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Sand injectites at the base of the Coconino Sandstone, Grand Canyon, Arizona (USA)

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ABSTRACT

In the Grand Canyon, large tabular and wedge shaped sand-filled cracks commonly occur at the base of the Coconino Sandstone, penetrating downward into the coarse siltstones of the Hermit Formation. All previous workers have casually identified the vertical sand-filled cracks as desiccation cracks. Until now, they have never been studied. Cracks and their associated features were found and examined at thirty locations; and it was found that they have characteristics difficult to explain using desiccation mud cracks or large playa cracks as a model. Instead, it was found the cracks have features commonly found in clastic dikes and sand injectites. Some lateral sand bodies associated with the cracks have clastic sill-like characteristics. Liquefaction and injection of the basal Coconino into the Hermit is indicated by 1) macroscopic and microscopic banding (flow structures) within the cracks, 2) bedded sandstone clast breccias in structureless sandstone lenses at the base of the Coconino, 3) lateral sand bodies which are connected to the vertical cracks, 4) a zoned depth distribution of cracks about the Bright Angel Fault zone, 5) insufficient clay mineralogy and particle size for the Hermit to crack by desiccation, 6) preferred orientation of the cracks roughly perpendicular to the Bright Angel Fault zone and several other features. Caution should be exercised when interpreting sand-filled cracks as desiccation features (i.e., "mud cracks"), even if the interpretation fits well with accepted paleoenvironmental models.

1. Introduction

Large tabular and wedge shaped sand-filled cracks can often be found at the base of the Coconino Sandstone penetrating vertically and sometimes horizontally into the mudstones of the Hermit Formation. The deepest known cracks occur along the Bright Angel Trail near Grand Canyon Village in Arizona. Some cracks are at least 15 m deep and 0.25 m wide (Fig. 1). They have been identified as desiccation cracks in the popular and scientific literature (White, 1929; McKee, 1934; Abbott and Cook, 2004) probably because of the fluvial and coastal plain environment favored for the red beds of the Hermit (Blakey, 1990), the eolian interpretation for the overlying Coconino (McKee, 1934, 1979; Blakey, 1996) and the tabular or wedge shaped pattern expected of desiccation cracks. Although known for at least 88 years (Noble, 1922), the cracks have never been extensively studied or described with the exception of White's (1929) single petrographic photo and brief comment. Several features of the cracks make their interpretation as desiccation cracks doubtful. These observations include the wrong clay mineralogy and particle size for the Hermit to crack via desiccation, cracks within the Hermit that taper upward and are not directly connected to the Coconino, vertical lineations found within many of the cracks and lateral sand bodies connected to some of the cracks. No one has reported this last fact, which may help explain McKee's puzzling observation (1934, p. 87) that there are "pockets" of the Coconino Sandstone near the top of the Hermit along Hance Trail. We think, based on associated features, the vertical cracks represent injected clastic dikes and the horizontal sand bodies may represent clastic sills, probably of seismic origin.

It is not uncommon for well established examples of desiccation cracks to be questioned or even reinterpreted (Donovan and Foster, 1972; Plummer and Gostin, 1981; Astin and Rogers, 1991; Cowan and James, 1992; Barclay et al., 1993; Pratt, 1998a,b) because of their similarity to other types of sand-filled cracks. Extreme caution should be exercised when interpreting all types of sand-filled cracks (mud cracks, synaeresis cracks, diastasis cracks, molar tooth structures, etc.) because of the similar features they share. Paleoenvironmental presuppositions can lead to erroneous interpretations of various features and might cause one to overlook important data. In this case, the cracks have never been examined closely because mud cracks are expected on desiccating mudflats, which is the accepted paleoenvironment of the Hermit. Subsequently, many important features of the cracks have never been recognized and their true origin has remained hidden.

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2. Methods and observations

2.1. Description of the sand-filled cracks

The Hermit/Coconino contact was visited at thirty-six locations in and around the Grand Canyon (Fig. 2, Table 1) so the broad extent of the cracks could be determined. Where hiking trails were not present, sand-filled cracks were observed with a telescope. At each trail location major cracks were numbered, measured, described and photographed (numbering more than 75 major cracks). At overlook locations, the presence, the relative number (few, many), and the depth of cracks (<1 m, ~1 m, >1 m) were estimated and recorded. Samples were collected from two sites within Grand Canyon National Park (SK and NH, permit # GRCA-2005-SCI-0011) and several sites outside of the park for thin section analysis. In all, ten different cracks from five different locations were sampled and studied petrographically. The samples were of sufficient size to make multiple petrographic slides of each sample collected, including different orientations. All of the sand-filled cracks sampled were from what have typically been called "mud cracks." Samples of the Hermit were also collected at several locations (at sites with and without cracks) for thin section and XRD analysis. Sample preparation and analysis was completed at Calgary Rock and Materials Services Inc., in Alberta.

The largest average crack depths occur in the vicinity of the Bright Angel Trail (>8.7 m). This is adjacent to the greatest displacement (61 m in the Permian rocks) of the northeast trending Bright Angel Fault (Huntoon et al. (1996) report 200 feet on their map). The fault is normal and dips steeply (85°) at the surface and then shallows at depth (to about 45°) causing reverse drag in the Paleozoic rocks (Huntoon and Sears, 1975). Average crack depths become shallower to the east and west, disappearing altogether along Tanner and South Bass Trails. McKee (1934, p. 86) shows a similar pattern of crack depths along the South Rim in his Coconino monograph (Fig. 3). Along the Bright Angel Fault on the north side of the Grand Canyon, where the displacement of the fault is less (15 m in the Permian rocks), we found cracks were still present but they are on average much shallower (1.2 m on North Kaibab and ~1 m further to the north at Vista Encantada). To the west, cracks are shallow or absent along Bill Hall Trail and Thunder River Trails. No cracks were found at places outside the map area (Fig. 2) including Andrus Canyon, Parashant Canyon, Whitmore Canyon, Hurricane Cliffs and near the towns of Show Low, Sedona, Seligman, Drake and Pine, Arizona. When found, cracks are variable in depths at all locations. For example, at Bright Angel Trail nine major cracks were measured having minimum vertical dimensions of 2, 10, 12, 15, 10, 2, 2, 10 and 15 m. Deep (>1 m) and thick (~10 cm) vertical cracks are never widely spaced (Fig. 4G); one usually occurring between 2 and 15 m at all locations (0.5–0.06 cracks per m).

Many of the cracks are deep and narrow (Fig. 1). However, several were found that tapered upward (Fig. 4A), some are "U" shaped (Fig. 4B), several cut directly through sand bodies within the Hermit (Fig. 4C), several appeared suddenly without any obvious connections to the Coconino (Fig. 4D), and some penetrated at a downward angle into the Hermit (Fig. 4E). Sometimes shallower and narrower cracks exhibit ptygmatic folds; deeper and larger cracks are usually planar. Most cracks are structureless in appearance and do not contain any obvious bedding, banding or layering. However, several cracks at each location usually contain vertical lineations or banding, parallel to crack walls (Figs. 4F, 5A, D, G). One thin section (of crack HN1) showed horizontal lineations within cracks, similar in scale and structure to the vertical lineations, although we never found this macroscopically. Macroscopic clasts of Hermit mudstone can occasionally be found in cracks, usually a few millimeters in diameter. The clasts are not common. All clasts were in a matrix of Coconino-like sand. Some large pieces of Hermit were found in several locations that were completely surrounded in a matrix of sand (see inset in Fig. 4C). Slickenside-like features (Fig. 6), which were different from the vertical lineations, are found within some of the cracks along the Bright Angel Trail and Jumpup Spring. The structures are sub-vertical, cutting through the cracks at an angle. No obvious offset was observed within the cracks, the surrounding Hermit, or the Coconino, so the features cannot be true slickensides, although they bore the striated and polished resemblance of slickensides. Thin section analysis of "slickensides" from Jumpup Spring showed calcite mineralization where the features occurred. The underside of the Coconino was examined at all possible locations in search of multiple generations (orders) of cracks that are typically found on modern mud cracked surfaces. No convincing evidence of multiple crack orders was found.

At several locations, cracks intersect with each other. At the Bright Angel location, an upslope view of two large intersecting cracks can be observed (Fig. 1). No cross cutting relationships at the crack intersection was obvious. Junctions of cracks were observed at several locations. Sixty-eight different cracks from nine locations were exposed in such a way that their orientations (strike) could be measured. All of the cracks had vertical, or near vertical dips. Dip was not measured. A rose diagram of the strike data is presented in the top corner of Fig. 2. The mean vector (μ) of the cracks was 142.8º, with the 95% confidence interval for the mean between 126.6° and 159.1°. Statistical tests for circular data in the software package showed the cracks were probably not randomly oriented. The Rayleigh Test had a ρ value of 0.003 and Rao's Spacing Test also gave a ρ value of <0.05. The rose diagram and statistics were plotted and calculated using *Oriana v. 3.13* software, copyright © 1994–2010 Kovach Computing Services.

Fig. 1. Two intersecting sand-filled cracks near the Bright Angel Trail, Grand Canyon. One crack is coming toward the viewer (white arrows) and another crack is intersecting the first (black arrows). Each crack is about 20 cm wide and they penetrate at least 10–15 m into the Hermit (the bottoms of the cracks were buried). The base of the Coconino Sandstone is at the tip of the upper white arrow.