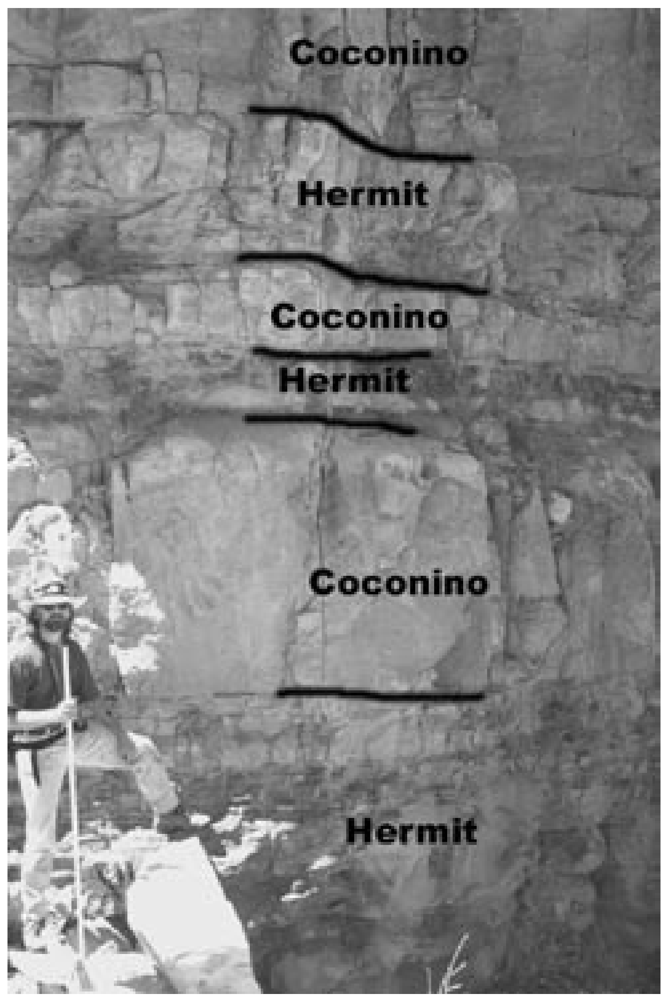

Figure 4. Interbedded transitional contact between the Hermit Formation and the Coconino Sandstone, Tanner Trail. Typically the transition between the Hermit and Coconino is sharp, with no evidence of unconformity or returning lithologies (see Figure 5).

Arizona. The burrows along the Tanner Trail are especially interesting because they occur on numerous inclined bedding planes, but very few of the bedding planes are burrowed thoroughly enough to erase the laminations in the sandstone (seen in cross section). Several types of burrows are present; many with both vertical and horizontal components. They begin 0.5 m above the Hermit/Coconino contact and extend upwards for several meters. A few large tracks (Figure 3) were also found in pieces of float at the Tanner site. Along the Bright Angel Trail, horizontal burrows were found only on four bedding planes, extending up to inclined bedding planes near the base of the Coconino. No vertical burrows were found at this location.

The Hermit-Coconino Contact

Nearly everywhere in the Grand Canyon, the contact between the Hermit and Coconino is sharp. Many workers have noted that no *obvious* unconformity or evidence of significant erosion exists (Baars, 1962; Blakey and Knepp, 1989; Blakey, 1990a; McKee, 1934). Along the Tanner Trail, the contact is transitional (McKee, 1934; Noble, 1922; Whitmore and Peters, 1999); a fact which has been widely ignored. At this location, in the far eastern Grand Canyon, the two formations grade back and forth three times at their boundary (Figure 4). Throughout the canyon, the contact is fairly easy to find, but at many places the top meter or so of the Hermit has been bleached, possibly by groundwater flowing out of the many springs at the contact. The contact may also be transitional at the North Bass Trail, but more field work is needed to confirm that.

East of Seligman and into the western Mogollon Rim region (south of the Grand Canyon), Blakey (1984; 1990b) observed the Schnebly Hill Formation between the Hermit and Coconino. He reported that the contact between the

Figure 5. One of the longest sand-filled cracks along the Bright Angel Trail on the South Rim. The vertical crack is near the center of the photo and is approximately 9 m long. Note how sharp the contact is between the Hermit and the Coconino and how the Coconino cross beds come directly down to the contact.

Table V

Location (see Fig. 1)	**Occurrence and Features of Sand-Filled Cracks**
Bright Angel Trail	Five large, unvenly-spaced cracks examined. Total length unknown due to covering of talus at cliff base. Longest estimated at ~ 10 m long and 25 cm wide. Average length estimated at >6 m. Internal bedding is massive. Possible slickensides at one crack.
Bill Hall Trail	Hermit/Coconino contact not accessible; no cracks observed from trail.
Cape Royal Overlook	Cracks observed at distance with spotting scope.
Dripping Springs	Ten large cracks examined at the Dripping Springs; spaced 1-13 m apart. Many others observed high above trail to springs. Largest crack was 10 m long and 3 cm wide. Shorter cracks ~ 2 m long; average length ~ 4 m. Widest crack was 13 cm; others much narrower. One U-shaped crack present.
Grandview Trail	Contact not observed at close range.
Hermit Trail	Contact not observable at close range, but cracks were visible at distance.
Hance Trail	Many small cracks averaging 0.4 m long; up to 1 m long. Width varies from a few mm to 15 cm. Fill includes small clasts of Hermit Fm. Cracks were greatly deformed and dipping to North. Load casts (one large, many small) present at contact.
Ken Patrick Trail	Cracks observed at distance with spotting scope from trailhead.
North Bass Trail	Five cracks observed, with average length of 1 m. Widths at median crack depth range from 4-10 cm. Cracks narrow downward to a few mm. Possible internal flow patterns visible in three cracks. Two cracks are "squiggly." Hermit/Coconino contact may be transitional, but more field work needed to confirm.
North Kaibab Trail	Ten large and several minor cracks examined. Average length was ~1.2 m. Average width was ~2 cm, ranging up to 10 cm, but many cracks were exceptionally narrow (few mm). Possible slickensides along some crack boundaries. Many narrow cracks were "squiggly." Several cracks connected to sand lenses within Hermit Fm. Cracks are unevenly spaced.
South Bass Trail	Contact accessible, but no cracks observed.
Point Imperial Overlook	Cracks observed at distance with spotting scope.
South Kaibab Trail	Seven cracks examined about 200 m east of trail, where contact is accessible. Average length of longer cracks is ~3.5 m; width ranges up to 20 cm. Total length obscured by talus and by cracks disappearing and then reappearing. Possible internal flow patterns in three cracks. Several cracks connected to sand lenses in Hermit Fm. Cracks are unevenly spaced.
Tanner Trail	Interbedded contact between Hermit and Coconino Fms. No cracks present.
Thunder River Trail	Five cracks examined. Average length is ~0.5 m, maximum is 1 m. Width ranges from a few mm to 5 cm. Cracks are "squiggly."
Vista Encantada Overlook	Cracks observed at distance with spotting scope.
Waldron Trail	Many cracks visible on cliffs high above trail.

Hermit and Schnebly Hill is also sharp, but that it lacks the sand-filled cracks so prominent in the Grand Canyon (Blakey, 1990a). The Schnebly Hill is in excess of 600 m thick near Holbrook, Arizona (southeast of the Grand Canyon).

Sand-filled cracks were found along every trail with the exception of Tanner and South Bass (Table 5). The cracks reach their maximum length and width along the Bright Angel Trail, which descends into the canyon along the Bright Angel Fault. Here, the cracks are up to 25 cm wide and 10 m deep (Figure 5). To the east, west and north, cracks become shorter (less than 2–3 m) and narrower (1 to 10 cm). On the South Rim, cracks disappear completely to the east (beyond Hance Trail) and to the west (beyond Fossil Mountain near Havasupai Point, Noble (1922). No cracks were found along the South Bass Trail. Many cracks

Figure 6. Short, wide sand-filled cracks along the Hance Trail, South Rim. The insignia on the pocket knife is about 1 cm long.

Figure 7. A sand-filled crack that is connected to a sand body within the Hermit Formation, North Kaibab Trail. Note that the crack continues below the sand body. Note how thin the crack becomes as it propagates upward. The left side of the scale is divided into 1 cm gradations.

Figure 8. "U" shaped crack, Dripping Springs, South Rim. The larger crack, on the left, has a U.S. penny on it for scale (approximately 1.9 cm in diameter), just below the number "7." Note the multiple thin cracks that propagate away from the crack on the right.

are long and narrow (Figure 5), but some are short and wide (Figure 6). Most are straight and vertical, but some are contorted. Along the North and South Kaibab trails, some cracks appear connected to lateral sand bodies within the Hermit (Figure 7) forming a dike and sill complex. In some cracks, narrow veins of sand branch and propagate upwards from the sides of larger cracks and sometimes two cracks are connected by a roughly horizontal sand fill (Figure 8). Most cracks narrow downward, but some noticeably narrow upward (Figure 9). Occasionally they intersect each other. At many locations, wide cracks split into narrow cracks. Some of the narrow cracks all but disappear, and then reappear (Figure 10). Some of the cracks appear to have internal structure (Figure 11), but most lack any obvious sedimentary structure. Possible slickensides were noted along and near crack walls at the Bright Angel and North Kaibab trails (Figure 12).

Load casts were found at the formation boundary along

Figure 9. Detail of one of the large sand-filled cracks along the Bright Angel Trail, South Rim. Note how the crack thins upward and downward.

Figure 10. Sand-filled cracks at Dripping Springs, South Rim. Note how the cracks can thin and disappear, and then reappear again. Note how cracks can widen downwards. The U.S. penny, just above the "1" on the largest crack is about 1.9 cm in diameter.

the Hance Trail. One very large load cast (Figure 13) was seen associated with multiple small ones (Figure 14). Load casts were not found at any other locations.

Structural History of the Grand Canyon Region

The structural history of the Grand Canyon region has been summarized in numerous works (Huntoon, 1976; Huntoon et al., 1996; Lucchitta, 1974; Shoemaker et al., 1974; 1978). Uniformitarians propose that major structural activity only occurred twice in the Grand Canyon region: during the Precambrian and Cenozoic. During deposition of Paleozoic and Mesozoic sediments, the area was tectonically inactive. Two major structural trends warp and break the Paleozoic rocks of the Grand Canyon. The first is a north trending series of faults and monoclines (underlain by reverse faults) that are thought to be Laramide structures that developed during deposition of the latest Mesozoic to early Eocene. Most of the tectonic forces were compressive, although a few normal faults were active late in the history of the north trending structures.

The second set of structures that break the Paleozoic rocks, trend northeast (Figure 1). They are thought to have formed after the north trending structures. Faulting occurred mainly during the Miocene and Pliocene, although some faults remain active today (Shoemaker et al., 1974). These faults are thought to have developed primarily through tensional forces because normal faults and grabens are common along the fault zones. Included in the northeast trending structures are the Sinyala, Bright Angel, Fence, Mesa Butte, Hermit, McKee, and Eminence Faults. The largest of these fault systems is the Bright Angel with a total known length of more than 300 km. It has a vertical displacement of about 62 m on the South Rim and about 15 m on the North Rim (Huntoon et al., 1996).

Mud Cracks at Lake Lucerne

Giant playa mud cracks occur on Lake Lucerne, California (Fife, 1977) and were examined by the author. Large irregular polygonal crack patterns were found with sides up to 60 m and diameters sometimes greater than 100 m. The

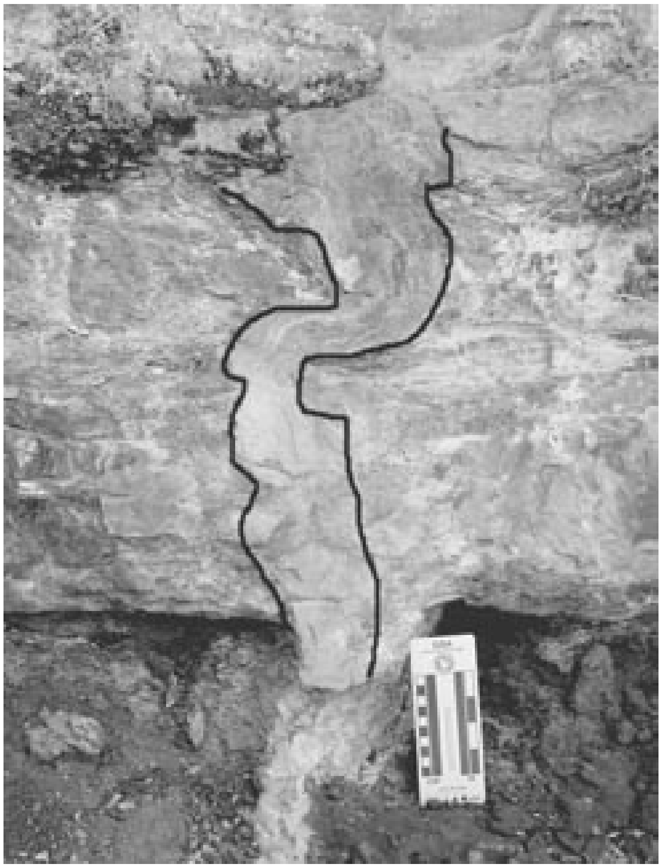

Figure 11. A sand-filled crack that shows probable flow structures along the North Bass Trail. The red-brown color of the upper part of the Hermit is often bleached to a color similar to that of the Coconino Sandstone, sometimes making crack boundaries difficult to see. The Hermit/Coconino contact is about 1 m above this photo.

Figure 12. The conjunction of two large sand-filled cracks along the Bright Angel Trail, South Rim. Vertical slickensides were found at the location of the arrow along the crack boundary. Note that the slickensides could not have been caused by the Bright Angel Fault, because there are no vertical breaks at the contact between the Hermit and Coconino above. The Bright Angel Fault (vertical offset of 65 m) is about 50 m to the left (east) of this outcrop.

Figure 13. A large load cast found along the Hermit/Coconino contact along the Hance Trail, South Rim. Load casts are caused when hydroplastic sediment (the Hermit) fails due to rapid loading sediment above (the Coconino). Sand-filled cracks can be seen just below the large load cast in the center of the photo.

cracks were up to 0.75 m wide and had unknown depths. The cracks were in the process of being filled and modified by material sloughing from crack sides into open cracks, wind-blown material, and small drainages using the cracks as stream courses. As a result, the typical "v-shape" of the mud cracks was becoming difficult to distinguish. Some of the cracks were becoming wider as a result of sloughing and stream course development. Sand dunes were present around the perimeter of the lake, but were stabilized by vegetation.

Discussion

Burrows and Trace Fossils

Many burrows have both vertical and horizontal components suggesting the burrowers traveled both vertically and horizontally through the Coconino sand. Note the circular features at the end of many of the burrows in Figure 2. It was difficult to tell which aspect of the burrow was made first. The burrows at Tanner trail suggest the rapid accumulation of the Coconino sand. Even though some bedding planes are extensively burrowed, the inclined laminae of

Figure 14. Multiple small load casts along the Hance Trail, South Rim. Note the sand-filled cracks just below the load casts. Scale bar is 10 cm.

the Coconino are still distinct. Thus, sedimentation may have occurred so rapidly that burrowers could not completely destroy bedding before additional layers of sand were deposited. Preserved sedimentary fabric is the result of the competing processes of sedimentation and bioturbation (Bentley and Sheremet, 2003). In modern marine environments, total bioturbation and loss of sedimentary structure can happen very quickly (Dott, 1983; Rhoads, 1963; 1967).

Long trails of both invertebrate and vertebrate tracks are well preserved in the Coconino. These sharp, distinct tracks suggest rapid burial. It is difficult to imagine how these features might have formed in a dry desert dune environment. Although experimental results suggest details like this can be made in dry sand, in order to be preserved, the sand must be subsequently dampened by dew or rain and remain undisturbed until it eventually lithifies (Brady, 1939; McKee, 1947). The experiments of Brand (1979) and Brand and Tang (1991) suggest that Coconino vertebrate trackways are best explained as having formed in underwater conditions. Perhaps the invertebrate trails formed in a similar environment.

Load Casts

Load casts, ball and pillow structures, and other related soft sediment deformation features form when coarse-grained sediments are rapidly deposited on softer, unlithified finer-grained sediment. The presence of both large (Figure 13) and small load casts (Figure 14) along Hance trail suggests that, at least here, the Hermit Formation was unlithified and that the Coconino was rapidly deposited or "loaded" on top of the Hermit. If the mud crack hypothesis is correct, the Hermit plains should have been well dried and cracked when the Coconino sand arrived. In that scenario, the formation of load casts would have been unlikely.

Transitional Contact

The interbedded contact between the Hermit and Coconino at Tanner Trail clearly indicates the absence of an unconformity between the two formations, suggesting that they interfinger (Walther's Law). Although many authors have suggested an unconformity is present (Baars, 1962; Blakey and Knepp, 1989; Blakey 1990a; McKee, 1934), there is no erosional evidence. At the Grand Canyon, their contact is exceptionally flat. The only reason some have suggested the passage of long periods of time between the two formations is the presence of the thick Schnebly Hill Formation to the south.

Sand-Filled Cracks

Mud cracks are the result of subariel shrinkage of clay rich sediments from desiccation. Syneresis cracks are the result of subaqueous mud shrinking at the sediment-water interface. They also can form interstratally (Pratt, 1998b). Diastasis cracks (Cowan and James, 1992; Cowan et al., 2001) are generally small sand-filled cracks that form substratally and are likely due to tectonic activity. Clastic dikes, also known as sand intrusions, have been long recognized in the literature (Diller, 1889; Harms, 1965; Jolly and Lonergan, 2002; Newsom, 1903). These are generally larger features than diastasis cracks, and occur when sand becomes fluidized and is intruded into surrounding rock. Tables I–IV provide criteria that can be used to distinguish between all of these sand-filled crack types.

At Grand Canyon, there are several problems with the mud crack interpretation for the sand-filled cracks at the Hermit/Coconino contact. Playa cracks do approach the scale of the large cracks found along the Bright Angel Trail, but if wind-blown sand had filled open Hermit mud cracks, the filling would likely exhibit horizontal layering. Smoot (1981) studied sediment filled playa cracks in Nevada and California and found that the cracks had multiple fills. None of the sand-filled cracks in the Hermit exhibited multiple fillings or horizontal stratification, even though the Coconino always shows clear and well defined layering. Instead, the sand in the cracks often exhibited what appeared to be vertical flow structures (Figure 11). Sipes and Peters (2000) suggested that what appeared to be vertical flow structures may be Liesegang banding, a groundwater staining feature. Even if Liesegang banding is present, sedimentary bedding can still be present. Thin section study of the sand fill will be needed to clarify whether Liesegang banding is responsible for the vertical structures or not.

At Lake Lucerne, sloughing of the crack walls was observed. Many large fragments of crack walls had slumped into the open cracks, partially filling them. I did not observe this to any great extent in cracks I examined in the Grand Canyon. Where layering in the Hermit could be seen, it usually exhibited undeformed horizontal bedding adjacent to the cracks, except along Hance Trail. The cracks were filled with tan Coconino sand. Only occasionally could small brown pieces of Hermit mudstone be found in the sand-filled cracks. The contacts between crack walls and the Hermit Formation were always sharp. Sometimes the cracks were only a millimeter or two thick (Figures 7–10). It is hard to conceive how wind-blown sand could have filled cracks in this manner. If the mud cracks stood open on a dry floodplain, we would expect the sand-filled cracks to have at least some laminations of Hermit dust that settled into the open cracks, resulting in laminated mixtures of Coconino sand and Hermit silt filling the cracks.

Figure 15. Oriented grains in a vertical sand-filled crack along the Hance Trail, South Rim. The crack edge is on the right.

On dry lake beds, mud cracks of the same order tend to all be approximately the same width and possibly the same depth. Mud cracks in the geologic record tend to have the same length and consistent spacing between them in cross section. At many of the locations studied in this project, this was not the case. Sand-filled cracks varied greatly in length and width, even those at the same location. Sipes and Peters (2000) claimed the Grand Canyon cracks have consistent depths at any one location, but this was not found to be true at the many locations examined in this study (Table 5).

Another criterion used to distinguish mud cracks in the field is that they are polygonal in shape, sometimes exhibiting several orders of polygons. In some cracks observed in this study there is a hint of polygonal structure. The largest crack along the Bright Angel Trail is actually the junction of two cracks (Figure 12). At some locations, a few cracks were nearly parallel to the rock face, creating a sheet of sand covering the Hermit. Poorly developed, smaller order, polygonal cracking was found along the South Kaibab, Bright Angel and Dripping Springs Trails on the underside of the Coconino where the Hermit had weathered away. However, where this pattern existed, it was very poorly developed in cross section and only occurred with very small, short cracks. This pattern could not be clearly connected to the larger sand-filled cracks. Injected clastic dikes can also have polygonal patterns (Froede, 1998; Reimnitz and Marshall, 1965; Silver and Pogue, 2002). So, even if the larger cracks are later found to be truly polygonal, it does not prove a mud crack origin.

Another criterion often used to identify mud cracks is that they are wide at the top and then narrow downwards (Smoot, 1981), although this is not always true. In this study, I observed sand-filled cracks at most sites that widened downward. Sometimes cracks thin downward, disappear, and then reappear further down and become very wide again (Figures 7, 9, and 10). At Dripping Springs, two vertical cracks (one meter apart) are connected horizontally (Figure 8). It is very difficult to explain these types of features by the filling of mud cracks by wind blown sand.

The sand-filled cracks might be better explained as clastic dikes injected during tectonic activity. Clastic dikes are known to occur abruptly during seismic events (Bourgeois and Johnson, 2001; Diller, 1889; Dott, 1966; Flower and Ives, 1946; Jolly and Lonergan, 2002; Matsuda, 2000; Pogue, 1998; Pratt, 1998a,b; Reimnitz and Marshall, 1965; Shoulders and Cartwright, 2004; Silver and Pogue, 2002), impact events (Kenkmann et al., 2004) and sudden loading from tsunami waves (Feldl et al., 2002; Stewart, 2003). It may be no coincidence that the longest and widest cracks known are in the immediate vicinity of a 62 m offset of the Bright Angel Fault. Crack length and width decreases to the east, west, and north of this location (Figure 1). Many features of the cracks can be better explained by this interpretation: (1) sand-filled cracks connected to one another and to sand bodies within the Hermit; (2) cracks that widen downwards; (3) cracks with no apparent connection to the Coconino; (4) apparent flow structures; and (5) small clasts of Hermit mudstone within the sand-filled cracks (Figure 15). These are all better explained by the sand being injected downward into the Hermit Formation from the unlithified Coconino. Clastic dikes commonly have no discernable internal sedimentary structures and often appear massive. However, flow structures, oriented grains, oriented clasts, and grading of sedimentary grains can be present (Diller, 1889; Dott, 1966; Haff, 1944; Harms, 1965; Hiscott, 1979; Jenkins, 1925; Laird, 1970; Peterson, 1968; Waterston, 1950). Most of the sand-filled cracks in the Grand Canyon are massive in appearance, but some do contain apparent flow structures.

Slickensides have been reported associated with clastic dikes (Harms, 1965; Waterston, 1950). At Bright Angel Trail, slickensides are present along at least one of the large sand-filled cracks (Figure 12). They are vertical, but there is no evidence of faulting at the Hermit/Coconino contact. The Coconino lies perfectly flat over the Hermit. These slickensides could not have formed from vertical movement along the Bright Angel Fault (about 50 m to the east). There is not even a joint in the Coconino above the crack filling (Figure 12).

Tables I–IV show the sand-filled cracks observed in this study have more features in common with clastic dikes than with mud cracks or syneresis cracks. Note they are very similar to diastasis cracks, except for size. Diastasis cracks might be considered "mini" clastic dikes. I believe that clastic dikes are clearly the best explanation for the sand-filled cracks that penetrate into the Hermit Formation. They exhibit many characteristics of clastic dikes, including slickensides, flow patterns and "U" shapes that cannot be explained by the other crack types.

Timing of Crack Formation

If the sand-filled cracks originated from injection due to tectonic activity along the Bright Angel Fault, the timing of this event poses an interesting dilemma for conventional geology. The Bright Angel Fault was initially active in the Precambrian but remained dormant until the Cenozoic (Huntoon and Sears, 1975). For Coconino sands to be injected into the Hermit, they would have to be fluidized. In other words, the Coconino had to remain unlithified from Permian time (when it supposedly formed) until the late Cenozoic (when faulting resumed), a period of more than 200 million years!

A clastic dike interpretation is of interest to Flood geologists in three ways. First, it refutes the uniformitarian interpretation which presumes long periods of time. It is more difficult to posit giant desiccation mud cracks during the midst of the Flood, but clastic dikes are compatible with a Flood model. Second, clastic dikes are injected as fluidized sand, not dry sand. Their presence indicates the Coconino was saturated at the time of deposition. This is consistent with the burrows, trackways, and load casts found in the lower part of the Coconino. Third, it suggests the Bright Angel Fault occurred before the Coconino was fully lithified. In uniformitarian terms, this would mean that the Coconino remained unlithified during the entire Mesozoic. This is much less of problem in the short time frame of the biblical model, since most or all of the Mesozoic in the Colorado Plateau region was probably deposited during the Flood.

The following sequence of events is proposed for the development of the sand-filled cracks in the Grand Canyon.

1) The Paleozoic and Mesozoic sections of the Colorado Plateau were deposited during the Flood.
2) The Hermit Formation was not very permeable because of its high clay content, so hydrostatic pressures grew in the permeable Coconino sand faster than in the clay-rich Hermit. As hydrostatic pressure in each formation increased with burial, the Coconino maintained a slightly higher pressure, sealed by the top of the Hermit.
3) Cenozoic tectonic activity along the Bright Angel Fault (late Flood or early post-Flood) caused fluidization of the Coconino sand and ruptures at its interface with the partially consolidated Hermit Formation. Following the pressure gradient, sand was injected from the Coconino into the Hermit. Cracks may have propagated from one or more locations (not necessarily directly above each crack mouth). Crack propagation occurred by forceful injection of the Coconino sand, and continued horizontally and vertically (along zones of weakness?) until hydrostatic pressures equalized. Theoretically, the rounded, fine grained sand of the Coconino would be most susceptible to fluidization and clastic dike formation (Jolly and Lonergan, 2002) during earthquake activity. Cracking at the boundary may have been initiated by the same tensional forces responsible for the Bright Angel Fault System (it is difficult to generate cracking in compressional regimes, like the north trending structures). Where clastic dikes are long and straight, the Hermit was better lithified (e.g., along the Bright Angel Trail) and where dikes are more "squiggly," the Hermit was only partially lithified (e.g., along the Thunder River Trail) at the time of faulting. All dikes were likely injected in more or less vertical propagation cracks, but became "squiggly" as the Hermit later was compacted (Figure 16). Compaction and dewatering may have occurred coincident with dike injection (Bourgeois and Johnson, 2001; Pratt, 1998a,b)
4) Erosion of the Colorado Plateau and the Grand Canyon.

Potential Problems for the Sand Intrusion Hypothesis

If cross beds from the Coconino are ever observed deep within crack mouths, this would support the mud crack

Figure 16. A "squiggly" sand-filled crack along the Thunder River Trail, North Rim. The crack probably became deformed as the Hermit compacted. Notice how the Hermit has been "bleached" on the sides of the crack, likely due to groundwater movement.

theory over the clastic dike hypothesis because the mud crack hypothesis would predict deep, open mud cracks on the Hermit surface prior to arrival of the Coconino sands. As dunes encroached over the area, some of these dune sands would then have partially filled the deep cracks. Coconino cross beds can occasionally be found directly on top of the Hermit at several locations (Tanner, Bright Angel and South Kaibab), although the Coconino more typically exhibits planar bedding just above the Hermit. So far, no cross beds have been found entering Hermit cracks. Cross beds were observed directly on top of a crack at South Kaibab Trail, but they did not enter it. If the cracks were filled from above by wind, layering transverse to the crack walls should also be present. If extensive horizontal laminations are found in cracks, it would be problematic for the clastic dike hypothesis, since this style of bedding has been reported in modern cracks that have been filled from above (Davis, 1889; Diller, 1889).

If the Coconino sands have indeed been injected downward into the Hermit, some deformation of the Coconino strata should be present directly above the cracks. However, it is possible for clastic dikes to inject sand downward with little apparent deformation of pre-existing sedimentary layering (Jenkins, 1925). It is also worth noting that clastic dikes can flow and move laterally (Matsuda, 2000). If after further study, no zones of deformed Coconino are found above the cracks, it would be problematic, but not an insurmountable problem for the clastic dike hypothesis.

Conclusions

The large, sand-filled cracks that occur at the base of the Coconino Sandstone in the Grand Canyon are best interpreted as clastic dikes or sand intrusions. The mud crack origin of these features is less likely because: 1) the cracks are not regularly spaced, 2) the cracks have no horizontal layering within them, unlike the overlying Coconino, 3) many cracks widen both downwards and upwards, and 4) many of the cracks are not clearly connected to the Coconino, like a true desiccation mud crack should be. The origin of the sand-filled cracks due to the injection of fluidized Coconino sand appears probable because: 1) vertical cracks are sometimes connected to one another and to thick sand lenses deep within the Hermit, 2) what appear to be flow structures (vertical lineations) are sometimes present within the cracks, 3) many of the cracks lack internal structure, which is a common feature of sand intrusions and clastic dikes, 4) the largest cracks occur in the immediate vicinity of the greatest displacement of the Bright Angel Fault, and 5) some of the cracks are bounded by slickensides which can only explained by sand flow. Evidence that the Coconino was water saturated at one time includes load casts, burrows, and trackways. Injection of the Coconino into the Hermit requires fluidized sand, potentially resulting from tectonic activity along the Bright Angel Fault. If found, factors which could potentially nullify the sand intrusion hypothesis are 1) cross beds which clearly penetrate deep into crack mouths, 2) horizontal layering within cracks, and 3) the absence of Coconino deformation above crack mouths. Incompletely burrowed sediments on inclined bedding planes and load casts suggest the Coconino was rapidly deposited on a soft, unlithified surface, at least at some locations. Identification of the sand-filled cracks as clastic dikes rather than giant desiccation mud cracks would be more compatible with a Flood model and eliminate the necessity of long ages required by the uniformitarian interpretation. Finally, if these features are clastic dikes, then it is likely that a short time period occurred between the deposition of the unlithified Permian section of the Grand Canyon and the later movement of the Bright Angel Fault, rather than the proposed 200 million years that supposedly separates the deposition of the Coconino and the Cenozoic reactivation of the Bright Angel Fault.

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